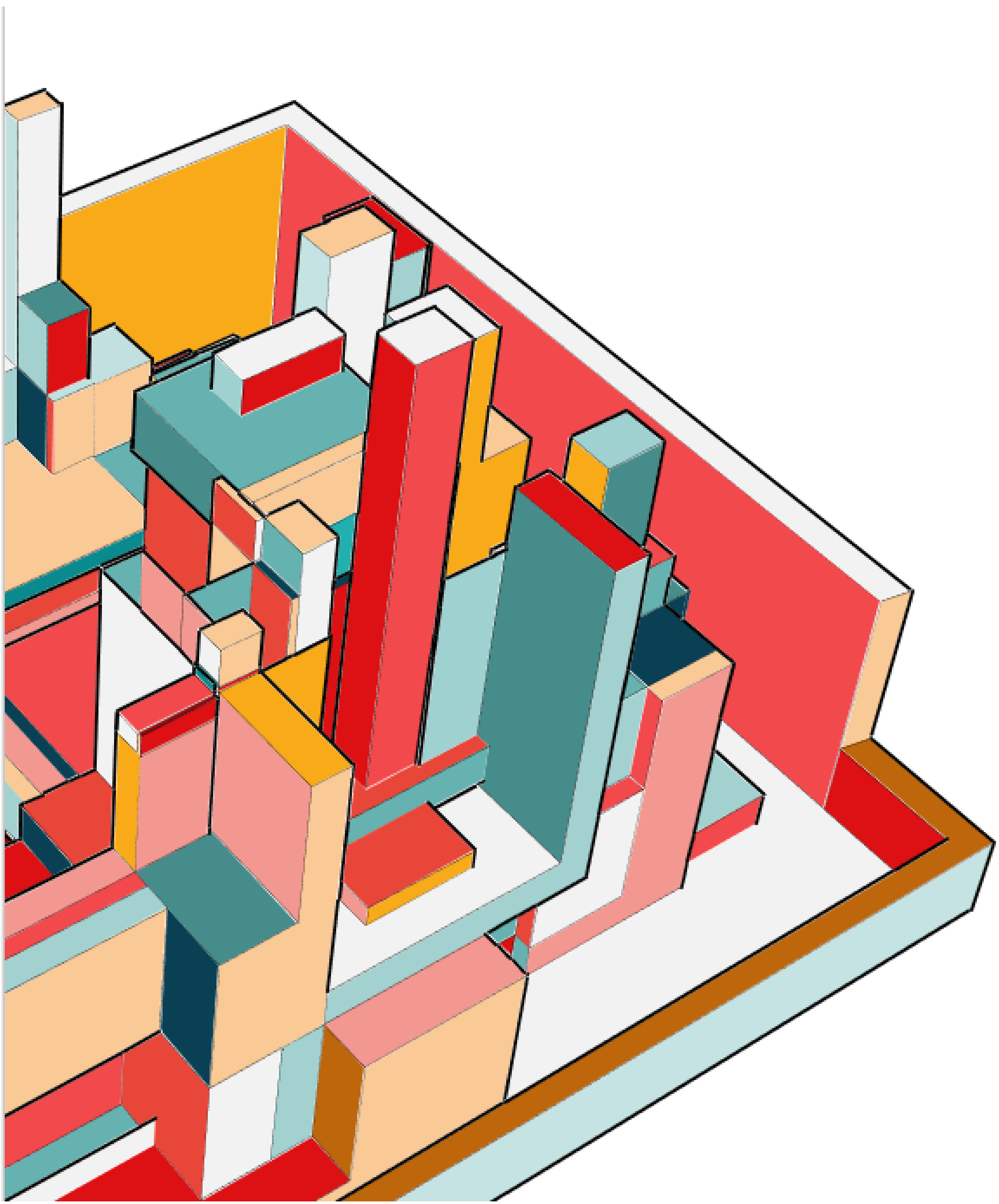
Challenges and opportunities for material recovery and reuse in the construction & demolition industry in Zuid-Holland and the role of Blockchain



Challenges characterizing recovery and reuse practices of construction elements/materials in Zuid-Holland and the potential application of Blockchain technology

by Alex Chiodo

to obtain the degree of

Master of Science

in the program Industrial Ecology at

Delft University of Technology
& Leiden University of Science

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"Always begin with the end in mind"

Stephen Covey's

7 Habits of Highly Effective People

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Report Details

Version	2.0
Presentation date	05/12/2022

Education

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Faculty	Technology, Policy and Management
Master	Industrial Ecology
Graduation laboratory	Circular Building Materials and (re)Manufacturing hub

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Executive summary

Urban areas are becoming more densely populated. More than 50% of the global population is already located in them. The Netherlands is among the countries with the highest population density. In 2017, 80% of its population was living in urban areas. It is expected that by 2050 the Netherlands will need between 300’000 and 1.6 million new homes. Construction & demolition (C&D) is characterized as a resource-intensive industry and among the largest consumer of natural resources. Urban areas account for 80% of global greenhouse gas emissions (GHG) and their infrastructures generate 50% of the total waste produced on earth. Additionally, the increased demand for housing and infrastructure will lead to increased demand for virgin materials and resources, and in turn more waste. From this perspective, the C&D industry will provide a significant contribution to sustainability and will be an important industry for the transition towards a circular economy (CE). The Netherlands has set very ambitious circularity targets for this industry. Specifically, the Government’s Real Estate Agency and Rijkswaterstraat must become fully circular by 2030. Circularity principles address the entire life-cycle of goods and resources, including waste management practices. The overarching objective is to keep resources within closed loops and at their highest level of utility without losing their technical and economic integrity. As of now, 88% of waste generated yearly by the Dutch C&D industry is currently down-cycled for road backfilling purposes, 1-3% is currently reused or up-cycled for high-value practices and the remaining is incinerated.

The objective of this study is to identify the challenges that are characterizing recovery and reuse practices in the C&D industry in Zuid-Holland and make a preliminary assessment on whether Blockchain (through DLT and Smart contracts technologies) can be a suitable solution for addressing them. The methods employed for conducting this study blend desk research with qualitative research (in the form of semi-structured interviews) and a decision-making framework to assess the use of Blockchain technology.

The results indicate that the materials and construction elements to be considered more interesting concerning reuse and recovery are bricks, steel profiles and window/door frames. The decision-making process driving their reuse and recovery is company-specific and differs significantly across firms. In general, the data required for assessing the feasibility of reuse and recovery for construction elements are the material composition of new and old buildings, supply-and-demand specific information (volume and timing), technical specification and quality-related data as well as market prices. Challenges characterizing reuse and recovery practices are several. First, construction and demolition activities and asset management practices are asynchronous and separated by large time gaps. Material procurement starts significantly earlier than demolition activities and the process needs to be accurate and based on reliable data. Data management practices are inconsistent and not harmonized among companies. Digital asset management tools (such as BIM), are employed by large companies only and their use on a national scale is neither harmonized nor compulsory. These aspect limit the economic feasibility of reuse and recovery practices as the accuracy and reliability of data for driving decision-making is poor or non-existing. Intra-project and intra-firm data sharing are therefore not possible. A Blockchain system which integrates smart contracts and distributed-ledger-technology (DLT) can partly address and tackle these issues. To address them fully, however, Blockchain technology must be combined with an asset management tool like BIM for making the solution consistent and scalable at an industry level which in turn requires the implementation of national and industry-wide data management protocols and standards that would harmonize the collection, management and distribution of data across the C&D industry. The Netherlands, unlike other EU member states, has, at this point, no government-driven digitalization strategy in place and is rather opting for a market-driven transition.

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List of abbreviations

(AMS) Asset management system
(AR) Augmented Reality
(BDR) Bouw Digitaliserings Raad
(BEP) BIM Execution Plan
(BIM) Building Information Modelling
(C&D) Construction and Demolition
(CAD) Computer-aided designs
(CDBB) Centre for Digital Built Britain
(CE) Circular Economy
(CEN) European Committee for Standardization
(DAG) Distributed Autonomous Government
(DAM) Digital Asset Management
(DAO) Decentralised autonomous organization
(DApps)DLT-based distributed applications
(DLT) Distributed ledger technology
(DPoS) Delegated Proof of Stake
(DSGO) Digitaal Stelsel Gebouwde Omgeving
(DT) Digital Twin
(EFSA) France Nuclear Energy regulator
(EIR) Exchange Information Requirements
(EMVI) Economisch Meest voordelige inschrijving
(EoL) End-of-Life
(EPR) Extended Producer Responsibility
(GDP) Gross Domestic Product
(GHG) Greenhouse gases
(GIS) Geographic Information System
(GPR) Ground penetrating radar
(GPS) Global Positioning System
(HREC) Human Research Ethics Committee
(ICT) Information and Communication technology
(IDAM) Integrated data assessment and modelling
(IoT) Internet of Things
(ISO) International Organization for Standardization
(LADAR) Laser Detection and Ranging
(LOD) Level of detail
(LOM) Level of Maturity
(LOMD) Level of model development
(MKI) Milieu Kosten Indicator
(MPG Milieu Prestatie Gebouwen
(MPT) Merkel & Patria trie
(NDT) Non-destructive testing
(OECD) (Organisation for Economic Co-operation and Development)
(P2P) Person-to-Person / Peer-to-Peer
(PAT) Physical Asset Tracking
(POA) Proof of authority
(PoS) Proof of Stake

(PoW) Proof of Work
(RFID) Radio Frequency Identification
(SAMP) Specific strategic asset management plans
(SI) System integrator
(TLC) Technology Life Cycle
(TTP) Trusted third party
(UTXO) Unspent Transaction Output
(UWB) Ultra-Wide Band

Glossary

Construction elements: A finite good that fulfils a specific function and can comprise different components or elements. For example, a window comprises a frame, the window, handles and many other components.

Construction material: Uniform raw material that fulfils a specific function. For example bricks.

Reuse: Construction elements/materials are re-employed for the same function or a similar function and did not undergo any refurbishment operation. Small adjustments are possible.

Recovery: Construction elements/materials are extracted from their current application without affecting their integrity.

Secondary materials: goods or items that were waste and are streamed back into use. These include materials from the technical cycle such as cement and metals as well as the biological cycle such as paper and wood. Measuring the input of secondary materials can be used as an indicator of the degree of circularity and the dependency on the extraction and addition of virgin raw material.

Renewable resources: these are goods or items that are generated from biological cycles. For example wood products, fibres and bio-based materials. Measuring the rate of renewable resources over the overall input of resources indicates how much of the resource consumption is sourced from sustainable sources.

Introduction

The following chapter outlines the relevance of this study and the research questions that will be addressed and answered through its execution.

Problem statement

Cities, and urban areas in general, are becoming more densely populated. Already in 2008 more than 50% of the global population was located in urban areas, and the trend was steadily increasing since then (Debacker, W., Manshoven, S., Denis, F., 2016).

This directly translates into the demand for housing and innovative infrastructure which in turn leads to high demand for resources. The construction & demolition (C&D) industry is for this reason regarded as a resource-intensive industry and one of the largest consumers of natural resources. (Munaro, M. R., Tavares, S. F., Bragança, L., 2020) have illustrated how this industry consumes 1/3 of the global energy throughout its supply chain. Cities, by extension, are an important contributor to climate change. Additionally, they have indicated that cities consume 75% of global's primary energy, account for 80% of global greenhouse gas emissions (GHG) and generate an amount of waste which accounts for 50% of the total waste produced on earth.

The Netherlands is listed among the most densely populated countries in the world, with 80% of the Dutch population living in urban areas. The population is expected to grow in the next years which is making the demand for housing increase significantly. It is expected that by 2050 the Netherlands will need between 300’000 and 1.6 million homes (Faessen W., Gopal K., van Leeuwen G., Omtzigt D., 2017) (Claassens, 2020).

In this optic, it is clear that the C&D industry will be an important one in the overall contribution to sustainability. But its importance is not limited to the environmental spheres because this industry is extremely important for the socio-economic stability and prosperity of countries too. On the European level, this industry alone provides more than 10 million jobs and it also contributes to 10% of the European Gross Domestic Product (GDP). In the Netherlands, around 7% of the total workforce (685’000 pp) is employed in the C&D sector (Poljanšek, M., 2017) (CBS, 2022) (Circle Economy, Metabolic , C-creators, 2022).

The Netherlands has set very ambitious circularity targets for this industry. One important objective is the mandate for the central Government’s Real Estate Agency and Rijkswaterstraat to become fully circular by 2030. But the journey is still long and many challenges need to be addressed first. These relate to the need for forming a specialized workforce and implementing innovative waste management practices, as well as defining and executing new collaboration models between C&D companies. Meeting the soaring housing demand, while fulfilling the circularity targets set forth by the Dutch government will necessarily need to identify and implement optimizations strategies aimed at maximizing the recovery and reuse of construction elements, optimising the use of available spaces and elaborating specific and goal-oriented transition pathways that can involve the required stakeholders and boost collaboration. Digitalization will play a pivotal role in this overarching plan (Circle Economy, Metabolic , C-creators, 2022).

Additionally, price increases and the volatility of global commodity markets, coupled with the risk of sudden supply chain disruptions are opening new opportunities and highlighting the urgency of implementing and transitioning towards circular economy (CE) principles. Resources and goods must therefore be kept at their highest level of utility without losing their technical and economic integrity. CE principles address the entire life-cycle of goods and resources and deal directly with design as well as waste management practices (Munaro, M. R., Tavares, S. F., Bragança, L., 2020).

In the waste hierarchy illustrated by (Kirchherr, J., Reike, D., Hekkert, M., 2017) it is discussed the importance of aiming for higher-value waste management practices (such as reuse) over lower ones (such as recycling and remanufacturing) which intrinsically demand additional energy and resources for being implemented. Looking at the material metabolism of the Netherlands' C&D industry it can be observed that lower-value waste management practices are favoured. The industry is still widely dependent on the input of virgin material and the input of secondary raw material is very limited. Virgin materials represent 18.1 million tonnes and only 0.8 million tonnes (4%) are sourced from bio-based materials while 1.7 million tonnes (8%) are sourced from secondary materials (see Figure 1) (Circle Economy, Metabolic , C-creators, 2022).

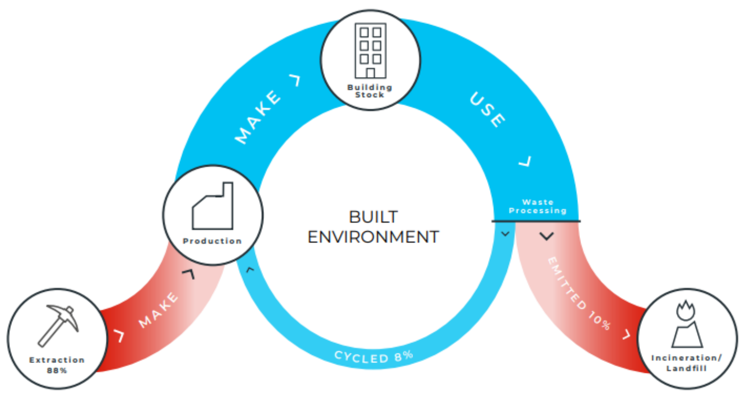


Figure 1 - Graphic representation of the Netherland's resource metabolism (source (Circle Economy, Metabolic , C-creators, 2022))

The problem is that of the 4 million tonnes of waste generated yearly by the C&D industry (infrastructure is not included), 88% is currently down-cycled for road backfilling purposes (the process of replacing the soil/ground removed during excavation) which in the perspective of the waste hierarchies, is a low-value waste management practice. Increasing the rate of reused resources will not fulfil completely the demand for virgin material, therefore the input of virgin resources will still be needed. But higher-value waste management practices will reduce the overall environmental impact of the industry while forcing the industry to innovate the way buildings are designed and constructed. Resources, according to the literature, should be streamed towards high-value applications when possible. Circularity practices have therefore a long-term effect on the transformation and evolution of the industry (Circle Economy, Metabolic , C-creators, 2022) (Rijkswaterstaat – Water, Verkeer en Leefomgeving (RIVM), 2015).

Despite its wide recognition, there is still little research on how higher-value retention strategies of resources should be achieved systemically in the C&D industry. In other words, there are no clear business and industry-wide models that can secure the competitive advantage of companies while allowing them to roll out circularity practices on a large scale. Circularity principles are at this point limited to ad-hoc pilot projects or waste streams. Also, literature outlined interesting insights on how to improve C&D waste practices on a theoretical level, but there is little insight on how to conceive and implement reuse and recovery practices in a market-competitive way (Chaba, K., Mridha, N., 2022) (Adams, K. T., Osmani, M., Thorpe, T., Thornback, J., 2017).

The C&D industry is characterised as a complex and conservative industry with a very fragmented and extensive supply chain. The supply-chain and construction technologies applied are still framed within linear models where buildings are designed and conceived as mono-functional monoliths which will be demolished once their function is fulfilled. Construction elements embedded into buildings are not designed and installed with recoverability and reusability in mind (Hobbs, G., Adams, K., 2017) (Durmisevic, E., 2016) (Durmisevic, E., 2019).

Reuse and recovery practices are still limited within the C&D industry in the Netherlands. Construction elements must be recovered with care to avoid irreversible damage. This requires identifying the construction elements of interest before the demolition process is initiated. Likewise, construction companies require very detailed information about reusable construction elements during the design phase of new projects. One important challenge identified by literature which is hindering reuse and recovery practices is the lack of sufficient information for helping C&D companies in assessing the feasibility and cost-effectiveness of the practice (Chaba, K., Mridha, N., 2022) (Gerhardsson, H., Lindholm, C. L., Andersson, J., Kronberg, A., Wennesjö, M., Shadram, F., 2020).

Digital asset management tools like the Building information model (BIM) can be employed for digital material mapping and creating material inventories, and therefore significantly improve the information flow across the stakeholder present in the C&D supply chain. To be operational on a nationwide level, BIM needs to be supported by a concise data management strategy which can harmonize the collection and distribution of information and in turn enable forward and reverse supply chains around material flows. The precondition is that data is secure and of good quality. Currently, information sharing is fragmented and limited to a project level. Nevertheless, circularity principles require to have multi-directional, intra-project and intra-firm data management (Şahin, H., Topal, B., 2019) (Hradil, P., 2014) (Gerhardsson, H., Lindholm, C. L., Andersson, J., Kronberg, A., Wennesjö, M., Shadram, F., 2020) (Prieto-Sandoval, V., Jaca, C., Ormazabal, M., 2018).

The conservative nature of the C&D industry, coupled with temporary relationships existing between companies which are limited to a single project, prevents companies to establish structured long-term collaborations, partnerships and joint data management processes. Information sharing is an important element for enabling circularity practices and cannot be regarded as an optional choice (Kouhizadeh, M., Sarkis, J., Zhu, Q., 2019). According to (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021) the C&D industry is characterized by important gaps in terms of information flow and the lack of important information brokers. Specifically, information is either not shared or not organized in a way to drive decision-making for stakeholders down or upstream in the supply chain.

Blockchain technology, widely known in the world because of "Bitcoins" is slowly by steadily extending its reach beyond the financial sector. The key characteristic of Blockchain technology is its capacity to create distributed software architectures which permit a network of untrusted, non-transparent and decentralized participants to formalize agreements and transactions in a decentralized and secure way. In other words, data exchange can be made secure, transparent and validated without the need for a centralized or third-party authority. The technology is composed of different building blocks which can be customized and configured for fulfilling very diverse project and company-specific objectives (Tasca, P., & Tessone, C. J., 2019).

Blockchain technology is currently not structurally employed in the C&D sector and some pilot projects have tested its application in conjunction with BIM and Smart Contracts. These tests are limited to assessing project and contract compliance and triggering automatic payment authorizations (Li, H., Arditi, D., Wang, Z., 2015) (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019).

The digitalization of the C&D demolition industry, together with the advancements in BIM, Blockchain and Smart Contracts is being investigated by academics as a potential solution to payment automation and contract compliance. However, there is currently no preliminary research investigating its practical and direct application for enabling reuse and recovery practices in the Netherlands and Zuid-Holland.

On preliminary analysis, the challenges that are hindering reuse and recovery practices can be addressed by the combination of Blockchain, Smart Contracts and asset management technologies. This preliminary investigation will be the focus of this research.

Relevance from an industrial ecology perspective

The approach brought forward by Industrial ecology is to look at sustainability from a systemic point of view. Graedel and Allenby state that Industrial Ecology "*is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized are **resources, energy** and **capital***" (Kapur, A., & Graedel, T. E., 2004).

This research can positively contribute to the overall body of research conducted in the domain of Industrial Ecology as it will investigate data-related challenges that characterize the reuse and recovery practices of construction elements in the construction and demolition sector in Zuid-Holland. The outcome of this analysis will help in understanding the systemic challenges and potential improvements in terms of invested resources, energy, and capital for improving and enabling circularity practices in this industry. Additionally, the topic of supply chain digitalization can benefit many other Industrial Ecology related fields of research such as Industrial Symbiosis, Closed-loop material management, and Life cycle assessment. Also, Industrial Ecology puts a strong focus on the role of technological change and company-specific processes, both key components in the research structure outlined hereafter.

To conclude, understanding how to improve data availability throughout any sort of supply chain is key to seeking systemic solutions and addressing sustainability in the long term. Industrial Ecology is strongly correlated to the availability and accessibility of supply-chain-related data, understanding the systemic challenges and opportunities that surround this topic is therefore paramount.

Research objective and research question (s)

The objective of the following research is to outline and investigate the challenges that are currently limiting and hindering reuse and recovery practices within the C&D industry in Zuid Holland. As briefly illustrated in the introduction, a large amount of construction and demolition waste is downcycled to lower-value uses. Circular principles and waste hierarchies clearly outline the need to move to more high-value retention strategies which can reduce the need for virgin raw materials.

The objective of this research is to have a clear understanding of why construction, architects and demolition companies prioritize practices at the lower end of the waste hierarchy, what construction elements are, from their perspective, interesting for recovery and reuse purposes and why, as well as mapping the current recovery and reuse processes and what information would be needed for making these more efficient. Lastly, this information will be used for determining whether Blockchain can be a solution to these challenges.

This research will aim at answering the following research and sub-research questions:

Research Question: *What challenges are characterizing recovery and reuse practices of construction elements/materials in light buildings in Zuid-Holland and can these be addressed and tackled by Blockchain technology?*

Sub-question 1: *What are the construction elements/materials of interest concerning recovery and reuse and why?*

Sub-question 2: *What is the step-by-step decision-making process for reusing and/or recovering construction elements/materials implemented by construction, architect and demolition firms in Zuid-Holland?*

Sub-question 3: *What is the data/information required for effective reuse and recovery practices and the challenges characterizing these practices?*

Sub-question 4: *Can Blockchain technology address and tackle these challenges and how?*

Theoretical background

The following chapter provides insight into key concepts useful for better understanding the theoretical background of the research and for framing the findings of this paper.

Characteristics of the Construction and Demolition industry

The supply chain of the construction and demolition (C&D) industry is considered to be highly complex. It involves a variety of multidisciplinary stakeholders, processes and activities which are strongly interdependent and interconnected. These stakeholders and processes must be aligned toward a common objective which is the construction or/and demolition of a building within a pre-defined timeframe and budget. The C&D industry is considered to be quite conservative and slow at adopting innovative approaches. This industry is also becoming more competitive over time, which is leaving little room for adopting innovative practices and testing new approaches (Behera, P., Mohanty, R. P., & Prakash, A., 2015) (Nanayakkara, S., Perera, S., Senaratne, S., 2019).

The complexity and the pressure exerted by the competitiveness of the market have also increased the degree of specialists involved throughout the life-cycle of a building and have diversified the number of suppliers of materials/components and sub-elements. As illustrated by (Ashworth, A., & Perera, S., 2018), the need for materials/elements and sub-elements increases the amount and diversity of supply chains that converge during the realization, as well as the demolition, of construction projects. This complexity requires tight coordination. The term Supply Chain Management was coined by Oliver and Webber back in 1982 and it refers to a *" (…) network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer "* (Stadtler, H., 2008).

From a different angle, a supply chain can be seen as a group of distinct organizations/entities that are interconnected through material, information and financial flows. The supply chain is not limited to producers and distributors of the resources employed in a construction project, but it also includes the end users. Also, supply chains are not linear, unidirectional and individual chains, but do rather develop on multiple levels and directions thus generating a complex matrix of resource and information flows that ultimately converge in the final product which is the execution of a construction or demolition project (see Figure 2). Consequently, the lack of such coordination would have a direct and relevant influence on the project's outcome (Stadtler, H., 2008) (Hatmoko, J. U. D., Scott, S., 2010) (Behera, P., Mohanty, R. P., & Prakash, A., 2015).

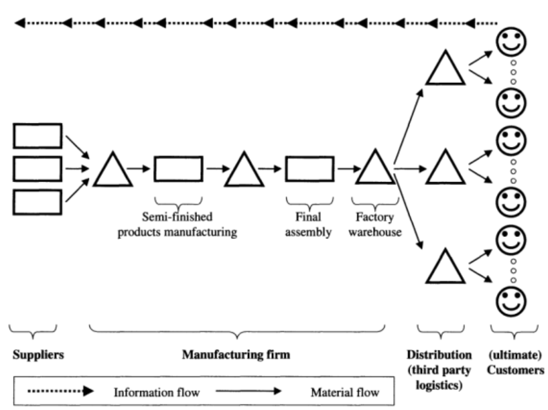


Figure 2 - Simplified supply chain in the construction sector (material and information flow) (source: (Stadtler, H., 2008))

As mentioned before, the C&D industry is becoming more and more competitive. Today, the competitiveness of delivered products and services is not solely bound to the improvement in a single process or unit, but rather to the improvement and efficiency of the supply chain as a whole. A good example is the employment of secondary raw materials in the manufacturing process. Recovering them is not sufficient if the manufacturers are not innovative or ready enough for dealing with them. And this applies the other way around as well. (Stadtler, H., 2008).

Generally, competitiveness can be reached by either providing a superior market-competitive service or by providing it at a lower price. Construction and demolition projects are also very peculiar because every project is intrinsically unique, and context-specific. This results in the convergence of activities from different stakeholders, such as architects, engineers, contractors and sub-contractors as well as material suppliers. While architects and engineers tend to negotiate pricing based on their fees, the rest of the supply chain (especially on the manufacturing and transport side) adopts a "low bid wins" pricing model (Stadtler, H., 2008).

This is an important characteristic of this industry because it defines the relationship between stakeholders as a short-term relationship. The market is, therefore, extremely competitive in terms of bidding procedures, and sharing of valuable information and data is not the norm. The C&D is also extremely conservative and a slow adopter in terms of innovation, and it operates in a context with limited sharing of best practices and collaborations. This trend is slowly changing and the industry is moving towards a more collaborative set-up where the sharing of innovation and know-how, together with the formation of and participation in construction consortiums is becoming the norm. In other words, the relationship is moving away from a linear flow of activities to a network of actors coordinating their activities and information to produce, deliver and utilise products, services, labour and equipment in a cost-competitive way (Ashworth, A., & Perera, S., 2018) (Stadtler, H., 2008) (Hatmoko, J. U. D., Scott, S., 2010).

Typology of construction projects

The type of projects within the construction industry can be segmented into **industrial**, **infrastructure** and **real estate** types of projects (Behera, P., Mohanty, R. P., & Prakash, A., 2015).

Infrastructure projects include airports, irrigation, dams, railway and power projects while **industrial** projects relate to steel, refineries industrial parks. On the other hand, **real estate** projects can be divided into retail, commercial and residential projects. Retail concerns large malls and multiplexes, commercial concerns hotels, office spaces and hospitals while **residential** deals primarily with small private housing (Behera, P., Mohanty, R. P., & Prakash, A., 2015).

An additional characterization of the construction industry, as defined by Behera et al, 2015, concerns the supply chain's complexity of projects. Construction projects can from this perspective be characterized as heavy or light (Behera, P., Mohanty, R. P., & Prakash, A., 2015).

Heavy construction projects are usually industrial and infrastructure types of projects where the supply chain is characterized by a high degree of complexity requiring highly skilled technicians, managers and engineers. Additional aspects concern the handling of materials and construction elements which need to be managed with extreme care and sophistication, to minimize delays and soaring costs. This last element is particularly important because heavy construction projects (such as bridges, highways and airports) need to meet very stringent quality criteria and damages to construction elements or materials can significantly impact the final costs of the project. Governments and/or public institutions are usually the project owners and because the allocated funds come from taxpayers, cost-effective management of the supply chain is extremely important. The supply chain of heavy construction projects usually includes design engineers, contractors and sub-contractors, suppliers of materials, manufacturers of specific construction elements, the project owner (public institutions) and finally financial institutions (Behera, P., Mohanty, R. P., & Prakash, A., 2015).

Light construction projects cover projects such as residential, office buildings and many more small-sized projects. In this case, the budget is allocated by commercial banks and/or by private commissioners. Also in this case the supply chain requires highly skilled expertise, but the quality standards, planning and execution phases are more standardized and characterized by a lower degree of complexity. Usually, engineers and architects collaborate in close contact during the design and execution phase. Because these projects are mostly financed by a private individual, the pricing model is strongly based on competitive bidding (Behera, P., Mohanty, R. P., & Prakash, A., 2015)

Supply chain in the C&D industry

What defines a supply chain is a commitment by different actors (or stakeholders) of labour, assets and resource for the delivery of a product and/or service. Its beginning and its end coincide with the creation and the extinction of the product and/or service (Behera, P., Mohanty, R. P., & Prakash, A., 2015).

As mentioned above construction projects can be categorized as heavy or light projects (Behera, P., Mohanty, R. P., & Prakash, A., 2015). The focus of this chapter is on light construction projects and the processes entailed in their conceptualization and execution.

According to Behera et al. 2015, a construction project can be divided into 6 interconnected and interdependent phases, namely concept, procurement, production, installation, winding up and demolition (see Figure 3). Different activities and stakeholders are involved in each phase.

The **first phase** (concept phase) is initiated by a private individual (can also be a public institution) who identifies his/her needs, and feasibility in terms of urbanistic development and budget allocation. Together with an architect, or directly with the construction firm, the project commissionaire defines the specifics of the project. In the **second phase**, the project commissionaire initiates a tender (or gives a direct commission) to the architect, construction or engineering firm able to provide the necessary competencies and expertise for developing the design and structural specification of the project, identifying the contractors to be addressed for material procurement and also for managing the installation phase of the project. The second phase concludes with a list of materials and construction elements required for meeting the design and structural specifications of the new project. The project commissionaire will also conduct monitoring activities to assess the progress of the project. In the **third phase**, the engineering and/or architect firm commissioned by the client, orders the required material quantities and construction elements from the suppliers and sub-contractors within their network. It can also occur that the client identifies the main suppliers to be involved in the procurement of materials. But in general, it is the engineering and/or architect firm that takes care of this process. These parties are selected based on their expertise and the budget allocated by the project commissionaire. Once procurement contracts are signed between the engineering and/or architect firm and the suppliers and sub-contractors, the **fourth phase** can start. This phase focuses on organizing the delivery of material on-site and on organizing the construction and assembly of construction elements. These activities can either be internalized by the engineering and/or architect firm or externalized to third-party organizations. During this phase, the client and the responsible firms assess the quality of the construction and if it meets the standards outlined in the concept phase. If this is not the case, the commissioned construction firm is responsible for re-executing part of the work. Once completed, the new construction (or asset) is delivered to the client who will be responsible for its maintenance. This is the **fifth phase** of a construction project. The last and **sixth phase** is the demolition phase. In this phase, the building owner is responsible for identifying and commissioning the demolition activity to a firm. The firm will plan and execute the demolition (Behera, P., Mohanty, R. P., & Prakash, A., 2015) (Segerstedt, A., Olofsson, T., 2010) (Lee, M. R., Ismail, S., Hussaini, M., 2014)

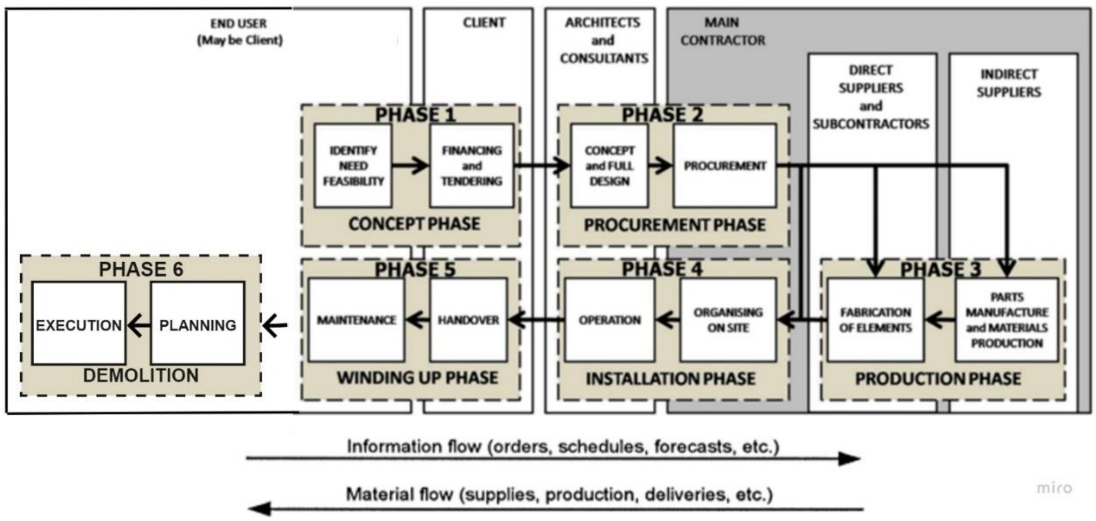


Figure 3 - 6 Phases of C&D project (adapted from (Behera, P., Mohanty, R. P., & Prakash, A., 2015))

The supply chain can also be seen as a supplier and customer relationship mediated by the system integrator (SI) which is usually the construction firm. As illustrated in Figure 4 different flows stem from and converge towards the different parties. For instance, the customer has a set of demands that the SI transforms into a flow of information toward the material suppliers. These generate a flow of material towards the SI which uses its expertise to convert these into a flow of services toward the customer.

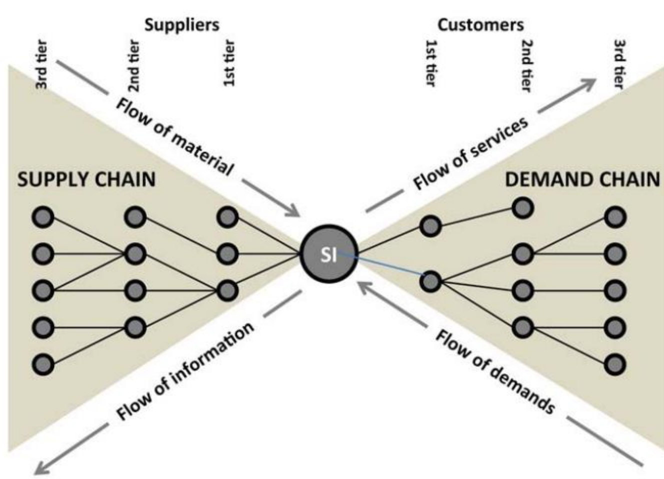


Figure 4 – Supplier, System integrator and customer (source (Segerstedt, A., Olofsson, T., 2010))

Linkages in the construction supply chain

The construction phases are characterized by activities carried out by distinct stakeholders at different points in time and also at different locations. Consequently, construction projects lead to the interlinking of firms and industries, and according to (London, K., 2004) and (Behera, P., Mohanty, R. P., & Prakash, A., 2015) different types of linkages are so far being identified. These are listed hereafter:

- project–firm: one-to-one linkage
- project–firm: one-to-many linkage
- linkages between isolated multiple projects and multiple firms
- network of many firm–project linkages
- network of many firm–project and firm– firm linkages
- network of many firm–project
- project–project and firm–firm linkages
- network of firm–many project and firm–firm linkages

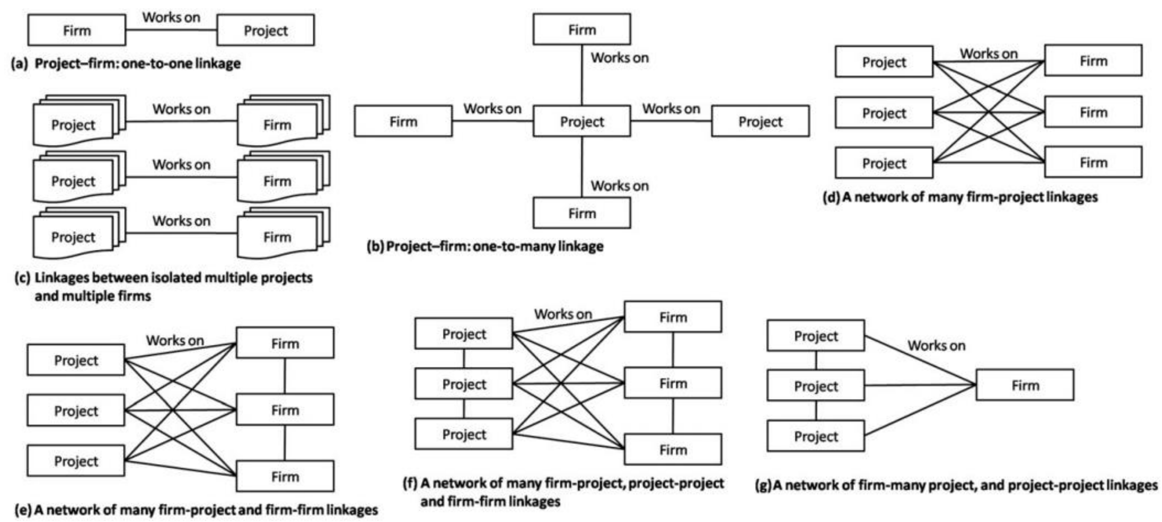


Figure 5 - Possible linkages of construction and demolition projects (source (Behera, P., Mohanty, R. P., & Prakash, A., 2015))

The nature of such linkages exerts a direct influence on the flow of information and resources, ultimately characterizing the management practices of the supply chain as a whole. Also, the type of linkages can have a repercussion on how efficiently circularity practices can be carried out (Behera, P., Mohanty, R. P., & Prakash, A., 2015).

Characteristics of the C&D supply chain

Extensive research has been carried out to identify and illustrate the key characteristics of the supply chain in the C&D industry. The following chapter provides a brief illustration of these characteristics and the complexities that can stem from them.

Customer influence: As illustrated in Figure 4 above, a project (especially for light construction projects) is initiated by a private client (or public institution) who demands specific functions and physical aspects from the final project. In this perspective the client influences the stakeholders involved in the project and the supply chain that merges for manufacturing, delivering and installing the construction elements/materials (Behera, P., Mohanty, R. P., & Prakash, A., 2015) (Vrijhoef, R., Koskela, L., 2000)

Fragmentation: The construction industry is extremely complex and it involves a very wide range of stakeholders such as commissioners, suppliers, contractors, sub-contractors, vendors and even public institutions. The involvement of all these stakeholders is fragmented in time and space and the information flow between them can be negatively affected by this, if not lost altogether. Also, the requirements, business opportunities and challenges are context and project specific and can therefore differ significantly for the involved stakeholders (Behera, P., Mohanty, R. P., & Prakash, A., 2015) (Albaloushi, H., Skitmore, M., 2008)

Number and nature of stakeholders: As illustrated in Figure 6, multiple stakeholders and organizations are involved during the concept, procurement, production and installation phases. What connects and ties them together is the flow of information, materials/products, services and the flow of funds between the architect/engineer firm, the client and all the contractors and suppliers. The flow of information flow is oftentimes hindered and reliant on human interaction due to the lack of harmonized information formats and data management standards (Behera, P., Mohanty, R. P., & Prakash, A., 2015) (Xue, X., Wang, Y., Shen, Q., Yu, X., 2007).

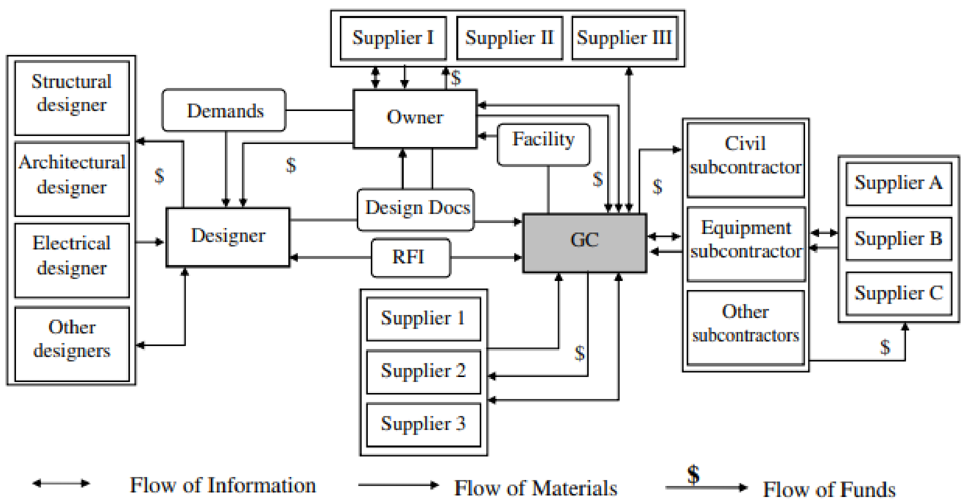


Figure 6 – General structure and flows within the C&D supply chain (Xue, X., Wang, Y., Shen, Q., Yu, X., 2007)

Buyer and supplier relationship: This type of relationship revolves mostly around transactions and the flow of resources. The relationship is usually characterized by conflicts and mistrust leading oftentimes to project delivery problems. The tender price is one of the most important parameters in this relationship and it guides the client in the bidding process (Cox, A., Ireland, P., 2002) (Behera, P., Mohanty, R. P., & Prakash, A., 2015)

Project-based relationship and coordination: Construction projects are intrinsically time-bound and project-specific, meaning that they are limited within a specified timeframe and focused on delivering a specific outcome which is different for each project. The implication is that the relationship among the stakeholders present along the supply chain is usually short-term and focused on the specific project around which all activities are carried out. This leads to short-term coordination and planning, which results in a context of opportunism where all actors attempt to leverage the best conditions from the construction project. This attitude can for example hinder circularity which intrinsically requires long-term commitment and coordination among stakeholders (Aloini, D., Dulmin, R., Mininno, V., Ponticelli, S., 2012) (Behera, P., Mohanty, R. P., & Prakash, A., 2015)

Innovation and change inertia: The construction industry is regarded to be conservative and a slow adopter of innovative practices and processes. As discussed previously, construction companies compete on bidding prices. To be competitive, these companies need to break even in terms of costs associated with the execution of the project. Applying or adopting innovative materials, practices and/or processes is regarded as highly risky because it can affect the final costs associated with the project and can thus jeopardise the project commissioning by the client. The adoption of new practices and/or innovative materials requires time before the prices can be competitive. In this perspective, the C&D industry can be regarded as conservative and a slow adopter of innovations (Behera, P., Mohanty, R. P., & Prakash, A., 2015) (Palaneeswaran, E., Kumaraswamy, M. Ng, T., 2003)

Make-to-order supply chain: Construction projects are conceived and executed for meeting specific needs, may these be private (having a spacious house) or public (improving urban infrastructure). In other words, it is the final client or end-user who initiates a construction project. Therefore, the construction supply chain is initiated by and develops around the needs of the end user (Vrijhoef, R., Koskela, L., 2000) (Behera, P., Mohanty, R. P., & Prakash, A., 2015).

Collaborative opportunities: Although, the collaboration among stakeholders is usually short-term and project-based (see above), organizations in the C&D industry are recognizing the value of inter-organizational innovation practices. These are facilitating the testing and implementation of innovative materials, practices and processes leading to improved production planning and procurement practices (Behera, P., Mohanty, R. P., & Prakash, A., 2015) (Akintoye, A., McIntosh, G., Fitzgerald, E., 2000)

Cyclical demand and supply: Construction projects have a life cycle ranging between 50-100 years (depending on the type of project) and the planning of new construction projects is strongly bound to zoning and urban planning which is a recurring activity for public administrations. As consequence, the release of material stock embedded in buildings can be regarded as predictable over time and can theoretically be forecasted if the information flow between stakeholders is sufficiently efficient (Behera, P., Mohanty, R. P., & Prakash, A., 2015) (Akintoye, A., McIntosh, G., Fitzgerald, E., 2000).

These characteristics have a direct contribution to the complexity of the C&D industry as a whole. The complexity, according to (Behera, P., Mohanty, R. P., & Prakash, A., 2015), is continuously increasing. Construction projects require large investments, efficient coordination between experts from different fields and scattered in different locations, and need to be carried out within pre-defined schedules while meeting increasingly stringent quality standards. **Time** plays a key role because delays can result in legal consequences and soaring costs. Pricing is directly dependent on the amount of time (and materials) invested into the construction activity. **Coordination** among multiple stakeholders is extremely complicated because a construction site is a labour-intensive and high-risk operation in which specific activities are carried out by different stakeholders. Specifically, one firm can perform one part of the work while many specialized sub-contractors move in and out to perform specific sections of work. In this perspective, the construction site transforms significantly over time, leading to the final and completed project. Inevitably, this leads to reduced coordination and collaboration among firms, contractors, sub-contractors and suppliers throughout the life cycle of a project. **Information** and **data** are therefore generated at various sources, with different levels of specification and with different standards and formats. This contributes significantly to data fragmentation resulting in limited communication between stakeholders which can impact the construction during its execution as well as during demolition activities. The execution can be affected by order changes, unsuitable design specifications, poor material quality, disputes on liability and ultimately to overruns in terms of price and time. The demolition phase instead can be hindered by a lack of information and data about the material content of buildings thus hindering the mining activities for specific construction elements and materials. (Akintoye, A., McIntosh, G., Fitzgerald, E., 2000) (Aloini, D., Dulmin, R., Mininno, V., Ponticelli, S., 2012) (Behera, P., Mohanty, R. P., & Prakash, A., 2015)

Contracts, Compliance and financial aspects

Being the C&D a high-risk and resource-intensive industry, the relationship among stakeholders is governed primarily by contracts. In the Netherlands, the "*Uniforme administratieve voorwaarden voor de uitvoering van werken en van technische installatiewerken 2012*" (UAV 2012) provides a standarad contract framework for defining the conditions for the execution of technical work and installations in the construction sector (De Minister van Economische Zaken, Landbouw en Innovatie, 2012). The framework requires clients to externalize to consultants, such as architects and engineering firms, the design of the construction concepts who further rely on third-party contractors. After the termination of the construction, this is handed over to the end user who is responsible for its maintenance and eventual demolition (Vrijhoef, R., Koskela, L., 2000) (Behera, P., Mohanty, R. P., & Prakash, A., 2015)

A construction project entails the transfer between stakeholders of services and physical assets with intrinsic financial value. This implies that besides a transfer of information there are also financial, as well as risk and liability streams throughout the supply chain (Olawale, Y. A., & Sun, M., 2010).

The objective of contracts is to identify and map the liabilities and risks of stakeholders' involvement in the project as well as their obligations and responsibilities towards the contractors. This is extremely important because risks can be identified at each stage of the construction and demolition process and each party involved in it aims at protecting themselves through the establishment of such contracts which outline penalties resulting from the violation of specific obligations and clauses as well as rewards associated with the execution of the commissioned work. Once all parties involved agree on the conditions and sign the contract, this comes into force (Behera, P., Mohanty, R. P., & Prakash, A., 2015) (Luo, H., Das, M., Wang, J., & Cheng, J. C., 2019).

When the contract obligations are met and there are no disputes about the deliverables, financial processes (payments) are fully or partially executed, depending on contract conditions. Financial resources are transferred between parties based on the contract's compliance criteria as well as the company's policies and processes (see Figure 7 (Behera, P., Mohanty, R. P., & Prakash, A., 2015).

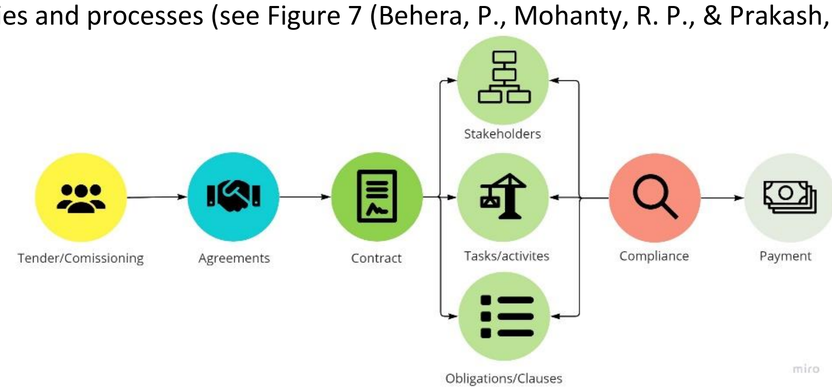


Figure 7 – Simplified schematics of contract flow

Contracts

In the Netherlands contracts employed in the construction sector must follow the guidelines outlined in the UAV 2012 (De Minister van Economische Zaken, Landbouw en Innovatie, 2012). According to (Luo, H., Das, M., Wang, J., & Cheng, J. C., 2019) general contracts must outline the following:

- Organizations, firms and parties involved in the execution of the construction project
- Activities and services performed by the different organizations, firms and parties for the execution of the construction project
- Clauses, penalties and rewards for services and activities

Clauses comprise specific obligations (what should do), permissions (what is allowed to do) and prohibitions (what should not be done) toward the involved parties (Luo, H., Das, M., Wang, J., & Cheng, J. C., 2019) (Ashworth, A., & Perera, S., 2018)

Obligations and activities are what bounds the contracting and the commissioning party together because it defines the exchange of an asset (such as money) for specific services and activities. In this perspective, contract obligations are a key element of construction activities and can according to (Mason, J., 2017) fall under these general types of obligations:

- *pay/build*
- *instruct/obey*
- *set deadlines/meet deadlines*
- *give access/take possession*
- *give design/ follow or complete design*

Consequently, the realization of a construction project requires a large number of contracts established between all the stakeholders involved in the project. The client commissioning the project establishes a contract with an architect or engineering firm that subsequently contracts manufacturers and so, making the cumulative number of contracts increase throughout the supply chain. Due to the temporary collaboration, the multitude of stakeholders involved and the security standards and risks required and associated with the construction project, contracts in this sector are numerous and complex (Luo, H., Das, M., Wang, J., & Cheng, J. C., 2019) (Eitjes, W., 2017)

Compliance

Contract management and compliance activities focus on making sure that obligations defined in the contract are met and respected by the parties involved. Such activities guarantee that functional and operational objectives outlined in the contract are respected and that the interactions between the parties are profitable. In practical terms, compliance activities must make sure that operations and tasks are carried out following contract terms and that all parties are actively pursuing the duties agreed upon. The right of one of the parties to monitor contract compliance is also outlined in the contract (Luo, H., Das, M., Wang, J., & Cheng, J. C., 2019) (Ashworth, A., & Perera, S., 2018)

As outlined in the previous paragraph, different forms of obligations exist.

For example, the Pay/Build obligation outlines the activities that need to be carried out and the financial reward that is rendered from the commissioner to the executing party for a specific result. The reward can also be executed in different formats, but generally, in the construction industry the payment is progressive depending on the completion rate of the project (Behera, P., Mohanty, R. P., & Prakash, A., 2015) (Mason, J., 2017)

Set deadlines/meet deadlines are another set of obligations that are extremely important in contracts. Delays in a construction project can directly impact costs. Therefore, the performance of a project is assessed through aspects such as meeting material delivery deadlines, execution of specific activities within pre-defined deadlines and adherence to the project's timetable (Luo, H., Das, M., Wang, J., & Cheng, J. C., 2019) (Mason, J., 2017)

Pay/Build and *set deadlines/meet deadlines* are important indicators for assessing the performance of a project. From this perspective, these obligations cover an important part of construction contracts and their compliance is extremely relevant for the successful, and cost-effective completion of a project (Mason, J., 2017)

Quality plays also an important role. Quality-related obligations are always indicated in contracts and compliance activity to assess these standards is performed by different stakeholders at different stages of the supply chain. As outlined previously, the multitude of stakeholders involved across the supply chain requires an equivalent number of contracts. Quality-related obligations can relate to the quality of the provided material/construction elements and/or to the performance of the construction work. Compliance activities are usually carried out by the stakeholder commissioning the work. For a contractor or sub-contractor, for example, it might be relevant to review and assess the quality standards of construction elements delivered on-site while for the construction firm might be more important to review the adherence of the overall construction to the execution plan(Behera, P., Mohanty, R. P., & Prakash, A., 2015) (Luo, H., Das, M., Wang, J., & Cheng, J. C., 2019) (Mason, J., 2017).

Compliance activities have also an impact on the overall costs because they require time for auditing, documentation and reporting activities. These activities, as mentioned previously, are conducted by each stakeholder. The allocation of resources by each stakeholder for compliance-related activities is primarily driven by the need for managing risks arising between parties and for reducing the chance of disputes and conflicts (Luo, H., Das, M., Wang, J., & Cheng, J. C., 2019) (Van Groesen, W., 2020)

A relevant aspect is that the compliance activity is conducted with company-specific procedures and systems, leading to the acquisition, processing and storage of data in a non-standardized way. The result is that compliance-related data are duplicated and scattered in different and usually independent databases. This can lead to potential discrepancies in data with the result of increasing mistrust, and the escalation of disputes. (Mason, J., 2017) has acknowledged how the availability of data that are regarded as trustworthy, transparent and traceable by all stakeholders can lead to reduced conflicts and disputes. Such availability of data depends strongly on the data collection, processing and storing processes. The current lack of single-source trustful records leads stakeholders to collect and record their copies of records and to regard these as correct and objective. Therefore stakeholders must accept the data collection and storing procedures undertaken by their counterparts (Behera, P., Mohanty, R. P., & Prakash, A., 2015) (Mason, J., 2017) (Luo, H., Das, M., Wang, J., & Cheng, J. C., 2019)

Compliance tracking is extremely important because it is tied together with the payment terms and clauses included in contracts. For example, the termination of specific activities within pre-defined deadlines and with specific qualities is a prerequisite for the payments to occur. (Behera, P., Mohanty, R. P., & Prakash, A., 2015) (Mason, J., 2017)

To reduce the additional costs incurred by compliance tracking activities, (Mason, J., 2017) has suggested either reducing the sheer number of tracking activities or increasing their efficiency through automation. Such automation must rely on trustful data acquisition tools and processes and the employment of a database that can guarantee the traceability and immutability of data. Due to the large number of stakeholders involved throughout the construction supply chain, the system should operate in a distributed manner. A distributed ledger technology can potentially address all these elements while providing a transparent, trustful and single source of truth in terms of compliance-related data. (Mason, J., 2017)

Financial

Payment conditions such as remuneration, terms and conditions and clauses are all stated within the contract signed between the parties. It is common to bind the payment terms to the successful completion of activities and the status of construction as a whole (Hughes, W., Hillebrandt, P., & Murdoch, J., 2000) (Tran, H., & Carmichael, D. G., 2013).

As illustrated previously, the supply chain in the C&D sector involves a multitude of stakeholders. As the supply chain information and activity flow start to diverge, so do the financial streams involved. Resulting in a chain of stakeholders dependent on each other in terms of financial, information and/or material flows. Whereby the acquisition of funds depends on the preceding stakeholder in the flow (Odeyinka, H. A., Kaka, A., 2005)

The interdependency between stakeholders and the structure of the supply chain can lead to potential bottlenecks in terms of financial flows because the unsuccessful payment by one stakeholder can create a cascade effect downstream in the supply chain. Additionally, the bifurcation of the supply chain has also a repercussion on payment speed and therefore on the availability of liquidity by stakeholders. In short, financial flow and the compensation by a specific stakeholder depends strongly on its position within the supply chain, leading to contractors and sub/contractors frequently experiencing payment delays (Hughes, W., Hillebrandt, P., & Murdoch, J., 2000) (Odeyinka, H. A., Kaka, A., 2005).

What happens is that companies incur upfront investments for conducting construction activities, even before being financially compensated. The investment is required for paying salaries, purchasing materials and dealing with fixed costs associated with the construction activity (Odeyinka, H. A., Kaka, A., 2005).

Innovative payment systems should tackle and solve payment delays, fund retention and reduce disadvantages associated with the position within the supply chain. Some studies are suggesting that performance-based contracts can help in reducing payment terms. The underlying principle of such contracts is that the executor of a certain part of the project is paid more frequently based on pre-negotiated progress rates. For example, the payment can be triggered when 20,40,60,80% of the project is achieved. The complexity of such a system is high as it requires an automated and harmonized compliance mechanism as outlined previously (Mason, J., 2017)

Circularity in the built environment

The topic of circularity is extremely important when associated with the C&D industry. After 2008, more than 50% of the global population is located in urban areas (Debacker, W., Manshoven, S., Denis, F., 2016). In Brazil for example, already 85% of the population is located in urban areas, and the expectation is that this number will be increased to 91% by 2050, and this trend is quite consistent around the globe (Munaro, M. R., Tavares, S. F., Bragança, L., 2020).

This exerts high pressure on the resources required for managing the built environment, making the C&D industry an important contributor to the transition towards sustainability. This industry is extremely important from a social and economic perspective. The construction sector is the largest industrial sector on the European level, providing more than 10 million jobs and contributing to 10% of the European Gross Domestic Product (GDP) (Poljanšek, M., 2017).

In other words, C&D is a resource-intensive industry and it is regarded as the largest consumer of natural resources, contributing to 1/3 of the total energy consumed on the planet. Cities on the other hand, directly consume 75% of the primary energy in the world and account for 80% of the greenhouse gas emission (GHG) with a generation of waste that equals 50% of the world's waste (Munaro, M. R., Tavares, S. F., Bragança, L., 2020).

In this perspective, the built environment and the C&D industry play both an extremely important role in reaching the sustainability targets set forth by countries. The economic model that has been conceptualized, developed and maintained so far is dominated by a linear approach, in which goods and resources are extracted, processed and manufactured into finite goods which are then used, discarded and incinerated as waste (Ellen MacArthur Foundation, McKinsey Center for Business and Environment., 2015)

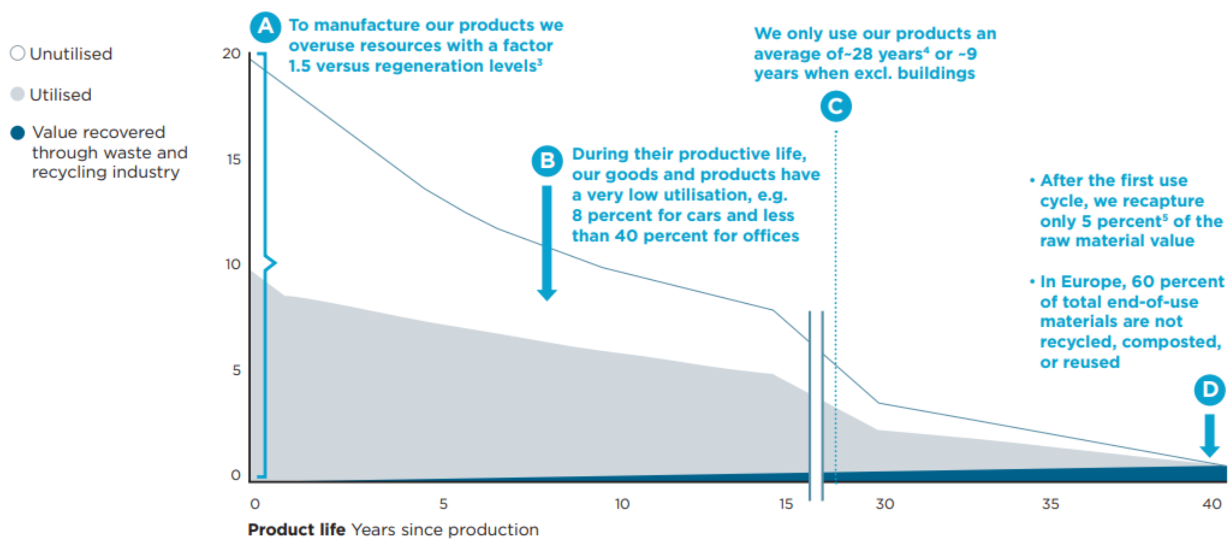


Figure 8 - Value loss of selected manufactured goods across the European economy [Value of manufactured products, % of GDP, EU, 2012] (source (Ellen MacArthur Foundation, McKinsey Center for Business and Environment., 2015))

This model intrinsically leads to value loss over time as many of the produced goods are not even utilized and are discarded after a very short time after their utilization (see Figure 8). For example, it is common to buy a new car even though for 92% of its life span it stays parked and is not utilized. Interestingly, around 60% of total end-of-use resources are neither recycled, reused or composted, leading to an important haemorrhage of valuable resources which need to be compensated by new and virgin resources. The built environment makes no difference in this way of dealing with resources and the structural generation of waste throughout its supply chain (see Figure 9).

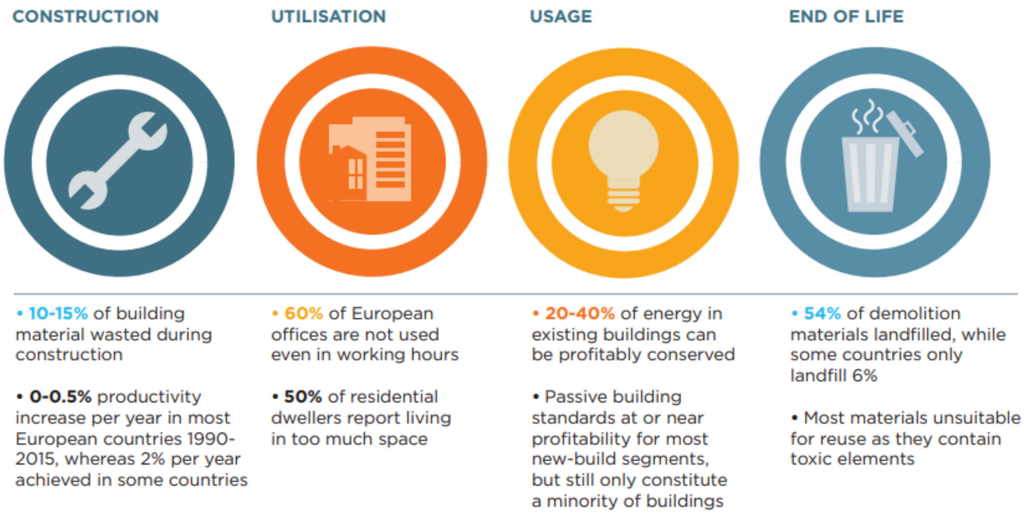


Figure 9 -Structural waste in the built environment EU (source (Ellen MacArthur Foundation, McKinsey Center for Business and Environment., 2015))

Price increases, significant volatility of global commodity markets and negative externalities affecting the environment have pushed countries to rethink how materials and resources are employed. As a result, a new economic model called Circular Economy (CE) has emerged, leading to a redefinition and adjustment of political agendas on a global scale. The core principle of CE is to decouple economic development and growth from the consumption of resources. The objective is to keep resources and goods at their highest level of utility without losing their economic value, thus leading to an economic model that is intrinsically circular, restorative and regenerative (Munaro, M. R., Tavares, S. F., Bragança, L., 2020).

CE is therefore directly linked to the entire life cycle of goods, from production to disposal. This taps into product design, as well as waste management practices. At the European level, the European Commission (EC) has drafted and adopted the Circular Economy Action plan which entails 5 key activities (see Figure 10) that directly relate to the life cycle of buildings.

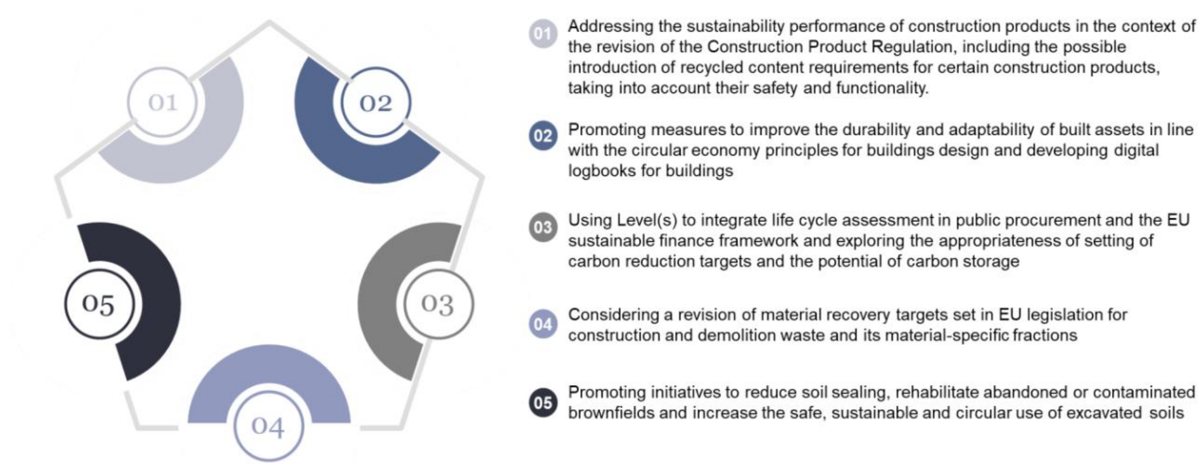


Figure 10 - EU Circular Economy Action Plan activities relating to the lifecycle of building and construction (source (European Construction Sector Observatory (ECSO), 2021))

Alongside the Circular Economy action plan, comes the Waste Framework Directive (Directive 2008/98/EC on waste) which has defined a 70% recycling target for construction and demolition waste, the EU Construction & Demolition Waste Management Protocol (2016) which outlines non-binding measures for the member states, and finally the EU Guidelines for audits before demolition of building (2018) which guides the member states on how to deal and manage construction and demolition waste (European Construction Sector Observatory (ECSO), 2021).

Circularity, waste hierarchies and the ReSOLVE framework

Although circularity, and more specifically CE, is a widely discussed topic, confusion about its definitions and concepts is still present (Kirchherr, J., Reike, D., Hekkert, M., 2017) The following concepts are meant to dispel any confusion and provide insights into different concepts relating to waste management and circularity.

In general terms, the main objective of the CE is to shift the economic model from a linear to a circular one. In other words, to move from a model that extracts and uses virgin resources (system input) and generates waste (system output) to one that is circular where the system's input is (partially) fed by the system's output.

According to (Kirchherr, J., Reike, D., Hekkert, M., 2017), circularity can also be assessed and classified under a 9 R framework (see Figure 11). These 9 R's represent a sort of waste management hierarchy in which R9 represents a linear model while R0 is a circular one. These R's are not mutually exclusive and this framework does not imply that the whole economy should move towards R0 type of waste management practices. Rather, it stresses the fact that for achieving a CE, the management of goods and resources should aim to move from R9 towards R0 (Kirchherr, J., Reike, D., Hekkert, M., 2017) (Van Buren, N., Demmers, M., Van der Heijden, R., Witlox, F., 2016).

Waste approaches ranging from R0-R2 focus primarily on smarter ways of manufacturing products and goods. In this range the focus is on designing goods and manufacturing processes that result in not needing more goods (R0), producing goods that can fulfil multiple functionalities or sustain the adoption by more users (R1), or that require fewer resources for their manufacturing (R2) (Kirchherr, J., Reike, D., Hekkert, M., 2017). R3-R7 waste strategies focus more on extending the lifespan of goods. For example, by making the goods reusable by another user (R3), making them repairable (R4), making them upgradeable with more modern pieces and components (R5), using parts of the goods for new goods (R6) or using the discarded good within a new good that has a different function (R7) (Kirchherr, J., Reike, D., Hekkert, M., 2017). R8-R9 waste strategies are the last options (concerning circularity) and focus primarily on finding end-of-life applications for discarded goods. This can be obtained by breaking down the goods to their chemical composition and using them for manufacturing new goods (R8) or by incinerating the good, breaking down the chemical bonds and harnessing the heat that is released as a result (R9) (Kirchherr, J., Reike, D., Hekkert, M., 2017).

Moving from R9 towards R0 waste management practices requires improving and bringing forward innovations in the field of product design, defining new revenue and business models as well as transformations on a socio-economic level (Kirchherr, J., Reike, D., Hekkert, M., 2017).

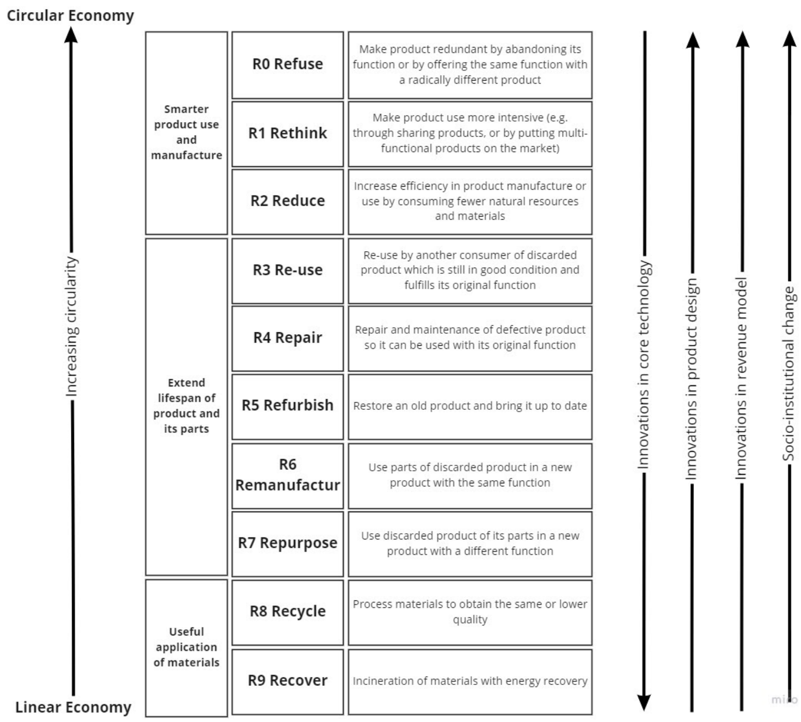


Figure 11 - 9R's framework (source: adapted from (Kirchherr, J., Reike, D., Hekkert, M., 2017))

A complementary way of looking at waste management practices that can lead to a CE is the ReSOLVE framework (see Figure 12) developed by the Ellen MacArthur Foundation. The framework entails biological and technical cycles that are intertwined with each other. The biological cycle represents the

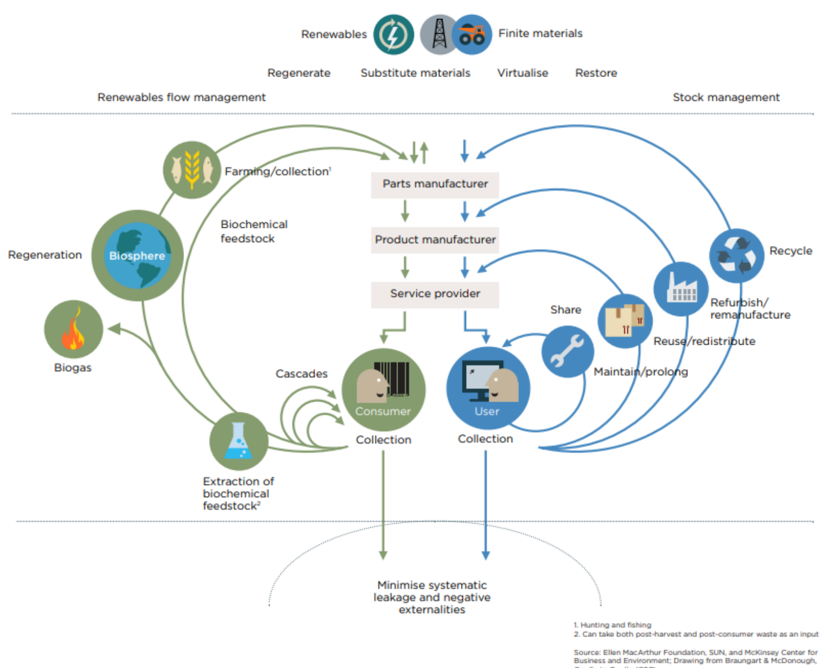


Figure 12 – Butterfly diagram / RESOLVE framework (source (Ellen MacArthur Foundation, McKinsey Center for Business and Environment., 2015))

resources while the technical cycle the practices and processes that can sustain these resources and process them into finite goods. Similarly to the waste hierarchy outlined in Figure 11, the ReSOLVE framework prioritizes waste management practices in terms of value retention.

According to ReSOLVE framework, there are 6 key principles (Ellen MacArthur Foundation, 2013) and steps required for an effective and sustainable transition toward a CE. The principles include ***Regenerate, Share, Optimise, Loop, Virtualise, and Exchange***. Figure 13 illustrates these key principles together with a short description of their practical application.

Figure 13 - Principles and actions entailed in the ReSOLVE framework (adapted from (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016))

Circularity in the built environment and the ReSOLVE framework

As outlined previously the objective of the CE is to reduce and stabilize within a closed loop the throughput of resources in society. When extended to the C&D industry, the purpose is to design buildings that require fewer resources or employ demolition practices that maximize the recovery of waste and allow for their re-employment in new construction projects.

(Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016) outlines the importance of applying systemic thinking for organically understanding the life cycle of buildings, the supply chain that sustains current practices and identifying practices aimed at creating better integration between stakeholders. For full circularity to be achieved, it is paramount that different scales (from city to region and country) are coherently integrated, enabling circularity on a city level only will not lead to full circularity.

To better understand how circularity is (or could be) applied in the built environment, some case studies are presented. These case studies are framed under the ReSOLVE framework illustrated in Figure 13 and can be found in Appendix X.

According to research conducted by (Ellen MacArthur Foundation, McKinsey Center for Business and Environment., 2015), implementing full circularity practices in the C&D sector could have a positive impact on the annual costs incurred by households. As illustrated in Figure 14, solutions entailed in each of the categories within the ReSOLVE framework (see Appendix X) can bring about different cost reductions.

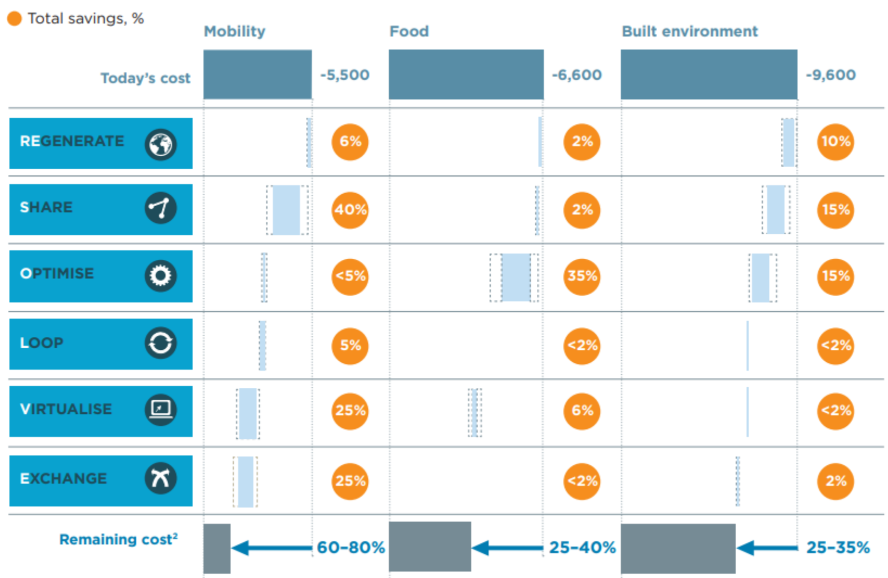


Figure 14 - Cost reduction potential. [Total annual cash-out costs per household; EU average 2012, €, improvement potential for 2050] (source: (Ellen MacArthur Foundation, McKinsey Center for Business and Environment., 2015))

Together, mobility, food and housing represent 60% of the average budget for a household while these industries represent 80% of the resource consumption in Europe. Improvement in these industries could therefore have a significant impact on the overall costs faced by households (Ellen MacArthur Foundation, McKinsey Center for Business and Environment., 2015)

Activities that would help to transition the built environment towards a CE entail green infrastructure, mixed-use buildings, modular design with pre-fabricated and sustainable materials and structured reverse logistic practices allowing for closed-loop resource management practices (Ellen MacArthur Foundation, McKinsey Center for Business and Environment., 2015).

Overall, the circularity practices so far presented are estimated to reduce the cost of buildings (defined in €/m^2) by between 25-35% compared to today's values (see Figure 14).

Circular built environment in the Netherlands

The Dutch government has set stringent and very ambitious targets for reaching a CE in the Netherlands. Despite this, the journey is still long and many challenges still need to be addressed. These include the fast ageing of the workforce, the mismatch between the offer and demand of secondary resources and the immediate need for reducing the sector's GHG emissions (Circle Economy, Metabolic , C-creators, 2022).

Population density and soaring housing demand and prices

The Netherlands is listed among the most densely populated countries on the globe. According to (Claassens, 2020), almost 80% of the Dutch population lives in urban and or sub-urban areas and the overall dutch population is expected to grow in the next decade.

The demand for bigger living spaces is also increasing but the demand is limited. For instance, the transition from student housing to large apartments is moving more slowly than in the past, and this is reducing the number of available spaces for incoming students and young adults looking for an independent space to live in (Lucassen, T., 2020). To address this challenge, it is estimated that by 2050 the Netherlands will need between 300000 and 1.6 million homes (Faessen W., Gopal K., van Leeuwen G., Omtzigt D., 2017)

Meeting this soaring housing demand while fulfilling the circularity objectives requires identifying optimization strategies for recovering demolition materials and using them for new buildings as well as strategies for optimizing the use of existing spaces and defining specific transition pathways and how to involve the right partners and stakeholders in this transition (Circle Economy, Metabolic , C-creators, 2022).

Estimates made back in 2020 indicate that the Netherlands hosts currently 8 million residential and 1.2 million non-residential (offices, shops and public offices) (Compendium voor de Leefomgeving., 2022). Also, in the same year, the statistics indicate that the number of homes hosting multiple families increased by 1/3 compared to 2021, suggesting that the focus is shifting to building smaller homes and densifying the population in cities with high housing demand (The Dutch Cooperative Association of Real Estate Agents and Valuers (NVM), 2020).

Another interesting insight is stat demolition activities are currently representing ¼ of the new construction projects, indicating that the potential availability of secondary raw materials cannot fully meet the demand. The forecast for 2030 indicates that by 2030 the construction of new homes will be around 50000 and the demolition around 20000, thus reducing the gap between the two activities (Arnoldussen, J., Errami, S., Semenov, R., Roemers, G., Blok, M., Kamps, M. Faes, K., 2020).

The housing crisis is therefore contributing to increasing the housing price, thus pushing people outside of cities because prices are just not affordable. Since 2008, the power of private house owners and developers got strengthened while the rights of tenants have been progressively weakened (Circle Economy, Metabolic , C-creators, 2022) (Bouwinvest, 2020)

CE principles (as outlined in the previous chapter) such as co-housing and co-renting solutions could reduce the housing shortage by 15000 buildings per year, and thus provide significant help to students, young adults and elderly people. Municipalities such as Rotterdam and Amsterdam are proactively promoting these types of projects but further support and initiatives are needed (Circle Economy, Metabolic , C-creators, 2022).

Skills and job opportunities

7% of the Netherlands' workforce (around 685.000) people are currently employed in the built environment sector. Nevertheless, since the financial crisis of 2008, the industry has suffered significant losses with an estimated 100.000 jobs lost since then (CBS, 2022) (Circle Economy, Metabolic , C-creators, 2022).

The transition towards circularity in the built environment will require to have a substantial workforce as well as the definition of new forms of collaborations and partnerships between businesses. This will require new and specialized skills supported by secure and competitive job positions. The new job landscape will be characterized by innovation, health and security (Circle Economy, Metabolic , C-creators, 2022).

Of the 685.000 people currently employed in the C&D sector, 174.000 are employed in the construction of buildings, 57.000 in infrastructure projects, 23.000 in manufacturing, 145.000 as architects and technical services and finally 286.000 in other construction. Future estimates indicate that 180.000 workers will be needed. 40.000 of these will be needed for replacing ageing employees, 70.000 to compensate for the job losses of the 2008 crisis and 70.000 for compensating the lack of appropriate skills (see Figure 15) (European Construction Sector Observatory (ECSO), 2020) (Circle Economy, Metabolic , C-creators, 2022).

Figure 15 – Present vs. Future workforce in the construction sector, Netherlands (source: (Circle Economy, Metabolic , C-creators, 2022))

Workforce-related challenges as well as strict regulation and high competition makes it extremely difficult for key actors to take risks and innovate processes and business model, hereby hindering any significant transition towards circular practices. The application of bio-based construction practices is a good example, the industry is lacking the required capabilities for shifting towards this industry. In general, it has been observed that the construction industry is very conservative when it comes to innovative C&D practices, making this particular sector slow in taking up and scaling circular practices. This aspect is also hindering the speed at which the skills of workers are upgraded and adapted to future needs. The quick appearance of innovations that are being enabled by digitalization are requiring the market to develop new skills relating to digital planning, software development as well as electro engineering (World Economic Forum (WEF), 2016) (Circle Economy, Metabolic , C-creators, 2022) .

Companies are therefore required to continuously upskill their workforce to be able to understand and deliver innovative practices, tools and processes. Nevertheless, low margins and high competition are reducing the willingness of companies to take risks and attempt the adoption of new practices. This affects the effort of upskilling the workforce and updating processes. Usually, C&D companies are not always willing to hire permanent workers and even less to invest resources in training professionals for market needs that are not yet palpable. Innovative companies should therefore help in tailoring training opportunities that reflect current and future market needs as well as helping in bringing about a collective shift in the industry's attitude and vision. This is paramount for delivering the skills required for meeting the transition of the industry toward circular practices (Holland Circular Hotspot, 2018) (Circle Economy, Metabolic , C-creators, 2022).

Policy landscape in the Netherlands

As mentioned previously, circularity requires a holistic approach and most importantly a policy framework able to support and promote its mechanisms and principles.

The first step undertaken by the dutch government was the establishment of the Raw Material Agreement (*Grondstoffenakkoord*) pact back in 2017 whose main objective was to boost resource efficiency throughout the economy and to align different parties toward this common objective (Circle Economy, Metabolic , C-creators, 2022).

The pact has then resulted in the development of a transition agenda named the Circular Construction Economy Transition Agenda. This agenda was converted back in 2019 into tangible and concrete actions through the establishment of a Circular Economy Implementation Programme (Uitvoeringsprogramma Circulaire Economie). One important objective is the mandate for the central Government's Real Estate Agency and Rijkswaterstraat to become fully circular by 2030. Other objectives are to make buildings constructed after 2018 energy neutral, and renovation or redevelopment projects must maximize the use of secondary construction elements. In this perspective, some municipalities have added in their demolition tender a complete demolition plan that entails the recovery and reuse of valuable construction elements (Circle Economy, Metabolic , C-creators, 2022) (Geerts, G., 2021).

The dutch government has also defined performance standards for assessing the sustainability of buildings. The Milieu Prestatie Gebouwen (MPG) is for example an indicator that helps at assessing the environmental impact of the materials employed in the construction, a lower MPG score indicates a more sustainable choice of materials. The industry has responded positively to these indicators, as they help designers and architects to quantify their decision-making process. Nevertheless, some complications did arise in the last few years. Specifically, the Bijna Energieneutrale Gebouwen (BENG) is a norm that requires calculating the consumption and the share of renewables in a building. From 2021 onwards, all buildings must meet the standards indicated in this norm. But when using more insulation or more solar panels for meeting this standard, the MPG score worsened. This indicates an intrinsic conflict between norms focused on the energy life cycle and the material life cycle. Some municipalities are setting even more stringent objectives. Amsterdam's municipality, for example, is requiring that 1/5 of buildings will be constructed with bio-based materials by 2025. It is expected that EU legislation concerning CO2 taxation will make prices for unsustainable materials soar significantly, thus accelerating the transition towards more sustainable materials (Circle Economy, Metabolic , C-creators, 2022) (Crook, L., 2021).

Innovation practices and initiatives contributing to the circularity transition in the Dutch landscape

The C&D sector is considered to be the least digitalized sector within the Dutch economy, but important developments are forecasted for the future (European Construction Sector Observatory (ECSO), 2021)

Data and digitalization can significantly contribute to reducing material use and boosting reuse and recycling practices. Specifically, data-driven practices and solutions can directly help with facility and asset management, operation and process management, material design, logistic optimization and waste management. Digitalization aimed at improving processes relating to safety management and quality control is seeing the largest interest in the industry (McKinsey, 2020) (Circle Economy, Metabolic , C-creators, 2022)

Other digitalization trends include the wider adoption of BIM which is, in fact, a 20-year-old technology. Alongside, construction technologies are focusing more on off-site manufacturing practices for making pre-fabricated and modular buildings and materials, which can significantly reduce the effort for disassembly and maintenance. Lastly, architects and designers are employing parametric design and artificial intelligence (AI) technologies during the design phase of buildings (Circle Economy, Metabolic , C-creators, 2022).

As mentioned previously, to make circularity successful a holistic approach and an aligned comprehension of the topic across the C&D industry are necessary. The objective of the CB'23 platform is to reach an agreement throughout the industry and tackle the data challenges that are hindering circular practices. Several parties are collaborating under the CB'23 initiative to develop nationwide agreements for the use of material passports in the construction sector. A similar objective is pursued by the BIM-loket project brought forward by the DigiGO team. The goal, in this case, is to identify protocols and standardizations for the collection, management and distribution of data (Circle Economy, Metabolic , C-creators, 2022).

The Cirkelstad initiative (Beslisboom Hoogwaardig Hergebruik Bouwproducten), on the other hand, is attempting to define a decision-making tree aimed at identifying construction elements that are highly valuable and which can be reused in the same or other projects (SGS, 2021).

At the same time, the Netherlands is seeing the rise of marketplaces adopted for selling and purchasing reused construction materials. Insert is one of the many marketplaces that allow demolition firms to showcase and sell construction elements recovered during demolition activities. The process of selling and purchasing these elements is still carried out manually by specialized employees delegated to this activity (Circle Economy, Metabolic , C-creators, 2022).

Material metabolism of the construction sector in the Netherlands

Before diving into the metrics defining the material metabolism in the Dutch construction industry, it is paramount to clarify the definitions adopted by the research team who has compiled this research. Many of these are already indicated in the Glossary, while the definition of Reuse and Recycle must be clarified once more. In this context, it refers to goods or items that are reused or recycled out of the demolition flow. These should be dealt with as two separate indicators (see R-waste chapter) but limitations in the waste statistics do not allow for individual estimations, hence the two metrics are merged and presented as one. This indicator is important for assessing the efficiency of material recovery practices while the share of reuse indicates circular economy practices.

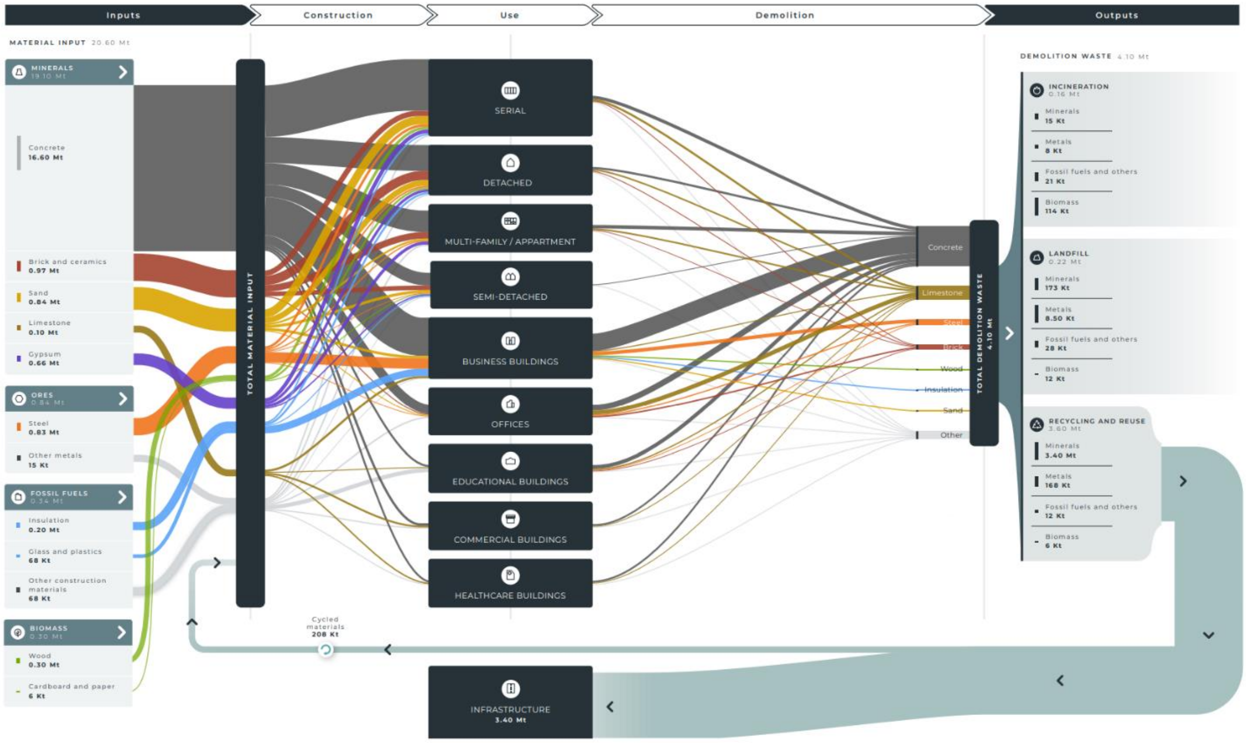


Figure 16 – Sankey diagram of material metabolism of Dutch's built environment (source: (Circle Economy, Metabolic , C-creators, 2022))

Figure 16 represents the material metabolism of the Dutch's built environment. The analysis is limited to residential (apartments, row houses, detached houses and duplexes) and commercial (business spaces, offices, educational buildings, shops and care facilities) buildings, while it excludes infrastructure and civil engineering projects.

The dutch construction sector is a resource-intensive industry, with a large input of raw materials and resources. Its footprint is due to the consumption of raw materials, water and energy throughout the supply chain of these resources (Circle Economy, Metabolic , C-creators, 2022).

In 2019 the mass of material that was streamed into the construction of residential and commercial buildings was quantified at 20.6 million tonnes. The analysis has divided the material flow into 4 resource groups, namely **Minerals** (bricks & ceramics, concrete, gypsum, limestone and sand), **Ores** (steel and other metals), **Fossil fuel-based** products and **others** (plastic, asphalt, insulation and glass), and **Biomass** (wood and paper & cardboard) (Circle Economy, Metabolic , C-creators, 2022).

As illustrated in Table 1, the largest input of resources comes from **minerals**, followed by **ores**, **fossil fuel-based** products and **others** and lastly **biomass**. The input is complemented by 0.208 million tonnes that are streamed back to commercial and residential buildings while 2.2 million tonnes are going to be stored in infrastructure.

Table 1 - Input per material category (adapted from (Circle Economy, Metabolic , C-creators, 2022))

Input		
	Mass (million tonnes)	%
Minerals	19.1	93
Ores	0.8	4
Fossil fuel-based products and others	0.3	1.5
Biomass	0.3	1.5
TOTAL	**20.6**	**100**
Secondary Materials (to commercial/residential building)	*0.208*	**n.a**
Secondary Materials (to infrastructure)	*3.4*	

Currently, the share of virgin material is significantly higher than the one of secondary and renewable materials. The construction industry is still largely dependent on virgin materials (Circle Economy, Metabolic , C-creators, 2022).

By analyzing the proportion of renewable and secondary materials over the total resource consumption in the system, it can be observed that virgin materials represent 18.1 tonnes (88% of total material input to the sector), and only 0.8 million tonnes (4%) are sourced from bio-based materials while 1.7 million tonnes (8%) are sourced from secondary materials. If compared with the values of previous years, a positive trend can be observed. The share of virgin material input has decreased (from 93% to 87%) while the share of secondary material has increased (from 5% to 8%). Similarly, the share of renewable materials (from 1.4% to 4%). Even though the number is promising, it must be highlighted that 90% of the virgin material is represented by concrete which is acknowledged to be a large contributor to GHG emissions. The remaining percentages within the mineral category are gypsum (3.4%), bricks and ceramic (2.2%) and sand (2.3%). The share of bio-based materials is currently below 1%. It can be observed that 2/3 of materials (14.8 million tonnes) end up in residential buildings while the remaining 1/3 (7,35 million tonnes) is streamed toward commercial buildings (Circle Economy, Metabolic , C-creators, 2022).

Looking at the waste generation resulting from demolition activities, it can be observed that the Netherlands generates yearly 4 million tonnes (infrastructure alone generates 14.6 million tonnes yearly). The waste stream is composed primarily of minerals with 3.6 million tonnes (90%), followed by ores with 185,000 tonnes (5%), fossil fuel and others 70,000 tonnes (2%) and finally with 132,000 tonnes (3%) of biomass related waste (Circle Economy, Metabolic , C-creators, 2022).

Besides the sheer mass, it is important to evaluate the type of waste that is generated during demolition as this aspect can have a repercussion on the share of recycled resources. Polluted and hazardous materials (such as asbestos) are difficult and very expensive to separate effectively in waste batches, therefore demolition companies tend to favour incineration practices over recycling ones in such cases. Additionally, traditional demolition practices are still the norm in the Netherlands, meaning that selective deconstruction practices are still rare and therefore the recovery of high-value resources is minimal**.** Nevertheless, it is important to outline the fact that the demand for virgin material is significantly higher than the total output of demolition. In other words, even by maximizing the rate of recycled materials, improving renovation and repair practices would only meet 1/5 (19.6%) of the total material demand. It is therefore relevant to focus on extending the lifetime of the building by improving maintenance and repair strategies and consequently favouring this approach to conducting new building projects (Circle Economy, Metabolic , C-creators, 2022).

Looking at the share of recycled and reused materials over a total waste generation, the metrics look promising. Of the total waste generated only 4% is incinerated and 6% is landfilled. The remaining 88% is recycled (Circle Economy, Metabolic , C-creators, 2022).

Concrete is the leading stream in **recycling**, accounting for 75% of the total stream. The rest is composed of brick (8.7%), limestone (6.4%), steel and iron (4.5%) and sand (3.8%) (Circle Economy, Metabolic , C-creators, 2022).

When looking into the **landfilling** flown stream it is interesting to observe that concrete is also in this case the largest contributor, with 65% of the total landfilling mass. Followed by gypsum (12%), insulation (8.8%), wood and timber (4.8%) and finally by steel and iron (3.4%) (Circle Economy, Metabolic , C-creators, 2022).

In the case of **incineration**, wood and timber is the leading stream with (71%), followed by insulation (8.6%), steel and iron (4.9%) and finally plastics (2.2%) (Circle Economy, Metabolic , C-creators, 2022).

An important element for boosting and sustaining circularity practices is to maximize the value retention of materials by trying to focus on practices at the high-end of the waste hierarchies such as repair, refurbishing, reuse and recycling. As outlined before, 88% of the waste stream is recycled, the issue is that most of this share is downcycled for road backfilling purposes (the process of replacing the soil/ground removed during excavation). This is a low-value application of resources. Even though this practice is usefully for avoiding the loss of resources, and because institutional bodies such as the Ministry of Transport have recommended the recycling of such resources based on their high-strength performance, this activity precludes higher-value recovery practices such as reuse. For instance, the current share of resources that are returned (not clear what the actual reuse percentage is) as input to the built environment is only **8%** of the total mass of construction materials used for new projects. In other words, the resources recycled (the distinction between recycled and reused is not possible) only represent 5.8% of the total outflow, the rest is downcycled to lower-grade uses (Rijkswaterstaat – Water, Verkeer en Leefomgeving (RIVM), 2015) (Circle Economy, Metabolic , C-creators, 2022).

The definition of what represents a high or low-value application is generating some debates and confrontations within the Dutch C&D sector. Depending on their position throughout the supply chain, stakeholders have come up with different interpretations. For instance, the infrastructure and civil engineering sector heavily rely on recycled waste for backfilling purposes and considers this application as a high-value recycling practice. Public institutions such as the Ministry of Transport and the government tend to agree with this vision because recycled aggregates are a fundamental prerequisite for building long-lasting and high-quality infrastructure. On top of this, the Netherlands does not have locations for stone quarrying. The literature is however aligned on the waste hierarchies practices (see Figure 11) and the fact that value retention should be prioritized. Resources and materials should be streamed towards their highest value retention option at all times. The best practices should in any case aim at prolonging the lifetime of resources and materials through repair and renovation activities as well as design principles that facilitate these practices. The Netherlands is however suffering from the availability of data that could help in accurately assessing the precise volumes of waste that are currently downcycled which could instead be used for higher value purposes (Circle Economy, Metabolic , C-creators, 2022).

The metabolism of the dutch C&D sector highlights the fact that some room for improvement remains and should be pursued. Secondary material use is still low and downcycling practices should be significantly reduced. Additionally, incineration and landfilling practices should be limited to the hazardous elements where other options are not possible, but surely not for wood and timber streams. The research team also outlines that policies (such as financial incentives) should be conceived to make selective demolition more attractive (Circle Economy, Metabolic , C-creators, 2022).

The case of Rotterdam

By zooming into the situation in Rotterdam (one of the most important cities in Zuid holland), interesting insights can be gained.

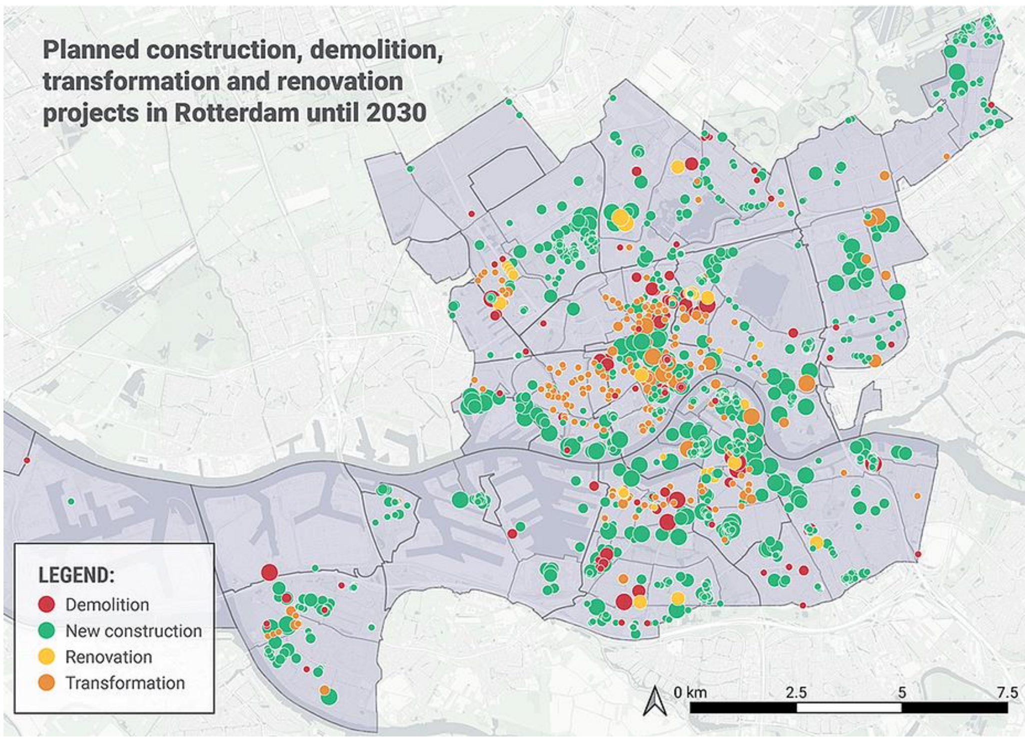


Figure 17 -planned construction, demolition, transformation and renovation projects in Rotterdam until 2030 (source (Merlijn B., 2021))

The targets set forward by the municipality of Rotterdam concerning circularity in the C&D industry are ambitious. For instance, the use of primary raw materials must be reduced by 50% by 2030 while simultaneously creating between 3.500 and 7.000 jobs directly contributing to sustainability (Merlijn B., 2021)

In 2021 the amount of construction waste was estimated to be around 400.000 tons in Rotterdam alone. Metabolic has investigated future demolition projects (see Figure 17) and have estimated that around 817.000 tons of construction material will be released for harvest up to 2030. As illustrated in the previous chapter and Figure 16, more than 85% will be downcycled leaving a large opportunity for increasing recovery and reuse rates. According to Metabolic's estimates, just 1% of the waste that could be recovered and reused account for 8% of the total environmental impacts generated in processing waste and can have an economic value ranging from around 43 million euros (Merlijn B., 2021).

In another study, Metabolic determined the amount of raw material required for new construction projects. As in the findings outlined in the previous chapter, urban mining cannot fully meet this demand. For instance, the demand for virgin raw material (5 million tons) in ten municipalities in the Utrecht region, is 20 times more than the supply estimates of secondary raw materials (Merlijn B., 2021).

Recovery and Reuse of construction elements (challenges and opportunities)

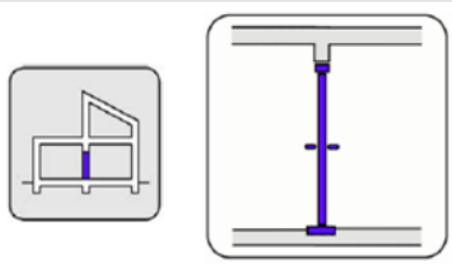
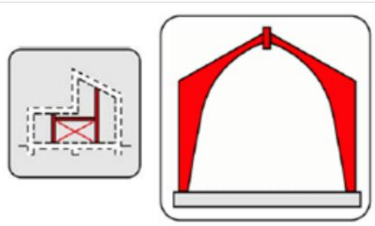
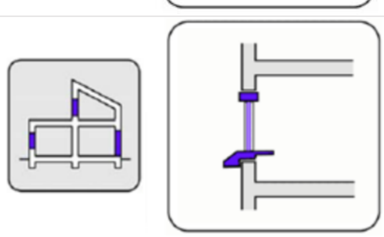
The following sub-chapter presents the topic of reuse which is the focus of this research. Specifically, the following chapter outlines the definition of reuse, what are the construction elements that considered as interesting in the Netherlands for reuse purposes and the challenges characterizing recovery and reuse as identified by literature.

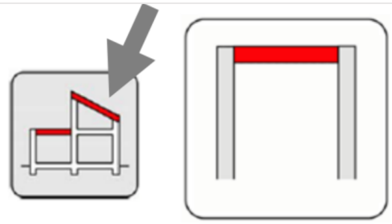
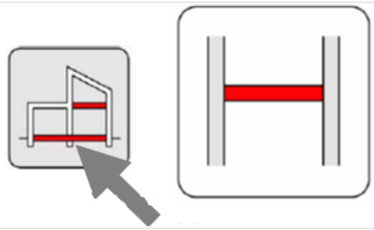
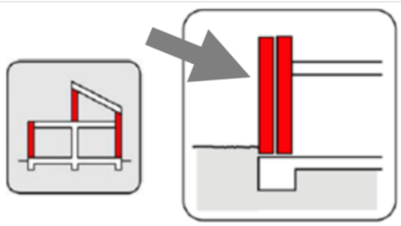
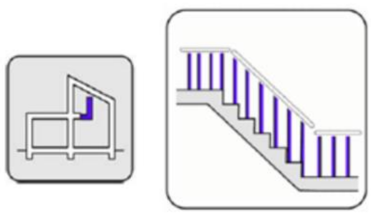
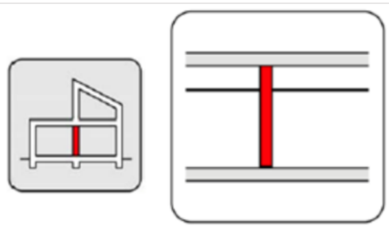
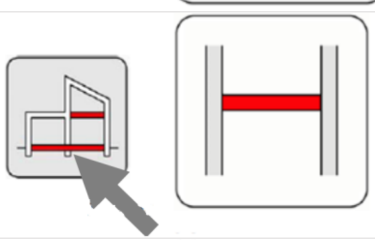
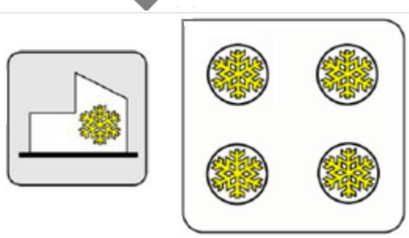
According to the framework illustrated in Figure 11, reuse (R3) considers elements/tools/goods which are in sufficiently good condition for fulfilling their original function and can be reemployed by the same or by another user without the need for repair or refurbishment work. According to (SGS, 2021), reuse in the dutch context should be considered when the function of the construction element is preserved, for example, a door-to-door or insulation-to-insulation function.

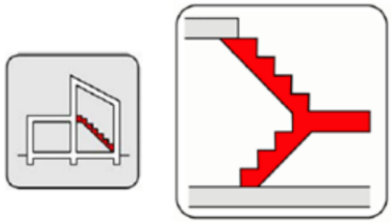
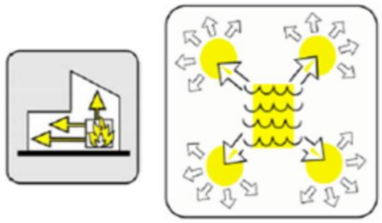
High-value construction elements for reuse purposes

(SGS, 2021) has conducted research among relevant construction and demolition firms in the Netherlands intending to identify what are, based on their experience, the most interesting and high-value construction elements where reuse practices should be pursued. These are outlined in Table 2.

Table 2 - High-value construction elements interesting for reuse purposes in the Netherlands (adapted from (SGS, 2021))

	Sketch	Description	Function
Doors		Doors and doorframes in internal walls	Access and visibility between internal spaces and separation of internal spaces (acoustic - protective - visual).
Construction		Load-bearing structures of the building. Consist mainly of columns beams and/or trusses and which, under their design and/or construction method are not separable into the groups (21.0) to (27.0) [see Appendix II – High-value reuse construction elements]	Load-bearing structure of the building
Frames		Collection of openings in exterior walls filled with windows.	Separation of internal and external areas (acoustic - security - climatic - visual). Entry of daylight and natural ventilation facility.

Insulation (roof/floor/external wall)		Collection of non-structural roofs, both inclined and flat, which form the boundary of the building on the upper side.	Separation of internal and external areas (acoustic - security - climatic - visual).
		Collection of non-structural self-supporting floors, including gallery floors, balconies and landings.	Load-bearing structure for the useful load of the rooms above and delimitation of superimposed rooms (acoustic - protective - climatic - visual).
		Collection of non-structural external walls which form the boundary of the building from the top of the foundation constructions to the top of the roof constructions.	Separation of indoor/outdoor spaces (acoustic - safety - climatic - visual).
Railings		Finishing of balconies, galleries, loggias, voids, stairs, slopes, floors, roof openings and eaves employing railings.	Protection of and support for people's movement
Internal wall		Non-structural internal walls.	Room delimitation (acoustic - safety - climatic - visual).
Floors		Non-structural self-supporting floors, including gallery floors, balconies and landings, extending to the inside of the exterior walls	Load-bearing structure for the use of spaces and boundary of superimposed spaces (acoustic-safety-climatic-visual).
Cooling systems (air conditioning)		Generating and distributing cold to maintain a comfortable climate.	Local generation of cold.

Stairs/Ramps		Stairways, both inside and outside the building, including the corresponding landings.	Connection of spaces at different floor levels and demarcation of spaces (acoustic - protective - visual).
Radiator/Heater		Equipment for transporting, distributing and dispensing heat using water as the climatic medium, from the main heat generator to the heat distribution units in rooms.	Heat distribution for indoor climatisation with water.

The research team has outlined much more construction elements of interest. These can be found in Table 23 in the chapter Appendix II – High-value reuse construction elements.

Challenges characterizing recovery and reuse practices in the built environment

Although the concept of circularity is widely accepted in the construction industry, there is still little research on how circularity can be achieved and implemented from a system perspective. Specifically, it is still unclear what is the right business model able to secure a competitive advantage for companies while allowing them to roll out circularity practices at full scale. For instance, the built environment has not yet experienced an industry-wide adoption and application of circularity principles. These are usually limited to ad-hoc projects and initiatives, or specific material streams. For instance, much of the academic research has focused on how to theoretically improve C&D waste practice with little or no focus on how to conceive and implement effective and market-competitive reuse practices (Chaba, K., Mridha, N., 2022) (Adams, K. T., Osmani, M., Thorpe, T., Thornback, J., 2017).

The main issue lies in the fact that the C&D industry is a conservative industry which developed and prospered within a linear economic model. All its processes and workflows are conceived within a linear framework which is intrinsically stiff and thus resistant to sudden and disruptive changes. In this perspective, buildings are conceived and treated as finite and static monoliths rather than organic and evolving structures that can adapt and transform with time. Conventionally, buildings are designed with the sole purpose of being demolished once they have fulfilled their function, making this approach the only one assumed to be feasible once the building reaches its end of life (Hobbs, G., Adams, K., 2017) (Durmisevic, E., 2016).

Modern buildings are designed as mono-functional buildings with a linear and progressive evolution going from use to demolition. Every building is made up of different components which have different durability rates (see Figure 18). Certain components might be replaced every decade (services) while other components like the building's frame might need replacement every century. In this perspective, the current assumption adopted during the design phase is intrinsically fallacious because this is not how the building evolves. Nevertheless, structures and materials embedded into the building are neither designed nor installed with reusability in mind, leaving disposal as the standard approach to follow (Durmisevic, E., 2019) (Chaba, K., Mridha, N., 2022).

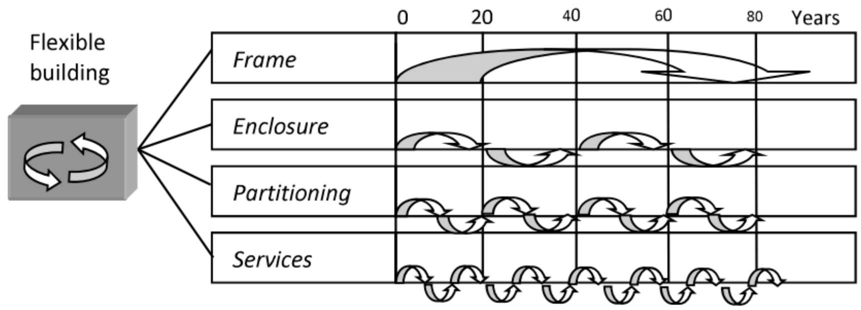


Figure 18 - Durability rates of building components (Durmisevic, E., 2016)

Several challenges are therefore limiting the transition towards circularity in the built environment. The biggest challenge, according to (Adams, K. T., Osmani, M., Thorpe, T., Thornback, J., 2017), is the lack of a holistic approach across the entire supply chain. This is because the benefits stemming from innovative circular practices are not immediately measurable and quantifiable. But the COVID-19 pandemic has demonstrated that the supply chain can be suddenly disrupted and that the focus of government and industries should be on increasing and strengthening the circularity of supply chains. Specifically, the supply chain should be made more resilient and resources should be managed more efficiently, and this can be achieved by focusing on localised ways of procuring resources as well as shortening supply chains, all principles that are clearly outlined within circularity principles (Organisation for Economic Co-operation and Development (OECD), 2020)

Reuse practices do not come without challenges. Recovering and reusing construction elements pose challenges that relate to the processes for carrying out these activities as well as the quality of the retrieved construction elements. One prerequisite for reusing construction elements in new buildings is that these are in good condition. This requires that the process of recovery, or selective demolition, is conducted with care without harming the integrity of the construction element. Today, traditional demolition practices are carried out with the sole scope of quickly bringing apart the building. This approach leads to irreversible damage caused to construction elements. Mapping and identifying interesting construction elements to be recovered could help in securing their safe and cost-effective recovery (Chaba, K., Mridha, N., 2022)

The following paragraph will present the main challenges, illustrated by literature, which are associated with reuse practices in the C&D industry. The overarching issue is that the industry needs to define and articulate a clear and holistic approach and strategy that is aligned throughout the entire industry and supply chain. Although circularity concepts are clear and well-defined their benefits are still perceived as unclear and uncertain, therefore the industry still prefers adopting linear and old-fashioned approaches. Reuse practices are therefore only favoured when the reuse strategy is forced top-down (Adams, K. T., Osmani, M., Thorpe, T., Thornback, J., 2017).

The main challenges that are acting as a barrier to a full-scale implementation of reuse practices are 1) Investment of resources, 2) Standardized processes focused on linear resource management practices, 3) Limited know-how and experience, 4) Market maturity, 5) Construction design and technology related challenges, 6) Quality and integrity of construction elements 7) Incentives, 8) Law, regulations and guidelines and 9) Logistic related issues (Chaba, K., Mridha, N., 2022) (Gerhardsson, H., Lindholm, C. L., Andersson, J., Kronberg, A., Wennesjö, M., Shadram, F., 2020)

Investment of resources

The construction industry is an extremely competitive industry in which tenders are usually attributed primarily to cost. Therefore minimizing costs is paramount for being competitive in the market.

One of the challenges limiting the wide adoption of reuse practices in construction and demolition relates to is the increased resources, in terms of time and money, required for enabling such practices. For instance, reuse practices require more time associated with designing and executing selective demolition. Additionally, additional costs might be associated with material testing and inspections on the construction element run by specialists (Hradil, P., 2014) (Chaba, K., Mridha, N., 2022)

Architects and designers need to invest more time in including potentially recoverable resources in the new design, which increases the overall budget of the project. This also includes conducting an on-site survey for assessing the dimension, technical specifications and status of the construction element. Being cost an important indicator for winning tenders, the additional costs associated with reuse practices are at this point hindering their implementation (Hradil, P., 2014)

(Tang, H., Hu, Q. G., Xu, Y. Y., Yang, Y. H., 2011) has outlined and mapped all the steps that directly contribute to the soaring costs when focusing on reuse practice. First, the architect/designers need to identify required construction elements (1), then a demolition project able to deliver these elements must be identified (2), plan and execute selective demolition (3), storage of the recovered construction elements (4), refurbishment and repair activities (5) performance and quality tests on the construction element (6). All these activities must be carried out manually and require additional time and resources, thus leading to soaring costs (compared to standard demolition and construction processes).

These activities must be planned well ahead of the actual start of the project. It becomes almost impossible to design reused construction elements as the start of the project approaches. Therefore, the mapping and procurement process must be considered at the early stages of the design phase, with clear requirements in mind. The interaction between stakeholders in this case, for either searching, offering or procuring elements is not automated and requires time for being executed in a coherent and structured way, thus avoiding delays and unexpected situations (Chaba, K., Mridha, N., 2022).

To conclude, reuse practices require additional time because they require additional processes to the standard one currently adopted in the C&D industry. These practices also demand new and innovative collaboration frameworks between stakeholders. For this reason, for making reuse practices cost-effective and successful, these should be initiated at the early stage of projects, at least during the design phase (Chaba, K., Mridha, N., 2022) (Tang, H., Hu, Q. G., Xu, Y. Y., Yang, Y. H., 2011).

Because reuse practices are not yet standardized additional planning time is needed, which in turn leads to increased costs. To overcome this issue, reuse practices must be conceived and structurally embedded within the company's standard practices. This includes the development of material inventories during construction which can then be employed at a later stage for material mapping and selection before the demolition is executed. The current lack of databases makes the mapping and procurement time extremely inefficient and time-consuming. Also, the lack of standardized processes leads to situations where there is no time to find buyers for construction elements that could be easily recovered and reused (Chaba, K., Mridha, N., 2022).

Standardized processes focused on linear material management practices

As outlined previously, the construction and demolition industry has seen significant developments in the last decades. Nevertheless, these are framed within a business model that promotes linear asset management practices.

In this perspective the industry is filled with cognitive biases and false assumptions about reuse, making this approach neglected and underestimated (Gerhardsson, H., Lindholm, C. L., Andersson, J., Kronberg, A., Wennesjö, M., Shadram, F., 2020).

The construction and demolition industry is also very conservative, making it a slow adopter of new technologies and innovative processes. Especially if these bring uncertainty in terms of costs and revenues. This creates a situation of lock-in where the industry, its processes and the supply chain as a whole, are tailored for conducting linear material management practices and not reuse-related ones (Park, J., Tucker, R., 2017)

In a study conducted on Swedish C&D companies, it has been highlighted that reuse practices are only considered interesting when carried out concerning waste management practices at the end-of-life of buildings, and not during the construction of new projects. Therefore, architects and designers are rarely considering reuse when designing and procuring materials for a new project. This creates an important gap in the process of reuse because reuse intrinsically requires streaming back the construction elements in new or in the same project and if it is limited to waste management practices only, it cannot be carried out effectively (Chaba, K., Mridha, N., 2022).

Several solutions have been outlined. (Park, J., Tucker, R., 2017) indicate that issues associated with cognitive biases can be overcome through ad-hoc training provided to both, construction and demolition firms, in which reuse practices are outlined and presented. Similarly, the entire supply chain and especially final users (or project commissionaires) should be informed about the advantages coming with adopting reuse practices. Developing a positive perception about reuse by the project commissionaire can boost its active participation in this approach.

In the long run, it is extremely important to establish an industry-wide vision and systemic collaboration blueprint between all stakeholders involved in the supply chain. All stakeholders, from the project commissionaire to the architect developing the design of the building should be involved. Not only for aligning and coordinating processes but also for developing shared know-how and best practices database (Park, J., Tucker, R., 2017) (Debacker, W., Manshoven, S., Peters, M., Ribeiro, A., De Weerdt, Y., 2017) (Gerhardsson, H., Lindholm, C. L., Andersson, J., Kronberg, A., Wennesjö, M., Shadram, F., 2020)

Limited know-how and experience

The lock-in that keeps the C&D industry fastened to a linear model is to be attributed to the lack of practical knowledge and experience concerning reuse practices. Even though the benefits are sometimes recognized, and the industry is willing to innovate its practices, the challenges with implementing reuse practices are characterized by a lack of a strategy for bringing this circular approach into practice (Chaba, K., Mridha, N., 2022).

In an extensive analysis, (Chaba, K., Mridha, N., 2022) discovered that the large majority of the C&D firms taking part in their research do neither have “specific goals” nor “guidelines” and “routines” for supporting reuse practices. (Adams, K. T., Osmani, M., Thorpe, T., Thornback, J., 2017) outlines the urgency to “ (…)

articulate the benefits of the circular economy transparently and measurably". (Nordby, A. S., 2019) has identified some improvement areas and activities that could help in promoting reuse practices within the industry while increasing the practical competencies required for this approach to be effective. The focus should be put on developing, together with academic institutions and knowledge hubs, pilot projects that could help in creating sufficient experience and know-how around the topic of reuse and material recovery. Such projects must be framed within a national development roadmap and should not be carried out as self-standing activities.

Gaining sufficient knowledge and experience within the industry will contribute to the adoption of reuse and recovery practices because the time, resources and uncertainties characterizing these practices will be significantly reduced (Gerhardsson, H., Lindholm, C. L., Andersson, J., Kronberg, A., Wennesjö, M., Shadram, F., 2020)

Market maturity

In a recent study, (Hobbs, G., Adams, K., 2017) identified that the market for reused construction elements is characterized by an imbalance between offer and supply. This aspect is also confirmed by (Park, J., Tucker, R., 2017) who assessed that reuse is significantly limited by the lack of demand by the project commissionaire. Even though the supply metrics are positive, without the market demand reuse and recovery cannot gain traction. The motives can be diverse.

(Hradil, P., 2014) outlined that the issue currently limiting the market growth is the lack of information and data about construction elements which are (or will be) becoming available during the demolition projects.

(Park, J., Tucker, R., 2017) have instead assessed that designers, architects, and developers are experiencing a lack of interest from the project commissionaire. The main reason is the perceived additional costs associated with reusing construction elements.

(Mahpour, A., 2018) has conducted a thorough analysis on what are the barriers limiting reuse in C&D and have identified that behavioural aspect, such as preferring new construction elements to overused ones, is an important barrier.

Similarly, (Hobbs, G., Adams, K., 2017) discuss the fact that project commissionaire assumes that old construction elements do not the standard and functionality requirements that are instead met by new ones. The current status, longevity and durability of reused construction elements are oftentimes unknown, making this aspect an additional barrier to marketing these products.

In other studies instead, the main barrier is attributed to the supply of construction elements, rather than to its demand. The limited supply makes it extremely difficult to scale up the market and meet the dynamic demand of those project commissionaires willing to employ reused construction elements in projects (Chaba, K., Mridha, N., 2022).

What (Kuehlen, A., Thompson, N., Schultmann, F., Nakajima, S., Russell, M., 2014) have identified instead is that from a supply perspective, demolition firms are experiencing some intrinsic challenges with how the linear C&D model is structured. Demolition projects must be planned and carried out within a very limited and stringent timeframe. Therefore selective demolition must be designed into the demolition plan beforehand. But the request to recover specific construction elements must come from somewhere or someone. Hence, this generates a chicken-egg paradox in which the issue of supply and demand is difficult to solve.

(Hobbs, G., Adams, K., 2017) have put forward some suggestions for addressing this market situation. According to their research, it is paramount to develop a system able to meet supply and demand for construction elements, especially when these are not re-employed in the same project. Such a system should also employ traceability mechanisms. A suggestion is to employ warehouses, hubs or online marketplaces that can link supply and demand in a flexible and adaptable way.

The adoption of online marketplaces is endorsed by several researchers. (Low, J. K., Wallis, S. L., Hernandez, G., Cerqueira, I. S., Steinhorn, G., Berry, T. A., 2020) indicate that sharing platforms or online marketplaces can facilitate the matching of supply and demand. (Bao, Z., Lee, W. M., Lu, W., 2020) have also outlined that limiting access to such online platforms to only some selected users can limit their effectiveness and make them fail in the long run. Online sharing platforms or marketplaces should therefore have an entry barrier that promotes their effectiveness but does not jeopardize their use potential.

Construction design and technology-related challenges

As outlined previously, the C&D has evolved within a linear economic model. Because of this construction technologies have not focused on tailoring their practices to circularity principles.

As outlined by (Akanbi, L., Oyedele, L., Delgado, J. M. D., Bilal, M., Akinade, O., Ajayi, A., Mohammed-Yakub, N., 2018), an important factor limiting recovery and reuse is that buildings are not designed for disassembly. This leads to the generation of non-recoverable waste as well as additional resources required for selective demolition practices.

The industry is now starting to conceive and develop design and construction processes that can boost reusability. Old building designs and construction techniques were non-adaptive and mono-functional, thus not allowing to easily and flexibly adapt the building to new functions (Adams, K. T., Osmani, M., Thorpe, T., Thornback, J., 2017)

Along with construction elements not being designed and installed with disassembly in mind, comes the lack of equipment designed for disassembly. Selective demolition activities are therefore difficult to perform and lead invariably to the damaging of high-value construction elements. (Kuehlen, A., Thompson, N., Schultmann, F., Nakajima, S., Russell, M., 2014)

(Hradil, P., 2014) has identified several challenges associated with how joints are currently made, this is especially true for concrete which is difficult to disassemble without compromising its structural integrity. In general, it is extremely complicated to retrieve and then integrate old construction elements into new projects.

The first improvement for addressing this issue is to start designing new buildings with circularity in mind. According to (Gerhardsson, H., Lindholm, C. L., Andersson, J., Kronberg, A., Wennesjö, M., Shadram, F., 2020), this will lay the foundations for boosting circularity in the construction industry, and reducing the challenges associated with selective demolition and meeting supply and demand flows.

Currently, architects and designers need to employ significantly more time and resources when the building design needs to be adapted for fitting reused construction elements. Also, this must be complemented with the uncertainty of whether the required construction elements will be available at the desired time and in the desired quantity. Because of these uncertainties, architects and designers prefer to employ new construction elements which do not bring along these challenges (Gerhardsson, H., Lindholm, C. L., Andersson, J., Kronberg, A., Wennesjö, M., Shadram, F., 2020).

New design approaches can address this issue in the future. An important aspect is to make buildings more flexible to change by, for example, designing them for multi-functionality and material disassembly (see Figure 19). According to (Durmisevic, E., 2019), buildings should be "reversible", meaning that once their function is fulfilled, buildings should be able to be transformed and/or their systems, products and materials should be dismantlable without causing damage to them. Embedding the reversibility principle in buildings could make reuse practices less resource intensive and more cost-effective.

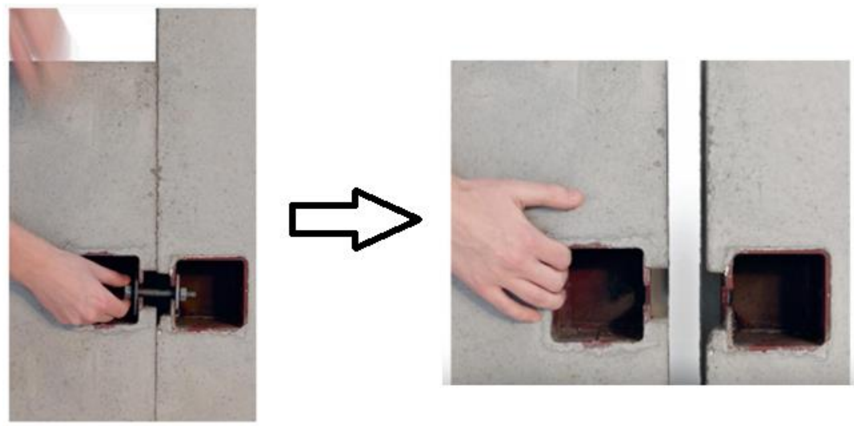


Figure 19 – Connection between elements made with bolds placed in precast recesses which are easy to fasten and remove (Merrild, H., Jensen, K. G., Sommer, J., 2016)

Technology will also be a positive contributor to circularity. BIM is being adopted more frequently in construction because it allows for optimizing the design and execution phase of projects. BIM allows to map and identify each construction element together with its specifications. Because these data can ideally be accessed by the whole supply chain, these data will play an important role in boosting circular practices in the industry. Therefore BIM can potentially lead to improved information flow and data management which are important prerequisites for achieving circularity in the C&D industry (Merrild, H., Jensen, K. G., Sommer, J., 2016).

Quality and integrity of construction elements

The current quality and structural integrity of construction elements, together with their original technical specification have been reported as critical factors limiting reuse practices in C&D. Several architects and designer point out the fact that it is almost impossible to assess the quality of reusable materials when the opportunity arises (Adams, K. T., Osmani, M., Thorpe, T., Thornback, J., 2017).

(Kuehlen, A., Thompson, N., Schultmann, F., Nakajima, S., Russell, M., 2014) also outlines that the fact that buildings were originally not designed with disassembly in mind, leads to construction elements being polluted with hazardous materials such as asbestos. Legislation can also impose additional barriers. For example, high certification standards required for a new building can pose some challenges concerning reuse. As mentioned previously, information and documentation about construction elements embedded in old buildings are oftentimes missing, thus it becomes very cumbersome for a designer or architect to assess specific information (Hradil, P., 2014)

Also, the quality and integrity of construction elements can be jeopardised during the deconstruction phase. As mentioned before, and confirmed by (Hobbs, G., Adams, K., 2017), demolition firms have very limited time for carrying out their demolition activity. Selective demolition requires more time than traditional demolition practices and oftentimes more care and attention for delicately recovering high-value elements.

The lack of data and information about the origin of construction elements, their technical specification and their current/past uses makes it difficult to assess their quality upfront. The lack of such certified information leads to uncertainty and risks that construction firms do not want to take (Chaba, K., Mridha, N., 2022).

In this perspective, correct material mapping and labelling could improve the information flow across the supply chain. Innovative asset tracking technologies can be connected to BIM which is already optimized for asset management and for handling building information through its life cycle, from the design to the demolition phase (Hradil, P., 2014).

On the same train of thought, (Gerhardsson, H., Lindholm, C. L., Andersson, J., Kronberg, A., Wennesjö, M., Shadram, F., 2020) indicates that long-term data management strategies should be designed and applied by C&D firms. These strategies should serve to have better and interrupted information flow between stakeholders intending to keep all respective material databases up to date. Additionally, an existing building should be complemented with digital material logbooks of the construction elements currently embedded into the building.

Incentives and market factors

Obstacles to reuse have also been associated with the lack of financial incentives. Specifically, (Park, J., Tucker, R., 2017) mentions that reusing building materials is more expensive than adopting virgin ones. This should take into consideration the time invested in mapping and designing the reuse of construction elements, as well as the quality and supply risks associated with their re-employment.

C&D projects are cost-driven processes, and the main objective is to maximize revenue while minimizing costs. Therefore project managers tend to prioritize activities and approaches that are aligned with this mindset (Chaba, K., Mridha, N., 2022)

Besides financial incentives, for how the market operates today, companies do not see social and environmental incentives either. (Rose, C. M., Stegemann, J. A., 2018) have studied the market for reuse products and have outlined how this market is currently very fragmented and lacking nationwide strategies. For instance, it is up to individual firms' interest or vision to carry out reuse practices. They do this by relying heavily on their local network and with ad-hoc procurement activities, making the whole reuse approach unattractive to the market.

According to (Gerhardsson, H., Lindholm, C. L., Andersson, J., Kronberg, A., Wennesjö, M., Shadram, F., 2020), incentives should be designed and offered in different forms to all stakeholders involved in the supply chain. For example, during the design phase incentives should be addressed to the property owners, project managers and architects, while during the procurement phase incentives should be addressed to contractors and suppliers. Incentives can also be framed within project tenders.

The lack of consolidated business models and direct incentives is therefore limiting the transition towards reuse practices and active collaboration among stakeholders is not encouraged. For circularity to work, it is paramount to have all key stakeholders involved and actively participating in the transition (Leising, E., Quist, J., Bocken, N., 2018).

Coordination among stakeholders is important as this can be a facilitator for change. For example, setting clear and concise waste minimization and reuse targets at the beginning of any project can align all stakeholders' activity toward this objective. The project commissionaire can, for example, set such waste reduction and reuse targets as binding conditions for winning a tender (Ajayi, S. O., Oyedele, L. O., Akinade, O. O., Bilal, M., Owolabi, H. A., Alaka, H. A., Kadiri, K. O., 2016).

The incentives are needed for disrupting standardized practices. As highlighted so far, the C&D industry is a conservative industry which is very resistant to change. The current indicators for assessing the performance of buildings relate primarily to the number of resources employed and the quality of construction elements during their use phase. Little or no attention is given to the building at its end of life (Ajayi, S. O., Oyedele, L. O., Akinade, O. O., Bilal, M., Owolabi, H. A., Alaka, H. A., Kadiri, K. O., 2016).

Studies have outlined the importance of developing some sort of indicators that can assess the reusability of a building after demolition. Such indicators might help the industry in designing and executing the construction project with resource efficiency in mind (Hradil, P., 2014)

Laws, regulations and guidelines

National laws, regulations and guidelines have tightened in the last decades, adding a certain degree of complexity to reuse practices. The most relevant ones to be mentioned are fire safety, disability and acoustic guidelines. Certain studies have outlined the impossibility of preserving certain parts of buildings during renovation work because these parts no longer fulfil the new quality standards and regulations. Usually, these standards are about acoustic and fire standards. The lack of information and data about old construction elements makes it difficult to assess precisely whether the element to be recovered can be employed or not (Conejos, S., Langston, C., Chan, E. H., Chew, M. Y., 2016).

Another point is the disability guidelines that need to be met for new and old projects. Whenever extensive renovation is carried out and construction elements are planned to be reused, these must meet specific guidelines. Old construction elements did not have these requirements. And new designs require specific door dimensions, ramps and entrances which can guarantee access to disabled people (Hein, M. F., Houck, K. D., 2008).

Another issue relates to the quality certification of construction elements. According to Dutch law, construction elements that are sold and employed in buildings must have a CE certification and labelling (see Bouwbesluit § 1.3. Article 1.6). For recovered construction elements, this is not possible. In a study conducted by Cirklestadt, it was assessed whether recovered and reused construction elements should have a CE quality label or not. According to their analysis, there is currently no legal requirement for a CE label for construction elements that are recovered and reused because they are not re-introduced in the market as new products (SGS, 2021).

An important element for boosting circularity in the C&D industry is to enable, on a national scale, data management strategies. This can be achieved through the digitalization of the C&D industry, which includes digital construction policies; digital platforms; public procurement; digital building logbooks and digitalisation of building permit systems. Within the EU, states can either adopt horizontal digitalization strategies (national policy covering multiple sectors, technologies and areas) or vertical digitalization (target specifically the C&D sector, covering the full supply chain and specific technologies such as BIM). The Netherlands has currently neither vertical nor horizontal strategies in place, this includes also funds and action plans (European Construction Sector Observatory (ECSO), 2021).

Overall, legislation and policies should be implemented to either boost the transition toward circular practices is to remove barriers that are hindering its implementation. In general, legislation should be more flexible around the topic of reuse. A practical example can be the creation of EU-wide labels (similar to the energy labels) indicating the reuse potential of construction elements. (Enkvist, P. A., Klevnäs, P., 2018). Another interesting approach could be a specific taxing system that would ideally boost reuse practices. For example, taxing could be shifted from labour to resources (Merrild, H., Jensen, K. G., Sommer, J., 2016)

Logistic-related issues and disrupted information flows

Logistics, project and process management are important aspects for enabling circularity in the C&D industry. According to standard practices, architects and designers need to purchase materials and construction elements already during the design phase. To fulfil such practice, construction elements that are planned to be reused should already be available during the design phase (Gorgolewski, M., 2008).

According to (Gorgolewski, M., 2008), this issue can be tackled by utilizing material hubs or storage facilities in which the construction elements will be stored from their recovery to their reuse. Nevertheless, (Park, J., Tucker, R., 2017) have outlined how storing construction elements can negatively impact the overall project costs, making this an unlikely approach.

Another important element is the distance between the demolition and construction sites. According to (Hradil, P., 2014), the lack of storage possibility or the availability of a material hub nearby, leads to travel distances leading to negative environmental effects and soaring costs. In this perspective, (Ghisellini, P., Ripa, M., Ulgiati, S., 2018) also identified the distance between the construction and demolition site as an important factor that needs to be assessed and considered.

It has also been identified that reused bricks can bring about a significant reduction in the overall environmental impact of a new building. The benefit would still be significant even if these would be transported over long distances (Chaba, K., Mridha, N., 2022).

Reverse logistics is the process whereby products and materials, at their end of life, are streamed back to either the distributor, manufacturer or dealer. It is in other words a method dealing with transport and stock management. In the case of reuse, currently, the supply chain is linear moving from the concept phase to the use phase and then disposal. Because circularity is still limited in the C&D industry, reversed supply chains are conceived and created ad-hoc, based on project-specific objectives or sustainability standards. Reversed logistics are therefore not the norm in the C&D industry (Chaba, K., Mridha, N., 2022). So information flow is an important issue.

According to (Prieto-Sandoval, V., Jaca, C., Ormazabal, M., 2018) a fully circular supply chain needs, according to circularity principles, to combine forward supply chain practices with the reverse logistic supply chain. This can enable circular economy practices, reduce demand for raw materials and ultimately reduce waste at the end-of-life of buildings. (Kouhizadeh, M., Sarkis, J., Zhu, Q., 2019) outlines how efficient and structural information sharing is key for enabling circularity practices while taking into account the emergence of digitalization and developments in Industry 4.0 practices.

Current information-sharing practices reflect the linearity aspects characterizing material flows. In other words, material and information sharing is mostly unidirectional and linear. Instead, circularity demands information sharing to be a multi-directional process at an inter-organizational level within the C&D supply chain (Şahin, H., Topal, B., 2019). The shared information must therefore be useful and practical for enabling circularity practices. According to (Lotfi, Z., Mukhtar, M., Sahran, S., Zadeh, A. T., 2013) "useful" and "practical" means that information is organized and accessible in such a way that it allows for data-driven decision-making.

As outlined previously, the C&D industry is conservative and its supply chain is fragmented with multiple stakeholders involved, each one having its specialization and information management practice in place (Liu, Y., Van Nederveen, S., Hertogh, M., 2017). Additionally, relationships between stakeholders are temporary and limited to the execution of single projects. This leads to a structural lack of long-term collaboration, the definition of data-sharing practices as well as knowledge harvesting (Ibrahim, C. K. I. C., Sabri, N. A. M., Belayutham, S., & Mahamadu, A., 2018). (Kouhizadeh, M., Sarkis, J., Zhu, Q., 2019) illustrates how Information sharing is paramount for connecting scattered stakeholders, developing long-term and robust relationships, increase efficiency while reducing risks. Information sharing is therefore not an option but a key element for implementing circularity in the C&D industry.

(Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021) have conducted a systemic literature review to synthesize the current information-sharing practices and their limitations within the C&D industry. First, relations that are important for the C&D but that are currently missing are named "Structural holes". These imply that stakeholders are not able to access information that is available to stakeholders preceding or succeeding them in the supply chain, or that the information flow is not well organized making useful information not available to other stakeholders (Chileshe, N., Jayasinghe, R. S., Rameezdeen, R., 2019). These structural holes can ideally benefit from information brokerage activities. The objective of these activities, according to (Jorge, S., Jorge de Jesus, M. A., Nogueira, S., 2016) is to bridge these structural holes in information-sharing practices by having specific stakeholders or processes focused on collecting, interpreting, organizing and transferring information to a specific group of stakeholders for a specific purpose, based on the context and needs. In other words, information brokerage activities are aimed at bridging structural holes and facilitating information sharing by connecting previously separated actors (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021).

The building life cycle can be separated into 5 sequential stages, namely project design, manufacture, construction, operations and end-of-life (Benachio, G. L. F., Freitas, M. D. C. D., Tavares, S. F., 2020). According to (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021) reverse logistics and information sharing are key for recovering material at the end-of-life stage and guaranteeing its re-introduction at the top of the supply chain (or at other stages upstream). Different practices can be adopted in each of these stages (see Figure 20). Although the practices are presented as separate, there is significant overlap between them. Also, 3 key information brokers (Government, Professional communities and Digital Platforms) have been identified by (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021) as important players addressing the structural holes currently characterising information sharing in the C&D industry.

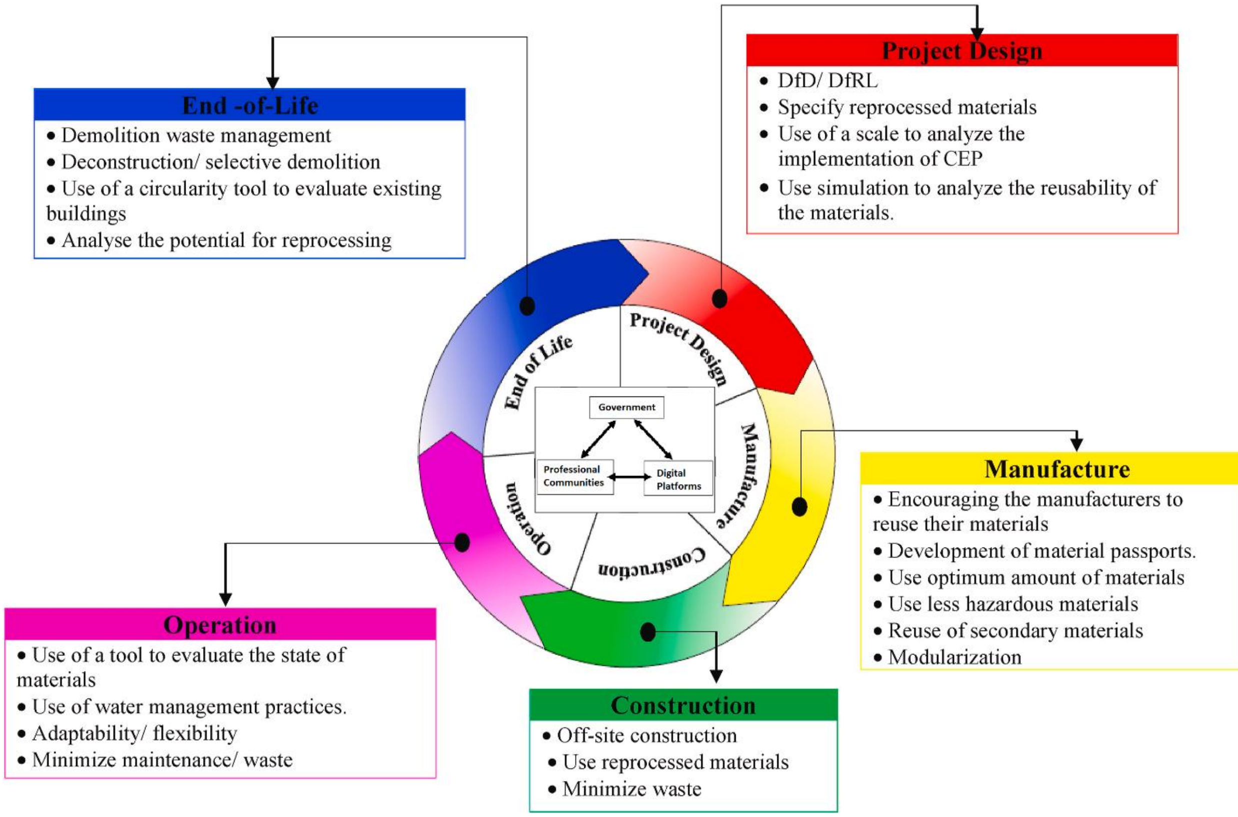


Figure 20 – Circular economy principles applicable at different stages (adapted from (Benachio, G. L. F., Freitas, M. D. C. D., Tavares, S. F., 2020))

Currently, the 5 stages are not well integrated and information sharing is not working correctly between the different stages, making useful information lost along the process (Debacker, W., Manshoven, S., Peters, M., Ribeiro, A., De Weerdt, Y., 2017).

Figure 21 presents the framework developed by (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021) which illustrates the different stages of a building's life cycles, the current structural holes and where and how each broker can contribute for resolving these structural holes.

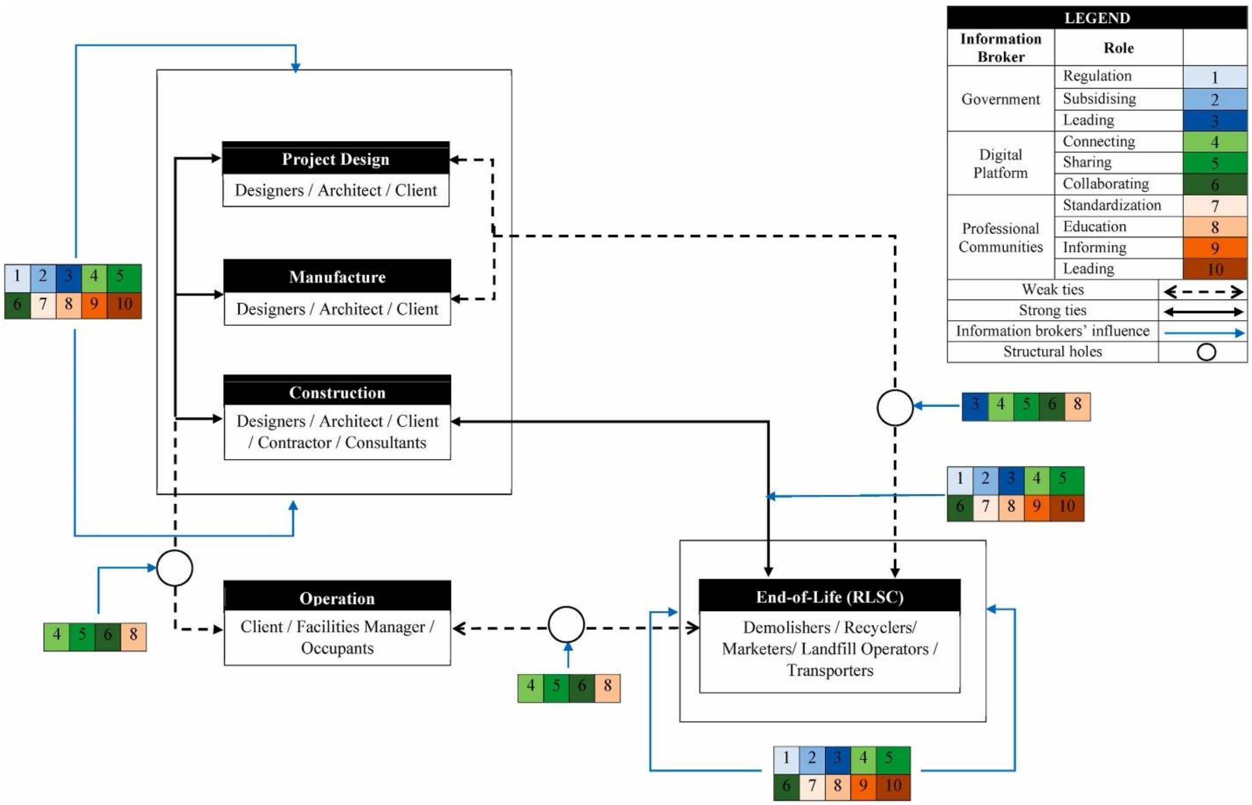


Figure 21 – Information flow in the construction supply chain, key brokers and structural holes (Source (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021))

As illustrated in Figure 21, the current structure of the C&D supply chain presents 3 important structural holes.

The first 3 phases, **project design**, **manufacture** and **construction** are strongly linked together while the study indicates that the links are not structurally reaching the **operation** stage. The information sharing at this stage is currently not structurally included in the forward supply chain, leading to useful information missing at the **end-of-life** stages. The second structural hole is instead present between the **operation** and the **end-of-life** stage. These two gaps are strongly influencing and hindering reverse logistics activities (Van den Berg, M., Voordijk, H., Adriaanse, A., 2020) (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021). The third important structural hole is the link between **end-of-life** and the **project design** and **manufacturing** (Ali, A. K., 2019). **End-of-life** and **construction** are instead characterized by a strong link, this is because **end-of-life** practices are currently the point of focus for implementing circularity in the C&D industry (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021).

According to these findings, the **government** plays the most important role as an information broker through roles like subsidizing, regulating and leading activities. Specifically, the government has a strong impact by enforcing laws as well as tax and levies implementation and application of strict governance practices. **Professional communities** instead, can bridge structural holes by performing educating, standardizing, informing and leading roles. Lastly, **digital platforms** can contribute as an information broker by enabling sharing, connecting and collaborating roles. Although the government's and professional communities' role is to generate information, digital platforms are paramount for handling them correctly and enabling circularity practices (Benachio, G. L. F., Freitas, M. D. C. D., Tavares, S. F., 2020) (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021)

The findings in Figure 21 also illustrate that the project design, construction, manufacturing and end-of-life (EoL) are currently well connected due to the influence of all 3 information brokers as well as the importance that waste management has on boosting circularity practices. For the same reason, all information brokers are actively involved in solving the structural gap existing between the end-of-life stage and the project design and manufacturing. End-of-life in the C&D industry is extremely fragmented and is characterized by several sub-structural holes within this phase itself. Literature indicates that government, professional communities as well as digital platforms will all have an important role in solving these sub-structural holes (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021).

Despite the importance of all 3, digital platforms are the only ones with a clear contribution to solving the structural gap. Studies have outlined the possibility for the other 2 actors to contribute, but at the time of writing, the literature does not present real-life efforts or case studies in which their actions have led to bridging the structural hole. According to (Ajayi, S. O., Oyedele, L. O., 2017) the government could adopt legislative measures for using secondary construction elements in public sector projects, or impose taxes on virgin materials while simultaneously exempting from it all secondary construction elements and/or raw materials. For (Chileshe, N., Rameezdeen, R., Hosseini, M. R., 2016) professional communities could provide support by introducing quality labelling for secondary construction elements as well as addressing specific parties to conduct quality control on these products before reintroducing them into the market.

To conclude, all information brokers can play an important role in bridging the structural holes currently characterizing the supply chain of the C&D industry. Their effort should be carried out collaboratively and cohesively if the supply chain is to be changed in a radical and long-lasting manner. The government plays a pivotal role as it provides the framework within which professional communities and digital platforms can contribute (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021).

The issue of information flow is very important as this can have an impact on the overall project costs.(Hatmoko, J. U. D., Scott, S., 2010) have conducted a study on the overall impact that delays in specific construction supply chain elements can have in terms of project performance. The elements include the flow of materials, information, plant/equipment and labour.

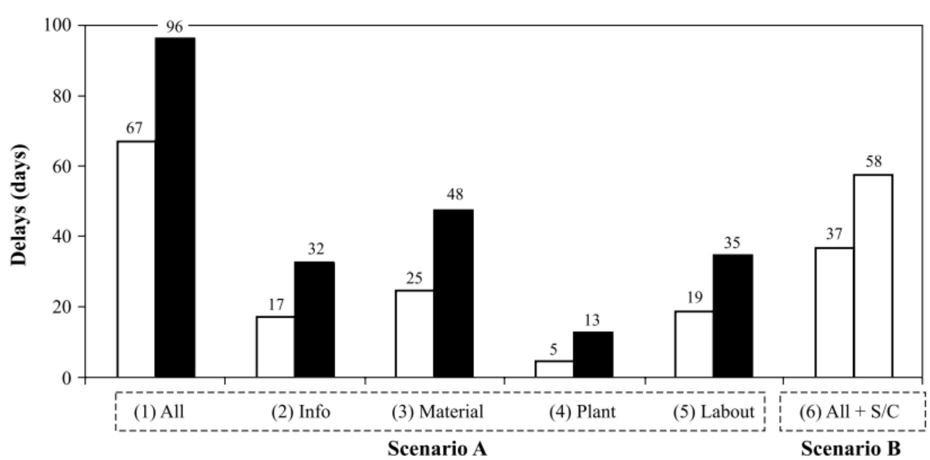


Figure 22 - Effect of supply chain delays on project duration (source (Hatmoko, J. U. D., Scott, S., 2010))

In the results illustrated in Figure 22 can be observed that a project's median delay, when all supply chain-related delays occur, is around 67 days (22% of project duration). Individually, each supply chain delay contributes to 5 to 25 days of delay (2% to 8% of the project duration). The biggest impact is generated by material flow-related issues with 25 days, followed by labour with 19 days, information with 17 days and lastly plant-related issues with 5 days. These delays must be seen as additional accosts which will impact the project's budget (Hatmoko, J. U. D., Scott, S., 2010).

Physical and Digital Asset Management in the built environment

Materials, information, knowledge and tool can be considered important assets in the construction sector. As mentioned previously (see paragraph: Contracts, Compliance and financial aspects) compliance with specific contract conditions and clauses is very important in the construction sector.

Planning compliance relies strongly on asset-related parameters and data. With the fast advent of digitalization, asset parameters and data can be included and tracked within the physical as well as in the digital environment (Sacks, R., Eastman, C., Lee, G., & Teicholz, P., 2018) (Van Groesen, W., 2020).

According to (Sacks, R., Eastman, C., Lee, G., & Teicholz, P., 2018) the digital environment in the construction sector is currently related to BIM models, documentation (for example planning and cost estimates) and digital physical data (technical specifications, cost documentations). While the physical environment relates to the actual physical objects that are embedded into the construction, the information that can be collected from physical objects (such as condition and location) need to be collected with the aid of external tools (sensors)/systems able to collect, interpret and process these data in a digital format (Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y., 2020) (Grieves, M., 2014) .

The two topics are interrelated and complementary, and as mentioned by (Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y., 2020) they can give rise to a digital twin between the physical and the digital environment. All paper-based data and information that could be collected manually and then transferred within a digital environment can now, thanks to information technology, be collected, processed and maintained almost automatically (Grieves, M., 2014). In this perspective, Physical Asset Tracking (PAT) and Digital Asset Management (DAM) can be combined for enabling a digital twin (van Groesen, W., Pauwels, P., 2022)

Asset data and parameters can be incorporated and managed within BIM models and according to (Sacks, R., Eastman, C., Lee, G., & Teicholz, P., 2018) the technology supporting BIM is now able to generate and analyse digital representations of physical assets. The representations can be created within the BIM model or be acquired from physical assets through the employment of external tools (sensors)/systems. For example, Internet of Things (IoT) sensors technologies can be coupled to physical objects and collect valuable data. (Mason, J., 2017) has shown that IoT technologies can be employed for acquiring geographical data about the physical asset, relate these to specific logistic information (e.g in delivery/ delivered/ lost) and eventually trigger automatic payments or feed the information into a material database. (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019) went a step further, and through specific case studies has shown the potential integration between BIM, IoT and Smart Contracts and how this could allow the collection and storage of asset parameters and data within a distributed ledger technology. This can be extremely beneficial for automating compliance tracking, payments and data management.

This short preamble highlights the potential of merging PAT and DAM practices and the potential benefits it holds for the development of circularity practices in the C&D industry. More will be discussed in the following chapters.

First, it is important to better understand what is asset management, how are physical and digital assets currently managed in the C&D industry and how can DAM be coupled to PAT practices and allow for semi-automated compliance activities for construction projects.

Asset, asset management and asset system

The most accurate way of determining what is meant by the term “asset” is to employ the description provided by the International Organization for Standardization (ISO), specifically in the ISO 55000:2014 standard. The standard defines an asset as: *“ (…) an item, thing or entity which is of potential or actual value to an organization (…) ”* ((ISO), 2014).

The interesting and relevant aspect to highlight is the value that an asset must hold for a specific organization. The value of an asset can vary throughout its lifecycle and can also hold a different value for a specific organization. The value is also connected to the risks and liabilities associated with owning and/or managing the asset and can therefore have a positive or negative value throughout its life cycle (Van Groesen, W., 2020).

Assets can also be divided into physical and digital assets, where the former represents a tangible asset (e.g tools, materials, machines) while the latter refers to non-tangible assets such as a database, a BIM model and even online documentation ((ISO), 2014). The two can sometimes be treated as complementary and interdependent, thus forming a so-called asset system. According to the ISO 55000:2014 standards, asset systems are *“ (…) assets which interact or are interrelated as they share common properties (…)”* ((ISO), 2014) A good example could be the BIM design of a window and the window itself. The digital and physical assets represent together an asset system.

An asset or asset system can also be regarded as critical from a safety, environmental or performance point ((ISO), 2014). In the latter case, it refers to the relevance the asset (or asset system) has for the achievement of companies’ goals/objectives. In a construction context, a critical asset system can be represented by the BIM design of a beam and its physical representation. Failing to correctly represent the BIM design can jeopardize the stability of the structure, thus characterizing the asset system as a performance-critical asset.

The next important element of assets is management. According to the ISO 55000:2014 standards, asset management is defined as “ (…) *operating a group of assets during the entire technical lifecycle, guaranteeing a suitable return and ensuring defined services and security standards (…) ”* ((ISO), 2014). This implies that an organization’s objective is to manage the assets in such a way that these would generate economic value throughout their lifecycle, this includes finding a balance between risks and costs associated with managing the assets. In this perspective, organizations develop specific strategic asset management plans (SAMP) that aim at mapping and outlining the resources, activities, information and time that assets (or asset systems) are required for achieving pre-defined objectives. In other words, SAMP outlines how to develop and carry out asset management plans concerning the asset management objectives (Braaksma, H.H., 2016) (Love, P. E., Matthews, J., Lockley, S., 2015). According to ((ISO), 2014), the benefits that stem from auditing and aligning asset management processes and procedures are the improvement of the overall financial performance, management of risks, enhance efficiency in service/product output as well as facilitating compliance activities. It is therefore important to identify the objective that the asset needs to achieve and retrospectively create coherent asset management plans (Love, P. E., Matthews, J., Lockley, S., 2015)

This leads to the next important element which is the importance of having a suitable asset management system. According to ((ISO), 2014) a management system and asset management system (AMS) can be defined as " (…) *or interacting elements within an organization to establish objectives, policies and processes to achieve those objectives (…) " and " (…) management system which is used for asset management, with the function to establish asset management policies and asset management objectives"* respectively.

The management system's elements are correlated to the structure of the organization, the functions and roles as well as the budget and planning aspects. The asset management system, on the other hand, is a subdivision of the management system as it deals with a specific set of operations and activities. Both need to be aligned and coherent toward the organization's goals and objectives. Processes and information systems and flows are important elements constituting the asset management system ((ISO), 2014). A practical example of what represents an information system within the C&D sector is BIM as well as activity logs and material databases. Information systems are therefore very important elements for accurate and effective asset management, especially in the digitalization process of supply chains (Love, P. E., Matthews, J., Lockley, S., 2015) (Braaksma, H.H., 2016) (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016)

Digital environment and asset management

Within the C&D sector, a large part of assets and processes are managed and carried out in a digital form and are therefore pertinent to the digital environment. For example, a BIM design of a building can be regarded as a digital asset that is subsequently transformed into a physical asset. In other words, asset management systems along with the information system subset allow the transformation of digital assets into physical assets which can then be managed through physical asset management practices (Love, P. E., Matthews, J., Lockley, S., 2015) (Van Groesen, W., 2020).

The amount and type of data required for building up a digital asset in the C&D sector are substantial and diverse. These include floor plans, contracts, procurement sheets as well as BIM models. Additionally, such assets can have different data formats (e.g. .pdf., .csv, .ifc) and can be stored in and managed through several Intra and inter-organizational databases and information systems. Therefore the mole of information and data contained within information systems can be substantial and complicated to manage, and correct documentation and management are essential for efficiently operating a digital asset management system (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016) (Re Cecconi, F., Dejaco, M. C., Moretti, N., Mannino, A.,Blanco Cadena, J. D., 2020)

This last point highlights the critical importance of information management for correct and effective asset management. As outlined in the previous chapter, an information system is a key element of an AMS, and in the C&D sector, the information system is currently covered by the implementation of BIM models (see Figure 23). BIM is capable to manage data and information with a higher degree of quality thus increasing its use and applicability.

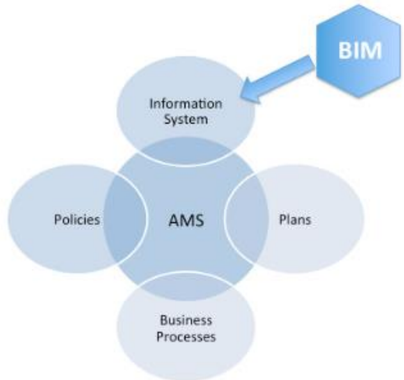


Figure 23- (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016)

The next paragraphs will focus on the current potential of the BIM model for managing the information system in the C&D sector. The objective is to outline what are the current practices and limitations, as well as the potentiality of the tool.

BIM in the construction sector

BIM has gained more interest in the C&D industry in the last decades due to its benefits concerning saving resources employed in designing, planning and managing buildings. BIM modelling started to make its appearance in the first pilot projects far back in the early 2000s. The main difference with traditional 2D computer-aided designs (CAD) models is that BIM allows the management of geometric as well as non-geometric data. More specifically, BIM allows the inclusion of geometrical data, the spatial relationships among elements, geographic information as well as specific properties of construction elements/materials, estimating costs, managing material inventories and last but not least mapping the project schedule and execution. BIM is way more than 3D models of buildings (see Figure 24; Figure 25), it allows buildings to manage and store intelligence which can be useful for automation and accurate asset management. Its strength is provided by the information and knowledge databases that can be connected to multiple software. This can improve the processes underlying sustainability, help in estimating costs, running structural analysis and also aid during demolition and reconstruction (Love, P. E., Matthews, J., Lockley, S., 2015) (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016).

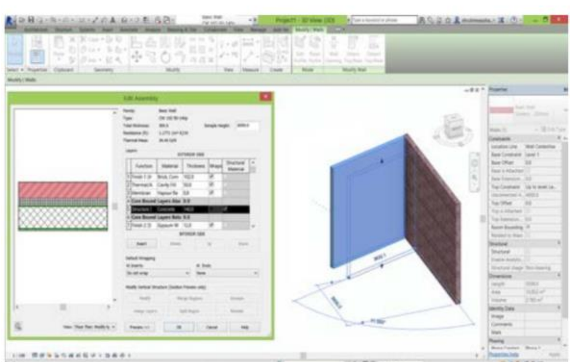


Figure 24 – 3D objects in BIM model (source (Sawhney A., 2015))

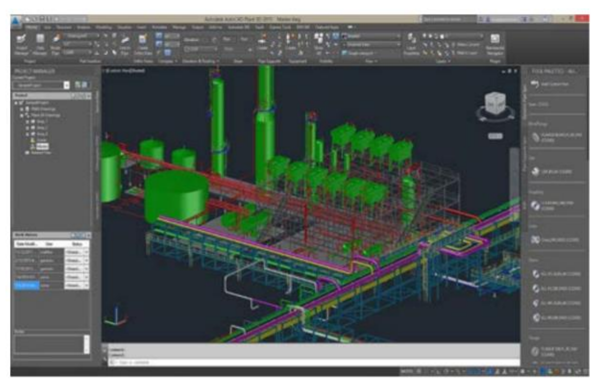


Figure 25 – Complex 3D designs in BIM model (source (Sawhney A., 2015)

To summarize BIM can potentially deliver the following functionalities:

- It can act as a building database because it can digitally represent the physical elements and materials employed in the building. The information can also enable more practical functions and facilitate asset management throughout the building's life cycle such as tracking manufacturer, vendor, specifications, operation and maintenance-related data as well as performance and energy-related data (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016)

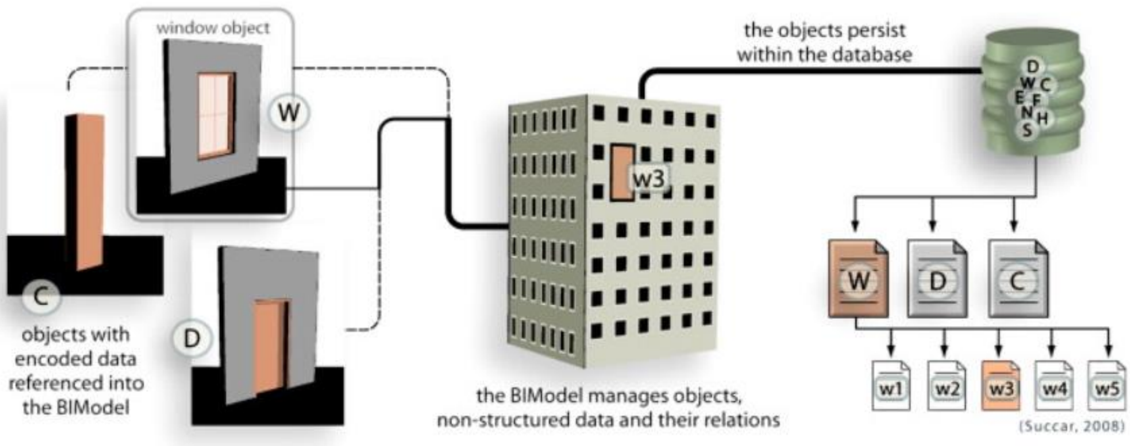


Figure 26 – Information and databases in BIM models (source (Succar, B., 2009))

- Information for carrying out facility management and information that can support timely decision-making (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016)
- Collaboration centre where multiple stakeholders can edit, add, remove, and update facility information at different life stages of the building (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016)

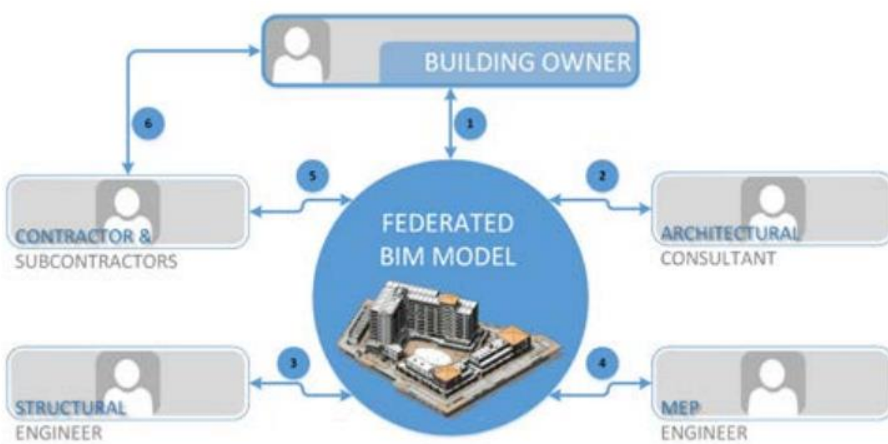


Figure 27 - Federated BIM model with multiple stakeholders (source (Sawhney A., 2015))

- Possibility for interoperability with other software and facility management tools (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016)

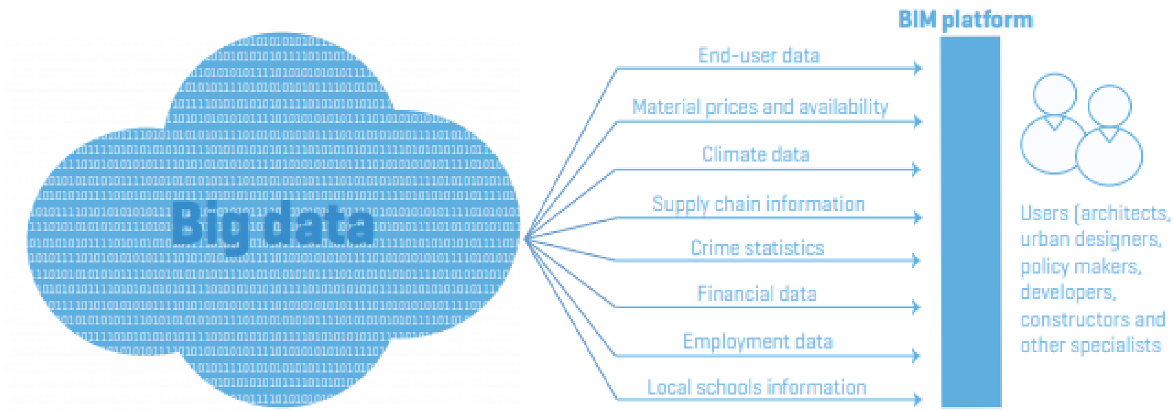


Figure 28 - Interoperability of BIM and external software and databases (source (Sawhney A., 2015))

- Allows integration with the asset management software or database utilized by different stakeholders. This means that BIM can be integrated with the company's asset information and management system (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016)

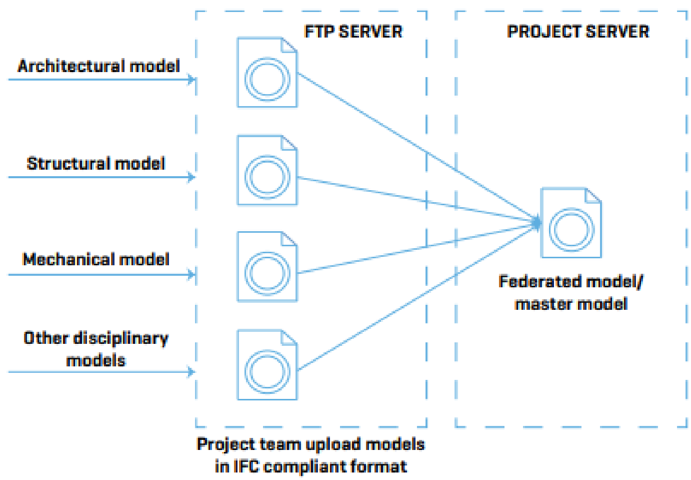


Figure 29 - Multi-stakeholder integration of BIM (source (Sawhney A., 2015))

BIM's application potential, dimensions, model and maturity level

As mentioned previously BIM is a relevant asset for managing data and information about buildings. With its continuous development and evolution, it will be capable of improving the qualitative and quantitative management of data, thus expanding its applicability within the construction sector (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016)

This requires the integration of other external software, asset management tools, and databases which requires determining what information is needed and in which form it is needed, as well as how developed the model is. The collection and centralization of data in information systems such as BIM depend strongly on the data fed by the stakeholders involved (Sawhney A., 2015).

Level of detail (LOD) and Level of model development (LOMD) define the volume and level of details of graphical and non-graphical information contained within BIM as well as their accuracy and reliability. As highlighted previously, BIM can also operate as an asset information and management system and the collaboration between stakeholders made possible by BIM depends on the system's Level of Maturity (LOM). In this optic, BIM can provide great support in centralizing information and data as well as facilitating and coordinating among stakeholders (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016) (Succar, B., 2010) (Liang, C., Lu, W., Rowlinson, S., Zhang, X., 2016)

The dimensions, LOM and LOMD are hereafter presented.

Dimensions

BIM models can store and handle different dimensions of information, from simple vectors to performance-related information (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016)

The dimensions have also a direct impact on the capabilities and functionalities concerning asset management and should be considered as indicators for determining the type of information present in a BIM model and their potential application. The dimensions are complementary and build onto each other, for example, price and cost-related dimensions are needed for enabling a performance dimension. Therefore, increasing dimension demand an increase in data availability and full integration with asset management and tracking practices (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016) (Vijayeta, M., 2019).

The dimensions currently entailed in BIM are depicted in Figure 30.

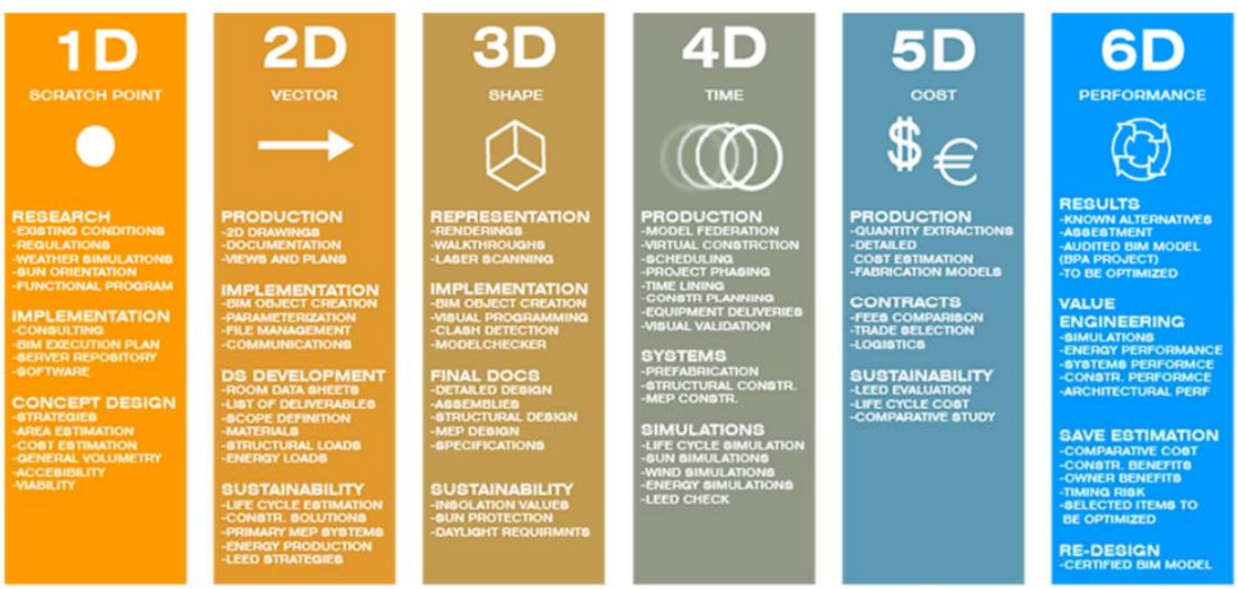


Figure 30 - BIM dimensions (source (Vijayeta, M., 2019))

The D indicated in Figure 30 stands for the dimension of information associated with the BIM model. For example, 2D indicates vector information such as 2-dimensional drawings that can represent floor plans and maps, and 3D represent 3-dimensional shapes that can be used for renderings and the development of building models. From the 4^{th} dimension onward, the information becomes dynamic as it can be related to asset and operation management. Specifically, 4D deals with time-related information such as the scheduling of construction and material procurement and delivery. This specific dimension can help in reducing logistic-related costs as materials can be delivered on-site at the right time and installed without any delay (Vijayeta, M., 2019). 5D deals with quantity, cost and contract-related information. This dimension can help with estimating and assessing cost variance, actual costs and forecasting (Vijayeta, M., 2019). 6D deals with performance-related information such as the physical state of a building as well as energy performance. This dimension can aid in enhancing a building's lifecycle and performance management (Vijayeta, M., 2019) (Van Groesen, W., 2020)

Level Of Model Development (LOMD)

The first step in this process is the determination of information needs. Two views have to be managed at the same time: the election of the element breakdown structure for the organization (until the so-called intervention level) and the level of detail (LOD). Determining what Level of detail (LOD) is necessary to achieve the benefit for that specific model element. The LOD describes the level of completeness to which a model element is developed. There are several ways in which LOD can be documented. The most widely accepted by the industry is LOD defined in the model progression specification and adopted in AIA E202 ((Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016; Van Groesen, W., 2020).

The level of model development (LOMD), on the other hand, depends on the level of information (LOI) and the level of detail (LOD) and it describes the development of a BIM model in terms of details recorded/stored in the form of in digital assets. In other words, the LOMD describes the development status of models. Parties can indicate, through the definition of the LOMD, the accuracy and level of detail of the model and consequently its degree of usability and reliability (Van Groesen, W., 2020).

LOMDs are depicted in Figure 31. **LOMD 100** can represent the mass and volumes of buildings, either in 3-d graphical elements or by sheer data. Between **LOMD 200** and **LOMD 350** are illustrated assemblies of different construction elements. **LOMD 400** are models that contain additional information such as assembly information, and planning and execution information. In general, this level of LOMD contains information suitable for project management and is usually defined as an "as-planned" model. The last one, **LOMD 500**, is considered an "as-built" model, meaning that it contains information that accurately reflects the status of the physical building. **The level of accuracy and the mole information contained within each model (such as quantities, volumes, location, costs and so on) increases with each LOMD and these models can also contain non-geometrical information** (Van Groesen, W., 2020) (Guillen, A. J., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., Shariff, S., 2016)

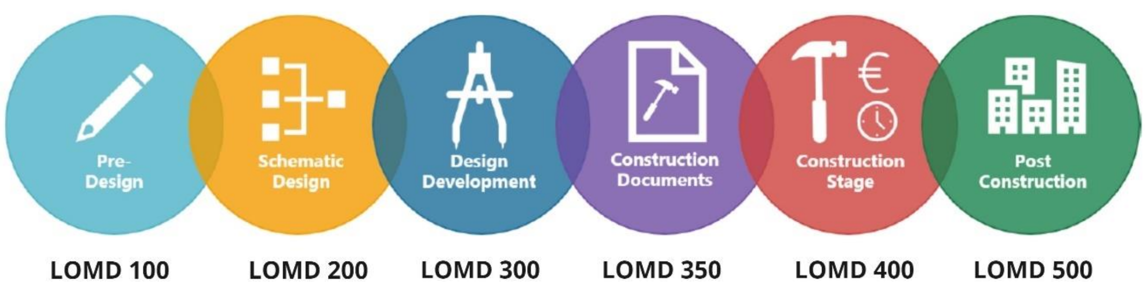


Figure 31 - Level of Model Development (LOMD) (adapted from (Van Groesen, W., 2020))

Level of Maturity (LOM) and BIM levels

The level of maturity of BIM models (also known as the Bew-Richards BIM maturity model) defines the level at which information is operated and managed for asset management (Dowd, T., Marsh, D., 2020). It indirectly defines the level of collaboration that is possible through BIM and how information systems can operate with each other (Dowd, T., Marsh, D., 2020) (Van Groesen, W., 2020) (Sawhney A., 2015).

A higher level of maturity can allow for integrated collaboration models and interoperability of data and information, thus unleashing industry-wide collaboration networks (Dowd, T., Marsh, D., 2020)

Figure 32 below provides a schematic of the different maturity models according to the Bew-Richards model.

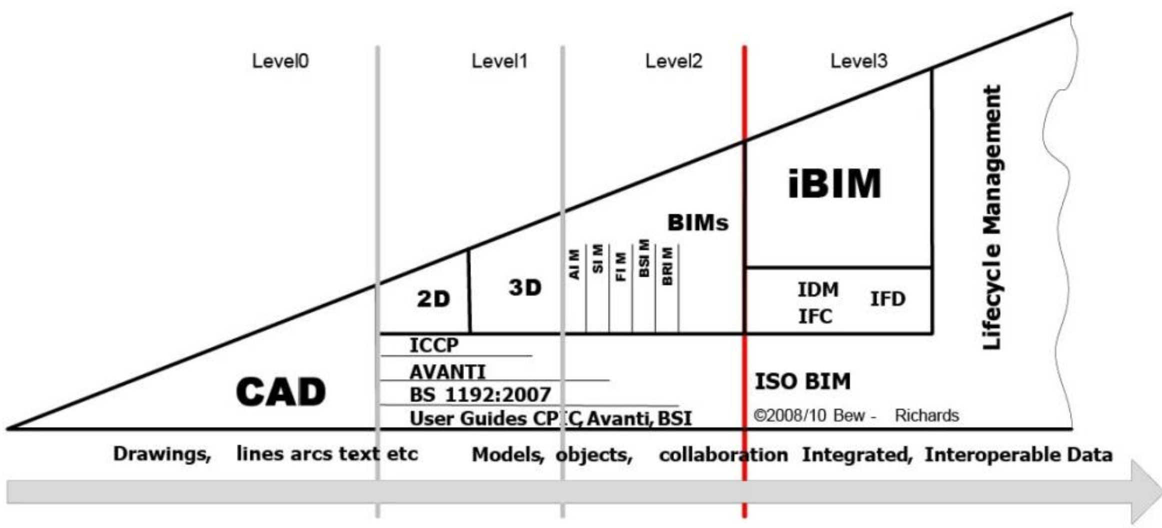
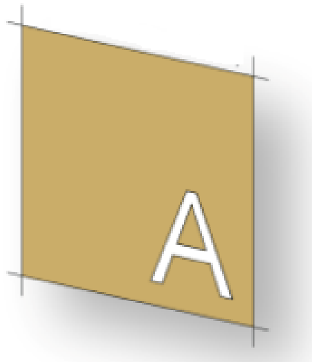
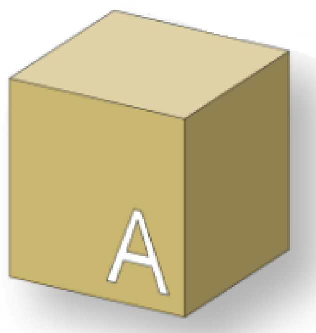
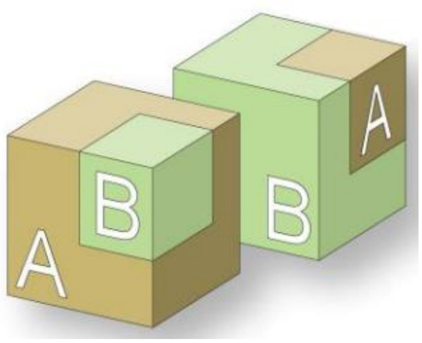
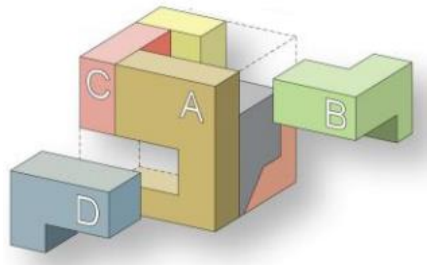


Figure 32 - Bew_richards BIM maturity model (source (Dowd, T., Marsh, D., 2020))

Table 3 on the other hand provides an extensive illustration of each level and its operability and capabilities (Van Groesen, W., 2020)

Table 3 - Level of maturity (LOM) (adapted from (Van Groesen, W., 2020) (Succar, B., 2010))

	**Pre-BIM level (or level 0)** *[Disjointed Project Delivery]* This level entails only 2D documentation aimed at describing a 3D reality. Even when 3D models are created, these are usually disjointed from each other and the level of detail is focused on documentation describing elements in a 2D. In this case, quantities, volumes, cost estimation and specifications cannot be derived from the model and cannot be attached to the model. In this case, the workflow of model development is asynchronous and models cannot be interoperable. In this case, the model is developed and maintained within an AutoCAD® or SketchUP® model
	**BIM level 1** *[Object-based Modelling]* At this level, the 2D representation is developed into a 3D model. In this case, the 3D models can include data that helps in determining volumes, costs and mass. Collaboration is still limited at this level as information flow is asynchronous and not coordinated and data exchange between different stakeholders is only unidirectional. Collaborative practices are therefore not possible at this level. Although the increase in detail can positively contribute to efficiency, contract compliance, risk allocation and intra-organizational practices are still similar to level 0 or pre-BIM levels. In this case, 3D design tools such as ArchiCAD®, Revit®, Digital Project® and Tekla® can be employed.
	**BIM level 2** *[Model-based Collaboration]* This level builds upon level 1 in which individual stakeholders develop their independent 3D model. The way the collaboration is carried out depends on the BIM software adopted by the stakeholders but two main model-based collaborations can occur. The first way is the interoperable exchange of models or parts of models through proprietary or non-proprietary formats. Collaboration can occur also between distinct life cycle stages of the project. For example design-design, design-construction or design-operations interchange. The 3D model can also be operated with other databases such as scheduling or cost estimating databases, thus allowing for 4D (time) and 5D (cost) analysis and estimations. This phase requires some adjustments to contract compliance practices as the workflow of auditing and document-based analysis is transformed. Also, models at this level have a higher granularity of details.

	**BIM level 3** *[Network-based Integration]* This stage allows for creating, sharing and maintaining information and data-rich models collaboratively across different life cycle stages of a building. This level of integration is achievable through cloud computing, model servers, databases and SaaS (software as a service). Level 3 models allow running a complex analysis of construction at the early stages of the life cycle such as the design phase. The model is not static and can allow for dynamic modelling practices such as lean construction and life cycle costing. At this point the model allows for interoperability of data, collaboration across multidisciplinary teams and expertise and the exchange of data information for advanced preliminary analysis, leading to target adjustments and adaptations of a project and its execution.
	**BIM level 4** *[Integrated Project Delivery* This level is regarded in the industry as a level of accuracy and interoperability suitable for considering BIM as an ecosystem blending technologies, processes and policies. This is not a pre-defined and static vision of what BIM will accomplish, but rather it includes all the possible development paths that can be taken. The core of this level is the real-time integrations of multi-dimensional models connected to multiple data sources and databases. In other words, this level will allow for the integration and to operate building management systems, with cost databases, logistic databases, physical asset tracking systems and so on.

Integration of Dimensions, Level of Model Development (LOMD) and Level of Maturity (LOM)

Dimensions, LOMD and LOM entailed in BIM should be considered as complementary aspects of the information/data that can be contained within BIM models and how these can be adopted for carrying out specific operations. For example, LOMD 400 models should contain 4D (time) and 5D (cost) data for allowing BIM models to be operated at a Level 2 (Model-based collaboration). LOMD 500, on the other hand, can contain 6D (performance data) that can be used for lifecycle management and unleash for BIM level 3 activities. Figure 33 below provides a holistic overview of BIM dimensions, LOM and LOMD.

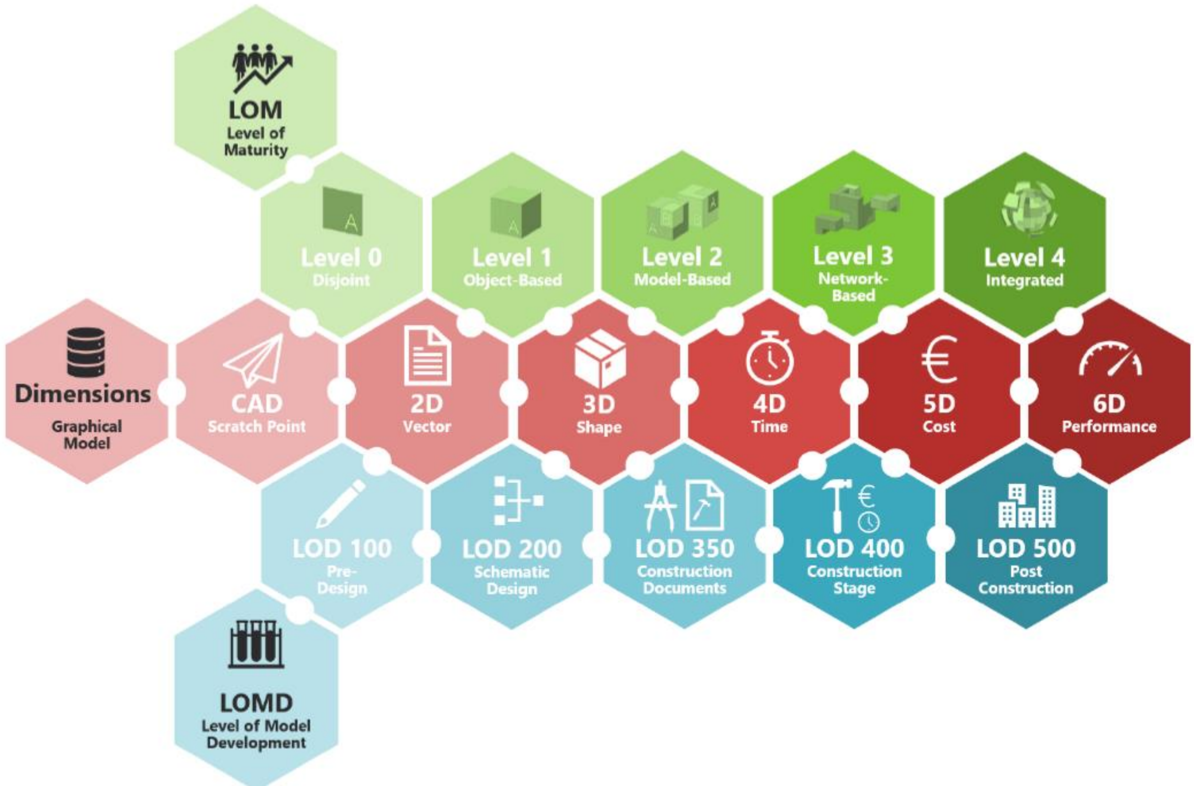


Figure 33 - Integration of dimensions, LOMD and LOM in BIM (adapted from (Van Groesen, W., 2020))

Data and information managed and stored during the design, as well as the execution phase of a building, defines the dimensions, the LOMD and the LOM of the digital asset and it also defines how the digital assets can be adopted. The additional or removal of information can expand or reduce BIM's application. The higher the level of the BIM model (which can be extended to a national level) the larger the mole of data and the interoperability with multiple databases is required (Van Groesen, W., 2020).

Nevertheless, to allow for complete life cycle management, the BIM ecosystem should include and continuously update physical asset data (Omar, T., Nehdi, M. L., 2016) (Kopsida, M., Brilakis, I., Vela, P. A., 2015). In other words, to achieve an up-to-date and near-to-reality BIM model that represents the physical environment, physical asset management tools and devices (such as sensor technology) are needed. The pre-requisite is that these physical asset tracking and management systems are suited for implementation with digital information systems.

Physical environment and asset management

As illustrated at the end of the previous paragraph, effective digital asset management (from BIM Level 2 and Dimension= 4D upwards) requires gathering, recording and processing physical asset data, in other words, PAT strategies are needed. For example, monitoring the position of a good across its supply chain can be adopted for contract compliance activities that can trigger payment procedures. In this case, physical data is collected and fed into a digital environment that triggers specific information and process flow (Van Groesen, W., 2020) (Succar, B., 2010)

Currently, the construction and demolition industry carries out PAT activities predominantly in a manual way. According to (Omar, T., Nehdi, M. L., 2016), this approach has several limitations concerning digital asset management. The manual execution has a significant impact on the resources employed, time and money, as well as the duration of such activities which can hinder swift decisions and interventions. Another limiting factor is the accuracy that can be achieved through manual data acquisition practices. Because these activities are carried out autonomously and individually by several stakeholders (to prove their compliance to contract terms) involved throughout the supply chain, the way information is collected and managed differs and does not allow for automated integration of data. According to (Omar, T., Nehdi, M. L., 2016), there are current technologies and ways for tracking the physical status of objects in an effective and automated way.

The focus on the devices, tools and processes presented hereafter is on their contribution to achieving a (semi) automated way of collecting and processing data within a digital environment. As mentioned previously, PAT is an important pre-requisite for achieving a higher level of accuracy and collaboration through digital asset management (Omar, T., Nehdi, M. L., 2016) (Kopsida, M., Brilakis, I., Vela, P. A., 2015).

The following paragraph outlines PAT technologies (see Figure 34) regarded as suitable for on and off-site physical asset tracking and digital asset management. The benefits and limitations of each technology are provided. Enhance IT technologies will not be presented as these fall outside the scope of the automation process.

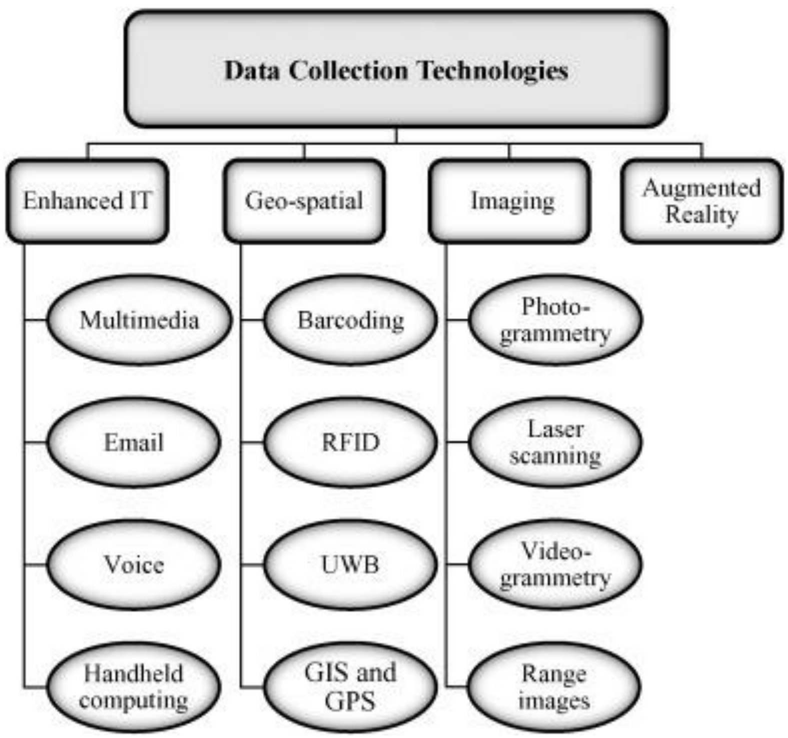


Figure 34 – Type and categories of PAT technologies (source (Omar, T., Nehdi, M. L., 2016))

Geospatial technology

Geospatial technology compromises a set of tools that are deemed feasible for assessing and determining the status and location of a good throughout its supply chain. It can positively contribute to assessing the compliance of planning agreements (Omar, T., Nehdi, M. L., 2016) (Van Groesen, W., 2020)

These type of technologies allows interaction and communication with goods through the employment of tags and/or sensors. These tags and/or sensors must be linked to the identity of the good, thus allowing pinpointing the location of these goods in space and time. For example, if contract terms require having a specific good in a specific location at a specific point in time, geospatial technologies can help in assessing this and determining compliance with the contract terms (Mason, J., 2017) (Omar, T., Nehdi, M. L., 2016)

A large variety of geospatial technologies are currently present in the market, the following paragraphs present those technologies that are tightly related to physical and digital asset management in the built environment.

Quick Response Codes (QR-Codes)

QR-Codes are 2D codes (see Figure 35) that can be generated and read by specific software. They contain static information such as the URL to a website, ID-related information, series of numbers that can be coupled to an individual or group of assets.

Figure 35 – Example of QR code (sourced from (Wikipedia, n.d.))

QR codes employ different methods for encoding data (Ramdav, T., Harinarain, N., 2018). Today the technology is quite popular and extremely easy to develop and deploy as it only requires a QR-code generator and a scanner. Scanner and QR-Code generators are already embedded in modern smartphones as well as available on free websites. QR-Codes can be employed for asset tracking, management of inventory as well as supply chain management. Nevertheless, asset tracking is in this case passive because the data flow is manual, meaning that someone or something needs to scan the QR code for retrieving the data. Also, QR-Codes are restricted to one code per scan only (Ramdav, T., Harinarain, N., 2018) (Van Groesen, W., 2020)

Today, QR codes are widely incorporated into the parcel delivered by delivery services. At each step of the process, the QR code is scanned, and the unique identifier embedded within the code is coupled to a specific status of the process. The status is then communicated within a database and retrievable by third parties. This is an example of the track and trace of parcels (Benatia, M. A., Remadna, A., Baudry, D., Halftermeyer, P., Delalin, H., 2018).

QR codes are employed similarly within the construction industry in which these codes are used for tracking the timely delivery of construction elements on site (Ramdav, T., Harinarain, N., 2018).

To conclude, QR code is beneficial for coupling digital information (such as the precise location in time) to physical assets. The application of QR codes in construction is still limited as it is complicated to couple the dynamic flow of information resulting from the construction environment to the static nature of data management of QR codes (Ramdav, T., Harinarain, N., 2018) (Kopsida, M., Brilakis, I., Vela, P. A., 2015)

Radio Frequency Identification (RFID)

This technology relies on wireless communication with the use of tags attached to the goods to be tracked. The tag contains specific data that is transmitted and received through radio frequencies. While the QR code requires writing and a reading device, in this case, the information flow can be managed in an automated fashion. RFID tags can be regarded as either passive, active or hybrid. Active tags have an internal power supply and can actively transmit the information to the reader (range=500m). Passive tags instead receive the energy required for the reading process by the readers themselves (range=15m). Hybrid tags can transmit data but need to be activated by a signal (Omar, T., Nehdi, M. L., 2016)

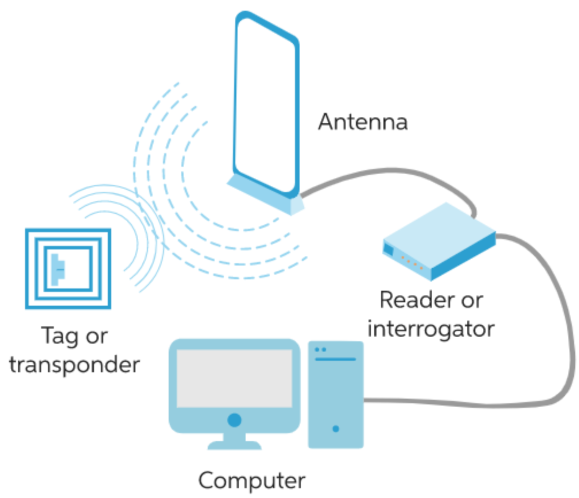


Figure 36 - RFID schematics (source (Chegg, n.d.))

These aspects have a direct implication on the asset management practices that can be enabled by these types of tags. Passive tags, for example, require to be manually scanned as in the case of QR codes, while active ones will do so without the need for a scanning activity. Hybrid tags for example could transmit data only when located in a specific geographical area. RFID readers can scan multiple tags at the same time (Van Groesen, W., 2020) (Omar, T., Nehdi, M. L., 2016).

RFID technology is widely applied in banking activities. Bank cards permit you to make wireless payments thanks to RFID technology. The same technology is also applied in supply chain tracking and inventory management. An interesting example is the tracking of linen within hotels. These goods are equipped with an RFID tag and when clients request new and clean linen, these are delivered based on an optimum route, after arrival, these are scanned and automatically added to the hotel's inventory, while dirty ones are automatically removed from it (Lodgher, A., 2009).

The construction industry has also seen the adoption of RFID technologies. For example (Ghanem, A. G., AbdelRazig, Y. A., 2006) used RFID wireless systems for assessing the progress of construction projects, while (Song, 2006) as used RFID technologies for automatically identifying and tracking pipes. In the last case, RFID has provided multiple benefits such as 1) reducing the time for identifying and locating pipes,

2) timely available and more accurate information about delivery and inventory, 3) reducing the number of misplaced pipes, 4) increasing reliability of the planning schedule (Song, 2006).

Another interesting application is the one tested by (Montaser, A., Moselhi, O., 2012) in which RFID systems were employed for tracking earthmoving operations. According to (Turkan, Y., Bosché, F., Haas, C. T., Haas, R., 2014) RFID systems can supply accurate data about the location of construction elements.

Overall, RFID technologies provide multiple advantages such as a wide reading range, the possibility of being operated remotely, and durability in a construction environment. On the other hand, RFID has high initial costs associated with investment and maintenance, reduced signal strength with time and a limited lifetime of batteries (for active RFID) (Omar, T., Nehdi, M. L., 2016) (Van Groesen, W., 2020).

Ultra-Wide Band (UWB)

Like RFID technology, UWB employs radio technology for its communication. UWB is composed of a network of receivers and tags which can communicate with each other on a large bandwidth and within a range of +1000m. This extends significantly the applicability of UWB technology (Omar, T., Nehdi, M. L., 2016).

The radio pulses emitted by the tags allow the system to identify the coordinates of a construction element on a 3D plane (Cho, Y. K., Youn, J. H., & Martinez, D., 2010). Other applications in the construction sector are extended to material and activity tracking on-site, both in simple as well as in difficult construction environments (Shahi, A., Aryan, A., West, J. S., Haas, C. T., & Haas, R. C., 2012) ; (Omar, T., Nehdi, M. L., 2016). (Cheng, T., Mantripragada, U., Teizer, J., Vela, P. A., 2012) have successfully tested the use of UWB for tracking and 3D mapping (see Figure 37) construction elements in real-time while (Shahi, A., West, J., Haas, C., 2013) have employed UWB for tracking the process of specific construction activities, demonstrating that UWB can be employed for a wide range of applications and at different construction stages within construction projects.

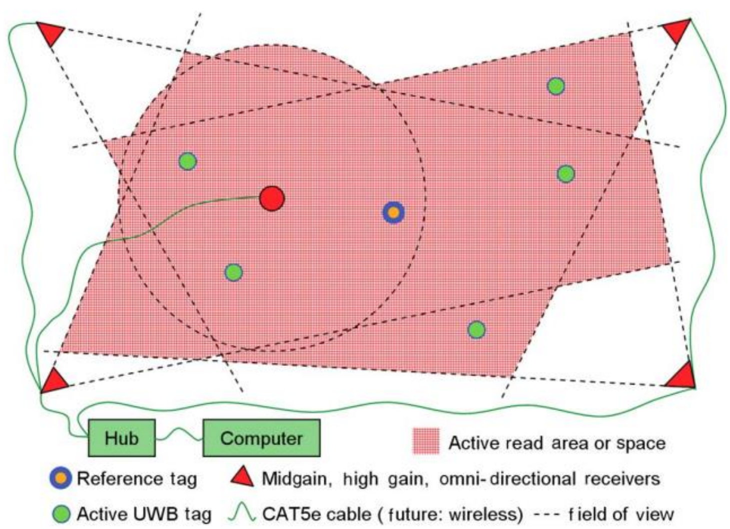


Figure 37 - UWB on-site configuration for tracking and 3D mapping of construction elements (source (Cheng, T., Mantripragada, U., Teizer, J., Vela, P. A., 2012)

The advantages of UWB application in the C&D industry are: 1) long read ranges, 2) can be adopted indoors and outdoors, 3) low energy requirement, and 4) does not require additional technologies and integrations for accurate 3D mapping (Omar, T., Nehdi, M. L., 2016) (Shahi, A., Aryan, A., West, J. S., Haas, C. T., & Haas, R. C., 2012)

Global Positioning System (GPS)

GPS is regarded as interesting and suitable when the objective is to track the position and the movement of construction elements throughout the construction project or along the supply chain. In this case, the technology relies on signals sent by satellites and received by specific tags attached to the good that needs to be tracked (Omar, T., Nehdi, M. L., 2016).

GPS is a widely known technology it has been adopted in construction for analyzing and managing data concerning procurement, management of pre-construction activities as well as monitoring construction sites and progress (Omar, T., Nehdi, M. L., 2016). GPS technology is regarded as interesting because it can collect and integrate spatial and non-spatial information.

For example, GPS technology has been employed in the tracking of steel structures, from the manufacturing to its long-term maintenance activities, even including inventory and installations (El-Omari, S., Moselhi, O., 2011)

(Shen, X., Lu, M., Fernando, S., 2012) have tested the use of GPS technology for aiding the guidance of boring machines in tunnels. The limitation, in this case, is that GPS can generate multipath errors in environments where the path signal can be disturbed, blocked, deflected and distorted.

GPS information can also allow the integration of 3D models with a fourth dimension (time), thus enabling 4D models. In this perspective (Liang, X., Lu, M., Zhang, J. P., 2011) have tested the use of GPS with other software and tools for tracking and visualizing the position and orientation of construction elements during construction.

(Bansal, V. K., Pal, M., 2009) instead, have integrated GPS information with Geographic Information System (GIS) and created a 3D animation of project activities that allowed them to assess the project schedule and detect missing activities and identify potential project errors in the project schedule.

Even though GPS allows for full automation and can be employed for physical and digital asset management, congested environments can significantly hinder the accuracy of the tracking tool and GPS tags are expensive, thus limiting their applicability on large-scale projects (Van Groesen, W., 2020).

3D Imaging Technologies

An alternative method for PAT to geospatial methodologies is imaging technologies. Imaging technologies employ digital images for creating 3D models and information about the construction element present on-site. This information can be employed for assessing the construction progress against a pre-defined 3D model of the construction progress at the expected point in time. In other words, it allows us to compare the "as-is" state with the "as-planned" 3D model and determine any discrepancy (Omar, T., Nehdi, M. L., 2016) (Van Groesen, W., 2020) (Kopsida, M., Brilakis, I., Vela, P. A., 2015). Several promising imaging technologies have been developed so far.

Photogrammetry

This method allows the capture of multiple pictures and the generation of an accurate 3D model. The resulting “as-is” model can then be compared to the “as-planned” model, and this allows for identifying and determining the degree of completion and assessing the construction’s progress (Memon, Z. A., Majid, M. Z. A., Mustaffar, M., 2005)

Photogrammetry is considered to be the imaging technology that is the most automated for measuring the progress of construction projects (Omar, T., Nehdi, M. L., 2016) (Van Groesen, W., 2020).

Different researchers have tested photogrammetry in construction activities. For example, (Dai, F., Lu, M., 2010) employed this technology for obtaining the 3D design of construction elements on site (see Figure 38).

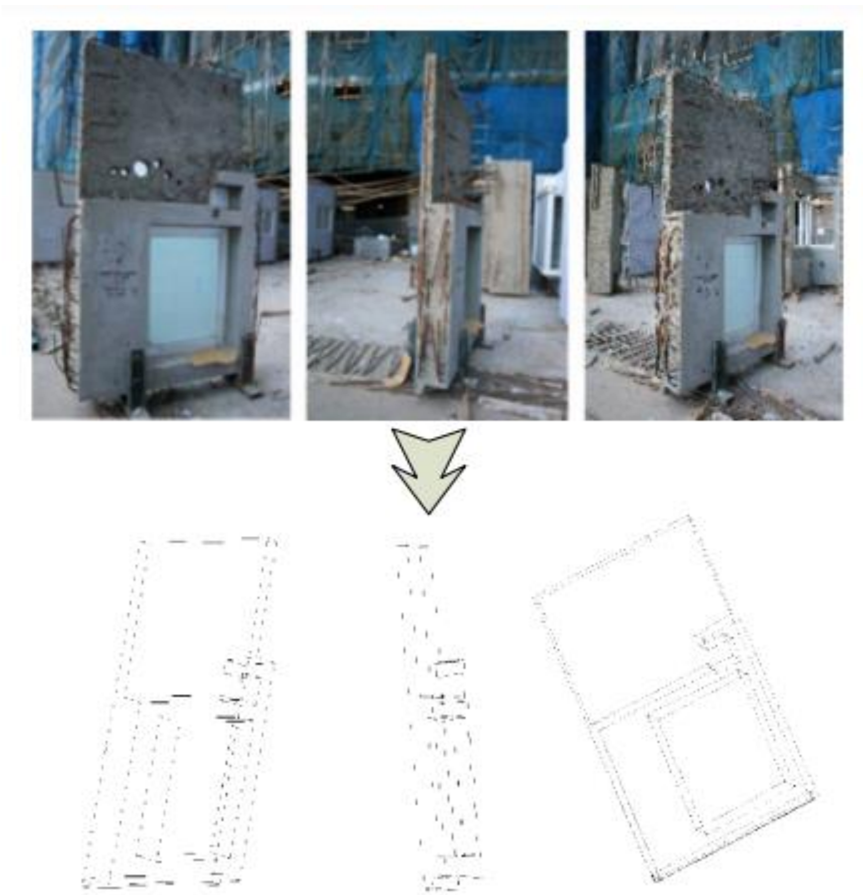


Figure 38 - Photogrammetry for obtaining 3D models of construction elements (source (Dai, F., Lu, M., 2010))

(El-Omari, S., Moselhi, O., 2009) have developed a system for tracking, through 3D images, the progress of a construction site and the work performed between 2 scans. A more recent study has used a similar approach for comparing the “As-is” status of a construction site with its “as-planned” status and subsequently updating the progress in a BIM model (Van Groesen, W., 2020).

The advent of smartphones integrating accurate cameras has significantly increased the number of pictures taken at construction sites. Despite the increase in quality and the reduction in costs, the application is still limited due to the need for human resources in taking pictures, thus making the process time-consuming and resource-intensive (Omar, T., Nehdi, M. L., 2016).

Overall, the limited application of this technology in construction projects is due to 1) resources in terms of time and computational power, 2) sensitivity to lighting differences and accuracy of image processing 3) progress monitoring is done on an element basis (Omar, T., Nehdi, M. L., 2016).

Laser Detection and Ranging (LADAR) / 3D Laser scanning

LADAR technology has been widely adopted in the engineering field for capturing 3D point clouds. This technology can recreate a complete 3D map of a room/space by emitting continuous pulses of laser lights and calculating the distances of the surface on which the laser is bounced off. Allowing in this way to collect 3D cloud points in the range of millions within a minute (Omar, T., Nehdi, M. L., 2016) (Turkan, Y., Bosché, F., Haas, C. T., Haas, R., 2013)

(Akinci, B., Boukamp, F., Gordon, C., Huber, D., Lyons, C., Park, K., 2006) employed LADAR for developing a specific framework for running quality controls on the construction site, thus avoiding construction errors that would lead to rework activities.

The same technology has also been employed for assessing and monitoring the structural health of a building by measuring the deformation of construction elements (Park, H. S., Lee, H. M., Adeli, H., Lee, I., 2007). LADAR has also proven successful in tracking the status and progress of construction sites by recognizing construction elements and comparing them with their 3D counterpart in BIM (Omar, T., Nehdi, M. L., 2016). Another interesting approach was to use LADAR for monitoring the progress of the construction site and simultaneously replicate the design in a 3D BIM model (Gao, T., Akinci, B., Ergan, S., Garrett Jr, J. H., 2012).

Although promising, the technology is not widely adopted in the C&D industry due to its high costs and the difficulty of operating the tool in crowded environments (laser needs a clear line of sight) and the continuous need for calibration. On a construction site, machinery and personnel are continuously moving and this can cause disturbance to the LADAR technology, thus requiring additional manual work for post-editing and adjustments. Additionally, there is a direct relationship between the distance of the LADAR tool to the construction element and its accuracy. Because of the reasons outlined above, the advantages presented by LADAR technology have not been perceived so far within the industry (Omar, T., Nehdi, M. L., 2016).

Videogrammetry

Similarly to photogrammetry, videogrammetry technology uses videos (in other words a sequence of frames) for constructing a progressive image of the construction site. With the improved resolution of cameras, videogrammetry is regarded as a fairly accurate technology (Omar, T., Nehdi, M. L., 2016).

Videogrammetry has been employed for detecting damages to construction elements as well as for conducting safety evaluations of constructions and infrastructures. (Dai, F., Rashidi, A., Brilakis, I., Vela, P., 2012) have instead adopted videogrammetry for mapping some bridges and some buildings and have reported a high 3D accuracy but have also reported that the technology can be affected by camera-specific features such as the brand of the camera, the focal length and its resolution. The same research team has also tested and compared the accuracy, quality and efficiency of videogrammetry against photogrammetry and LADAR technology (see Figure 39). They have indicated that video and photogrammetry can produce 3D models of moderate accuracy but at a significantly lower cost than LADAR technology, thus making the technology interesting for future research.

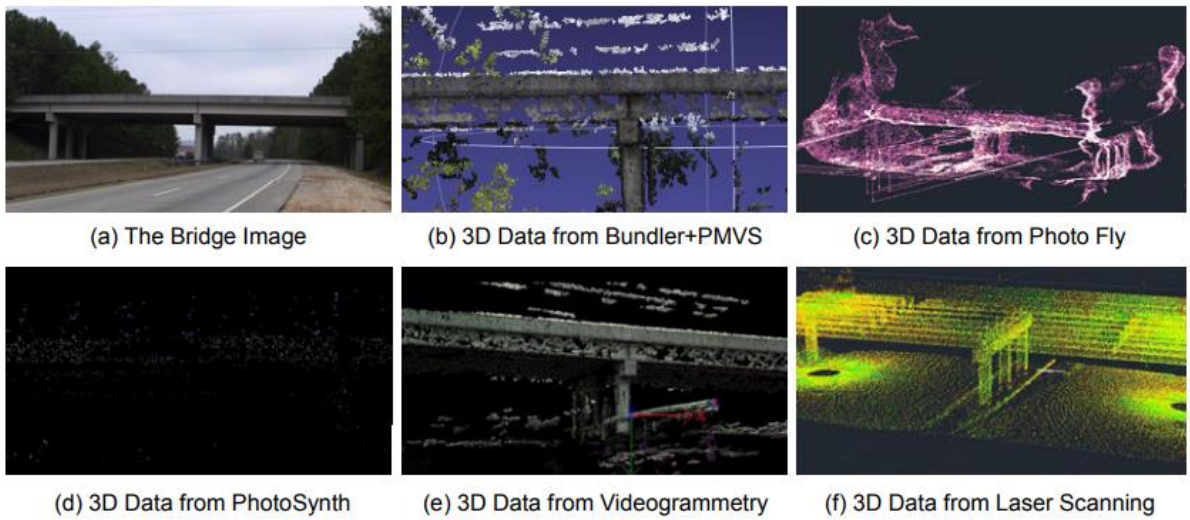


Figure 39 - Snapshots of 3D point clouds collected by different methods (source (Dai, F., Rashidi, A., Brilakis, I., Vela, P., 2012))

Range Images

Range images are a unique type of depth images. Instead of using light, they use range sensors able to accurately recreate the shape of 3D objects inexpensively. In other words, it is possible to capture the physical environment into a 3D digital object (Omar, T., Nehdi, M. L., 2016).

This technology has been proven efficient for tracking machinery, construction equipment and construction elements as well as detecting their characteristics on-site (Omar, T., Nehdi, M. L., 2016). In an interesting study, (Bosche, F., Haas, C. T., Akinci, B., 2009) adopted range images for mapping obstacles on the construction site and designing specific routes for avoiding them and therefore reducing the likelihood of accidents. The recent development of RGB-D (Red, Green, Blue plus Depth) cameras can bring further advantages. These cameras can take pictures at multiple resolutions and depths, thus increasing their flexibility of use (Omar, T., Nehdi, M. L., 2016).

Range cameras have multiple benefits. They are cheaper than LADAR technology but slightly more expensive than cameras for photogrammetry and videogrammetry, can cover a wide field of analysis and are not influenced by exposure and backlight, making them more suitable for outdoor analysis (Omar, T., Nehdi, M. L., 2016)

Augmented Reality (AR)

According to (Wang, X., Truijens, M., Hou, L., Wang, Y., Zhou, Y., 2014), the term augmented reality refers to *"a live, direct or indirect view of a physical, real-world environment whose elements are augmented by virtual, computer-generated imagery".*

AR is not a self-standing technology, but it relies rather on the integration of multiple hardware and software such as a head mount, GPS and smart positioning devices. Also, its application is not straightforward. AR can be employed for simulating, visualizing, communicating, collaborating, modelling and for practical purposes such as inspection and safety assessments within construction sites. It has been applied to municipal infrastructure, highways, residential and commercial buildings as well as industrial projects (Omar, T., Nehdi, M. L., 2016) (Shirazi, A., Behzadan, A. H., 2015).

Multiple applications have been identified for AR and asset tracking in construction. For example, a direct application is to use AR for assessing and comparing the project status. To compare 3D models to the actual construction site, AR requires first collecting data on site through photo/videogrammetry, or LADAR and then comparing the obtained 3D model with the original 3D model (see Figure 40). This work of comparison requires the involvement of a person who can determine the status of the project, and its defects and decide whether specific actions must be taken (Omar, T., Nehdi, M. L., 2016) (Brilakis, I., Fathi, H., Rashidi, A., 2011) (Ibrahim, Y. M., Kaka, A. P., Aouad, G., Kagioglou, M., 2008)

Figure 40 - Videogrammetry 3D model compared to original 3D model (source (Ibrahim, Y. M., Kaka, A. P., Aouad, G., Kagioglou, M., 2008))

An interesting development in the AR context is the integration of BIManywhere and SMART REALITY. The combination of these 2 software can employ the 2D floor plan of a building as the basis and overlay a 3D model over it, thus allowing one to visualize how the building will look (see Figure 41). The tool works also the other way around.

Figure 41 – Workers using BIManywhere (Omar, T., Nehdi, M. L., 2016)

Despite its adoption in construction, AR is still considered to be in its research stage and its potential has not been fully unleashed yet. Some limitations identified by researchers, such as user comfort, limited use in congested environments, use in outdoor conditions, ability to filter data interferences and the need for more interactive features must be addressed first (Omar, T., Nehdi, M. L., 2016).

Evaluation of physical asset tracking and monitoring technologies

PAT is an important prerequisite for effective project management in construction. From this perspective, it is important to employ technologies that can track and monitor these assets accurately and efficiently. The technologies so far presented have all specific advantages and disadvantages and have certain features making them suitable for specific C&D phases and applications. Table 4 provides a summary and comparison of the technology categories presented in the previous chapters.

Geospatial technologies are very effective for tracking and visualizing objects from a geographic perspective. Information/data are provided in real-time and, in general, these tools are considered to be sufficiently resistant for enduring construction environments. An additional advantage is the possibility of tracking objects throughout the entire supply chain. Despite initial investment costs and high maintenance costs limiting their adoption in construction, information and data from geospatial tools are starting to be integrated with BIM and other tools (Omar, T., Nehdi, M. L., 2016).

3D-Imaging is currently the most widely adopted technology in construction for collecting 3D point clouds. This is primarily attributed to its high accuracy, range and efficiency. These technologies allow tracking of the progress of construction projects by scanning the "as-is" situation and comparing it with the "as-planned" 3D model in BIM. Although very promising, this approach is limited due to the complexity of the software required to operate this approach and the high costs associated with the equipment. Making this solution unfeasible for small projects. Photo/Videogrammetry overcomes the cost-associated issues, but is still limited by the low accuracy. 3D imaging technologies can also be employed for recreating a 3D model of physical objects (Omar, T., Nehdi, M. L., 2016).

AR allows the visualisation of 3D virtual objects in a 3D environment. The technology is regarded as a promising one for the C&D industry due to its versatile application. For example, AR was employed in the renovation of the Oakland medical centre. In this case, AR was complemented with the software BIManywhere and QR stickers were placed on specific construction elements. By scanning the QR code placed on a specific construction element, the device would be connected to the BIManywhere server and get access to the 3D model of the construction element, documentation, drawings and technical specifications (Omar, T., Nehdi, M. L., 2016).

Table 4 - Comparison of technologies for physical asset tracking and monitoring (adapted from (Omar, T., Nehdi, M. L., 2016))

	Geospatial	**3D Imaging**	**Augmented Reality (AR)**
Setup and cost	Moderate	Very high	High
Automation level	Semi-automated	Automated	Automated
Automated Analysis	Automated	Automated	Automated
Applicability	All projects	All projects	All projects
Training required	Low	High	Moderate
Pre-processing level	Low	Moderate	Low
Integrated readiness	Moderate	High	High
Meaningful support for decision-makers	Low	High	High
Computational cost	Low	High	Low
Project Size	Small/Moderate	Moderate/Large	Moderate/Large

Integration of PAT and monitoring technologies

All technologies so far presented can provide very interesting advantages concerning asset tracking. Integrating them can overcome some limitations that characterize these technologies when sued individually. A good example is the integration of photogrammetry with LADAR technology (see Figure 42), which significantly increase the rendering speed of the 3D model and its accuracy, thus allowing for an even more precise project status assessment (Golparvar-Fard, M., Peña-Mora, F., Arboleda, C. A., Lee, S., 2009).

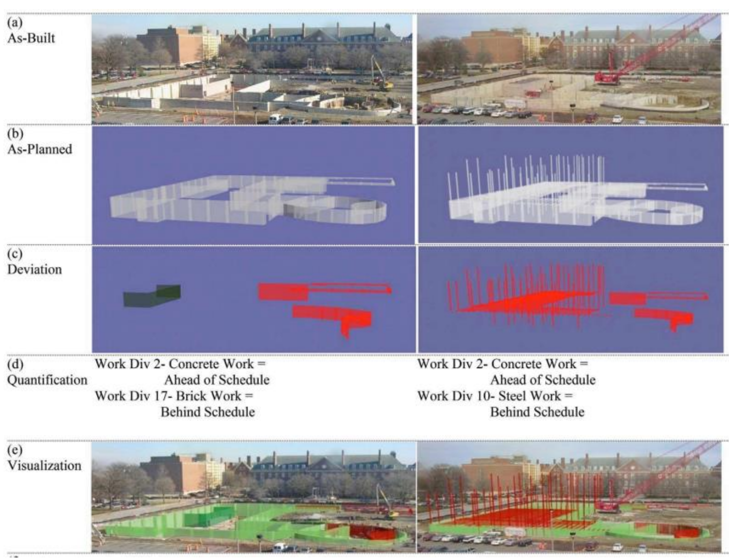


Figure 42 - Visualized monitoring report: (a) as-built photographs; (b) 4D snapshots; (c) colour-coded virtual components; (d) quantification of the deviation; (e) augmented photographs (source (Golparvar-Fard, M., Peña-Mora, F., Arboleda, C. A., Lee, S., 2009)

Data acquired from photogrammetry and LADAR can also be combined with other technologies such as RFID and UWB as well as information technologies such as BIM (Valero, E., Adan, A., Cerrada, C., 2012).

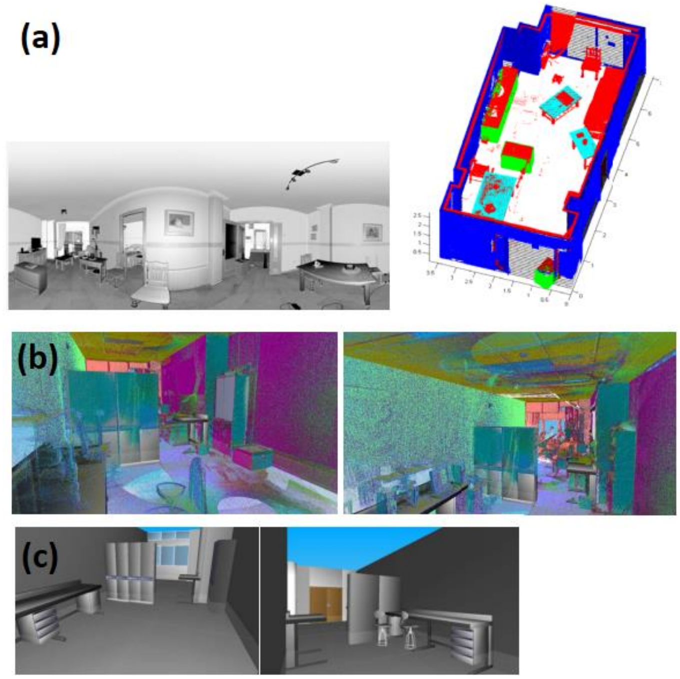


Figure 43 - (a)Panoramic image of a room under study and cloud points, (b) insertion of the modelled furniture onto the cloud points, (c)final basic 3D model (adapted from (Valero, E., Adan, A., Cerrada, C., 2012))

(El-Omari, S., Moselhi, O., 2011) have instead conceptualized a model that integrates barcodes, RFID, LADAR and photogrammetry which can collect data directly on-site and assess the rate at which work is performed and also track materials. In other studies, tags were coupled to GPS antennas to obtain the exact location of construction elements (Omar, T., Nehdi, M. L., 2016). Very interesting research has instead developed a model that integrated passive RFID tags with a dynamic BIM model. This integration allows real-time tracking (see Figure 44) of construction elements, materials and equipment (Costin, A., Pradhananga, N., Teizer, J., 2014).

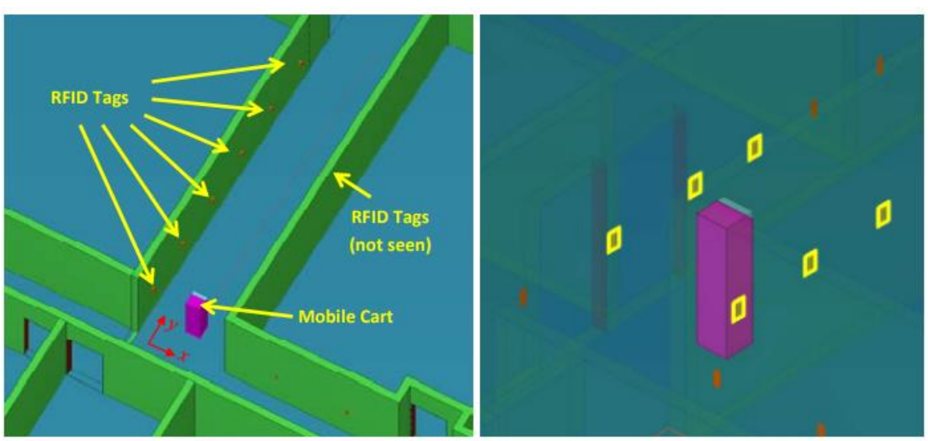


Figure 44 - Facility model with RFID tags and mobile cart (left) and visualization of localization in a BIM model with highlighted tags (right) (source (Costin, A., Pradhananga, N., Teizer, J., 2014))

Several studies have investigated the effective integration between BIM and GIS. (Kang, T. W., Hong, C. H., 2015) have illustrated how this integration could be employed for the management of facilities by municipalities and public institutions, enabling benefits such as increased reusability and extensibility of goods.

The integration of BIM with tools able to assess the "as-is" situation (3D-imaging technologies) is increasing the adoption of BIM during the execution phase in construction. The benefits are multiple, but the most relevant one is the ability to assess the "as-is" situation with the "as-planned" situation, identify divergencies and delays, and consequently increase coordination and communication between the stakeholders involved (Golparvar-Fard, M., Peña-Mora, F., Savarese, S., 2011).

3D-Imaging technologies (such as photogrammetry) have been efficiently integrated with 4D BIM models (3D elements + Time). (Han, K. K., Golparvar-Fard, M., 2015) used photogrammetry for developing a 3D model of the construction site which was then superimposed on the 4D BIM model to assess the progress of the construction project and identify delays and errors (see Figure 45).

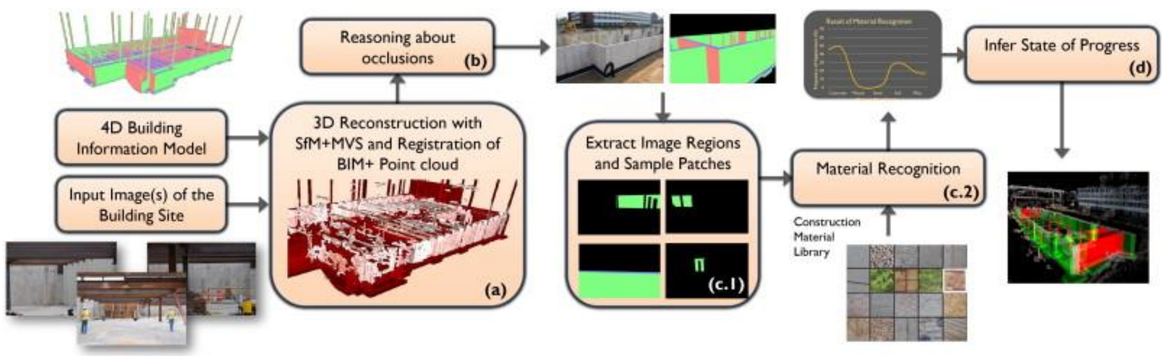


Figure 45 - The method takes as input a 4D BIM and a collection of photos of a construction site and infers the state of progress at the operational-level details for each BIM element (source (Han, K. K., Golparvar-Fard, M., 2015)

Due to the relevance that BIM is gaining in the C&D industry and the lack of a BIM model for old construction, (Pătrăucean, V., Armeni, I., Nahangi, M., Yeung, J., Brilakis, I., Haas, C., 2015) has pinpointed the state of the art with regards to efficient models able to automatically recreate "as-built" BIM.

Concerning the **automation** of asset tracking, some technologies are more promising than others. **Geospatial** technologies, for example, are extremely efficient for tracking goods both on as well as off-site. Sometimes manual scanning procedures are required, thus leading to semi-automated procedures for asset tracking. Nevertheless, it is not feasible to tag every construction element (such as a brick), making geospatial technologies more suited for tracking large or expensive construction elements throughout their supply chains (Van Groesen, W., 2020). **3D Imaging** technologies are instead more suited for capturing on-site conditions, rather than off-site ones. As illustrated so far, 3D imaging technologies work very efficiently for measuring construction progress status but not for tracking construction elements throughout their supply chain. **AR** is in itself a hybrid of the previously mentioned technologies as it requires the integration of multiple technologies and software to operate efficiently. To effectively reach physical asset tracking throughout the entire life cycle of a construction element, requires conducting tracking activities both on as well as off-site. Full asset tracking would therefore require the integration of geospatial, 3D imaging as well as AR technologies (Van Groesen, W., 2020).

Digital Twin, the integration of PAT and DAM practices

The term Digital Twin (DT) was first employed in 2003 in a Product Lifecycle Management course held at the University of Michigan. The concept was first used in the aerospace industry and has after migrated to the product manufacturing industry and only recently to the smart city field (Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y., 2020). DT describes the possibility of having an almost perfect digital representation of the physical world within the digital (virtual) world. In this regard, DT comprises 3 components (see Figure 46) the physical component, the virtual models and the data that connects them.

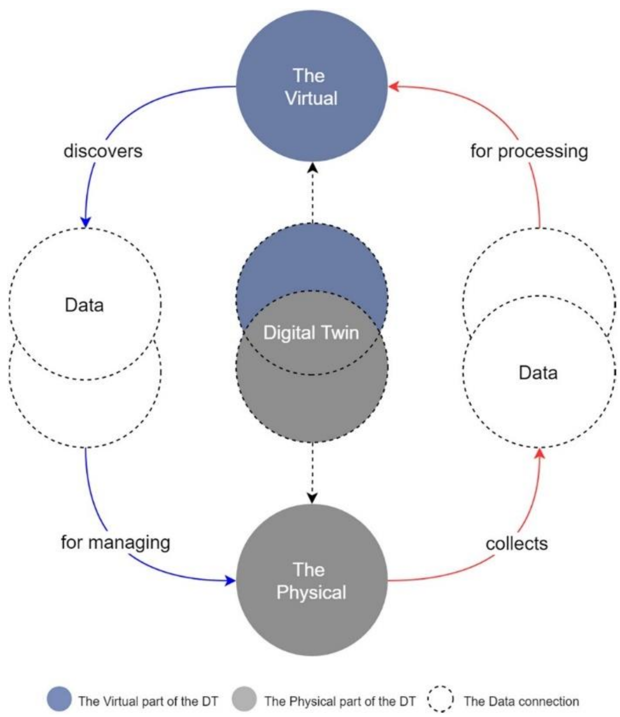


Figure 46 - The Digital Twin paradigm (source (Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y., 2020))

Relating the digital twin concept to the PAT and DAM practices so far presented, it could be said that the **virtual** part can represent BIM while the physical can represent the built environment. The data have in this case 2 directions, **Physical -> Virtual** could represent the information collected via PAT tools while the data going from **Virtual -> Physical** could represent the BIM information useful for DAM.

According to (Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y., 2020) data from **Physical -> Virtual** are raw data requiring processing (the 3D imaging technology is a good example) while the data **Virtual -> Physical** requires transformation (can be knowledge stored across multiple digital models). In other words, the **physical** collect real data from the world which needs processing while the **virtual** provides information that can be adopted for dealing with the physical world.

The topic of digital twins is becoming more popular, with the first academic paper being published in 2011 (Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y., 2020). Before this time technologies were not ready for scaled data collection and processing, resulting in a limited amount of information present in the virtual environment, most likely due to the information being stored on paper and with collection methods that were predominantly manual and not digital. In the last decade development in information technology has advanced significantly allowing for more efficient methods for collecting, processing and maintaining data (Van Groesen, W., 2020).

According to (Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y., 2020) several abilities can be attributed to the DT with the current technologies and developments in the information technology field. These are identified in Table 5. The allocation to a specific part of the digital twin is just for the sake of explaining, in fact, the DT works only if operated in complete unison and synergy.

Table 5 - Identified Digital Twin abilities and their roles within the Virtual-Data-Physical paradigm (adapted from (Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y., 2020))

	Ability	Description
Physical	Sense	To observe the physical in real-time through sensor deployment
	Monitor	Keep track, inform and issue warnings based on physical occurrences
	Accurate	Change & (de)-activate physical components based on virtual decisions
Data	BIM (can also fall in Virtual)	Integrate & consume BIM data sets in various formats & standards
	IoT	Integrate & share data communicated by IoT devices
	Link Data	Integrate & share data via Semantic Web protocols
	Knowledge	Store facts about the system, support rules and reasoning capabilities
Virtual	Simulation	Apply engineering simulation models from various domains
	Prediction	Predict the behaviour of the physical based on digital simulation & sensing
	Optimize	Optimization methods and recommend dynamic resource allocation
	Agency	Delegate AI agent to manage & actuate the physical based on digital

When extended to the topic of asset management and automatic asset tracking, DT provides an interesting framework and lens. Data acquisition in the physical environment, through the tools and technologies presented in the previous paragraph, needs to be interconnected to a virtual environment that can receive this information. The processes and information flow sustaining a DT need to be aligned and coherent to the objective that the DT must fulfil. An important aspect is to define the behaviour, protocols and objective of the digital twin (Van Groesen, W., 2020) (Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y., 2020).

Concerning reuse and recovery practices in the C&D industry, it is important, as highlighted in the previous paragraphs, to acquire data on the physical status of assets and process these in a digital environment. When operating in the physical environment it should be possible to retrieve information from the digital environment that can aid in assessing the reusability and recoverability of assets. The decisions that follow thereafter will inevitably affect the physical environment and again update the digital environment.

Blockchain technology (more specifically Distributed ledger technology (DLT)) in conjunction with smart contracts can enable a semi-automatic information flow between the physical and the virtual environment. For example, if the information in the digital environment meets a specific pre-requisite (defined by the specific use case) in the smart contract protocol, then the information flow is triggered and action is conducted in the physical environment. On the other hand, once a set of actions conducted in the physical environment meet certain prerequisites of a smart contract, an information flow is triggered towards the digital environment. More information about DLT and smart contracts is provided in the next paragraph, but to clarify, smart contracts are a set of pre-requisites that once met can trigger a sequence of behaviours, depending on protocols that are built afterwards (Van Groesen, W., 2020) (Mason, J., 2017).

Nevertheless, to create an efficient digital twin between the physical environment and the digital environment within the construction industry and with the inclusion of BIM, it is paramount that BIM can sustain integrated project delivery (BIM level 3 and 4) and a semi-automated data exchange protocol. BIM and DLT + smart contract can be a powerful way for creating such a digital twin (Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y., 2020) (Van Groesen, W., 2020) (Mason, J., 2017).

Some examples in the EU

DT is starting to be developed across the EU. These can be used for digitalizing the cadaster information and have up-to-date building stock information, providing accessible data to firms and citizens as well as for developing data-driven urban projects. The application can be on a project level on a city, regional and even national level. Antwerp's Port Authority has initiated a project that includes private and public stakeholders for creating the port of the future which includes 3D interfaces, drones, and 5G technology. This allows the authorities to detect oil spills, the location and routes of ships and also how much energy is the port generating and consuming. All information is provided in real-time to an easy-to-access dashboard (Port of Antwerp-Bruges, n.d.)

Figure 47 - Example of real-time information provided by the digital twin at Antwerp's Port (source (Port of Antwerp-Bruges, n.d.))

Extending to a city level, we see the case of the city of Helsinki which has developed a 3D map of the city and coupled it to the urban planning projects as well as real-time data sourced from buildings (European Construction Sector Observatory (ECSO), 2021).

On a regional level, we can look at the project initiated by the region of Flanders, Belgium. The Smart Flanders project aims at creating a Digital Twin in the region by bringing together 13 cities. The overall objective is to make data democratically available to citizens, companies and service providers and to employ government data for driving policy making. The goal of the DT, in this case, is to 1) create a smart region where all stakeholders have access to key data, 2) support cross-industry collaboration, 3)Improve policy and decision-making processes by involving citizens and companies and 4) Define data standards, maximize efficiency and boost new markets (DUET, n.d.) .

Introduction to Blockchain, Distributed Ledger Technology (DLT) and Smart Contracts

Blockchain technology is the combination of a multitude of existing technologies and digital processes, namely, consensus protocols, Merkle tree hashing, distributed ledger technologies and public-key encryption (Tasca, P., & Tessone, C. J., 2019) The term Blockchain gained popularity with the advent of the cryptocurrency named "Bitcoin", introduced by Satoshi Nakamoto back in 2008 (Nakamoto, S., 2008).

Blockchain has unlocked the possibility of creating distributed software architectures which permit a network of **untrusted**, **non-transparent** and **decentralized** participants to formalize agreements and transactions in a decentralized and secure way (Tasca, P., & Tessone, C. J., 2019).

Most importantly, these transactions can be regulated without the need for a centralized authority/body and supervision. Such software architecture can guarantee trust among a network of anonymous actors without the need for a central body or supervisor in charge of auditing and verifying the validity of any record stored in a digital ledger. The historical progression of these components is presented hereafter:

- 1950: Hashing [" process of translating a given key into a code" (Claudio Buttice, 2021)] is employed in cryptography for securing sensitive information and verifying the integrity of messages.
- 1970: Ralph C Merkle's proposed the Merkle Tree which entails the use of concatenated hashes structured within a software tree for guaranteeing digital signatures.
- 1980: Leslie Lamport highlights how hash chains can be employed for secure login activities.
- 1990: The web is becoming accessible to private users and the concept of using cryptocurrency for electronic cash flow is described.
- 1994: Hash chain concept was refined and further developed by Neil Haller.
- 2002: Adam Back elaborates the hash-cash concept
- 2008: The first cryptocurrency (Bitcoin) is presented to the public by Nakamoto.

Blockchain technology is still at its dawn but its conceptual application is extending to many sectors and industries (Tasca, P., & Tessone, C. J., 2019). World Economic Forum has elaborated statistics and extensive reports where the global interest in this emerging technology is highlighted (McWaters, R. J., 2016).

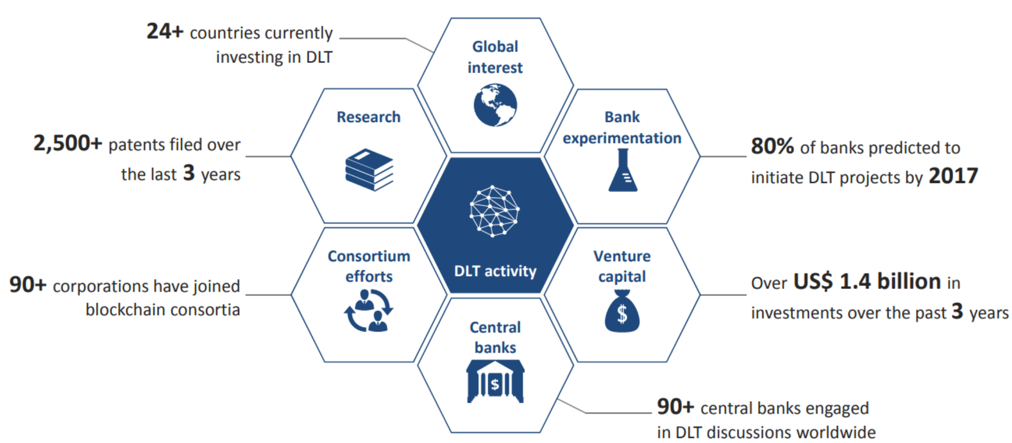


Figure 48 – Global interest in Blockchain technology (source (McWaters, R. J., 2016))

According to the World Economic Forum, Blockchain can positively impact industries in the following ways.

Operation simplification: it can reduce and eliminate manual activities focused on reconciling and resolving disputes among actors in a network (McWaters, R. J., 2016).

Improvements in regulatory efficiency: it allows for live monitoring of financial interactions between parties (McWaters, R. J., 2016)

Multi-actor risk reduction: agreements and obligations are coded and executed in a shared and transparent environment, thus avoiding the need for trust between actors (McWaters, R. J., 2016)

Time reduction for auditing: the built-in verification system eliminates the need for third parties focused on transaction verification and validation (McWaters, R. J., 2016)

Prevent lock-in on liquidity: it provides transparency into the activity of sourcing liquidity for assets (McWaters, R. J., 2016)

Fraud dampening: assets and transactions are recorded within a single source of truth thus hindering fraud activities (McWaters, R. J., 2016)

Across different industries, working groups and consortia are forming and using Blockchain as the basis of their interactions and processes (Tasca, P., & Tessone, C. J., 2019). This highlights the relevance that Blockchain can have as one of the most promising technologies which will significantly impact the society of the future.

Looking at Blockchain technology under the lens of the Technology Life Cycle (TLC) theory (a method to assess the technical performance over time) as interpreted by (Gao et al., 2013), it can be observed that Blockchain is currently entering its growth phase (Gao, L., Porter, A. L., Wang, J., Fang, S., Zhang, X., Ma, T., Huang, L., 2013). This means that the technology has a high competitive impact but is not yet been structurally integrated into new products or processes (Gao, L., Porter, A. L., Wang, J., Fang, S., Zhang, X., Ma, T., Huang, L., 2013). (Tasca, P., & Tessone, C. J., 2019) outlines the fact that this has an important implication for the future development of Blockchain into alternative and unpredictable technological and development paths.

Blockchain is currently being employed in different and heterogenous ways, because the business objectives underlying its use are very different and because Blockchain is constituted by re-arrangeable building blocks, the way it is therefore designed and operated can be extremely versatile. Consequently, there are countless heterogenous Blockchain-based projects under development in the world, starting from the most successful applications such as Ethereum and Bitcoin, to extremely complicated architectures for resource tracking (Tasca, P., & Tessone, C. J., 2019).

Because of this flexibility in the software architecture configuration, the heterogenous application of the technology, and the lack of standardised Blockchain reference architectures and taxonomy, there is confusion about what the public generally refers to and understands with Blockchain. Some of the current and future issues as identified by (Tasca, P., & Tessone, C. J., 2019) entail:

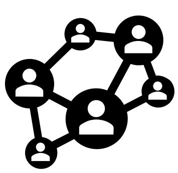
- Difficulty in drafting laws and policies regulating Blockchain
- Consumer protection laws and regulations are ambiguous in the context of Blockchain
- Hindering accuracy of academic research for new applications and solutions of Blockchain
- Increasing complexity and reducing the understanding of how Blockchain can be applied in different sectors and aid in achieving social, economic and environmental objectives.
- Lack of interoperability between existing and new software architectures

To provide a better understanding of Blockchain's components, Appendix I presents an extensive Blockchain taxonomy according to the research conducted by (Tasca, P., & Tessone, C. J., 2019) which focused on outlining the correct "identification, description, nomenclature, and hierarchical classification of Blockchain components". The advantages of identifying and classifying the building blocks of Blockchain technology are diverse, it allows us to have a guide in the possible software architecture configurations and compare design options for different applications.

The driving principles/features of Blockchain technology

The building blocks of Blockchain technology can be arranged and organized in different ways, according to the needs and the process outcomes required. Nevertheless, the key features and principles can, according to (Aste, T., Tasca, P., Di Matteo, T., 2017), be summarized as follows.

Decentralization of consensus



It allows us to relate consensus activities and processes to pre-set rules. These rules can be customized and adapted, but generically, these affect whether a transaction is allowed, and the amount of reward involved in the transaction/exchange. Additionally, the system records and holds a chronology of all transactions that occurred in the system, thus certifying the ownership of whatever has been exchanged through the network, be it resources, value or information (Tasca, P., & Tessone, C. J., 2019) The decentralized consensus mechanism, which governs and manages the update of the digital ledger and the nodes through which this information flows, is responsible for verifying and logging the information. Due to a lack of central authority, there is no single point of trust and failure (Tasca, P., & Tessone, C. J., 2019).As illustrated in Figure 49 below, Blockchain consists of blocks of text containing information about transactions/exchanges. The new block of information is composed of the hash ("mathematical function which turns any type of input data into a fingerprint of fixed size" (Tasca, P., & Tessone, C. J., 2019)) number of the previous block pus a randomly generated one, thus making every block a unique piece of information.

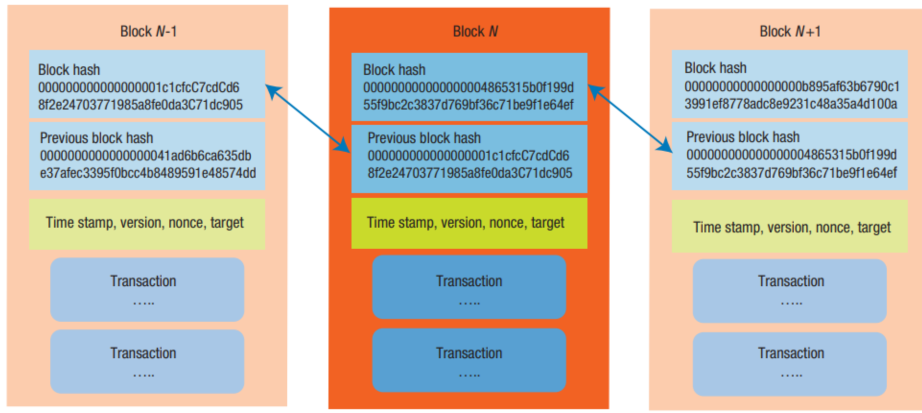


Figure 49- Blockchain information exchange mechanism (Aste, T., Tasca, P., Di Matteo, T., 2017)

Transparency

Information and records can be verified and audited by all or a defined set of stakeholders in the network, depending on how "open" and "accessible" the network is. In public Blockchain networks, anyone with an internet connection holds equal rights to access and audit the digital ledger. Therefore, all records are transparent and traceable in the Blockchain network. Stakeholders in the network can based on their CPU computing power, update information in the digital ledger (Tasca, P., & Tessone, C. J., 2019).

Security

Information/data in a Blockchain system are shared, in a manipulation-free and irreversible way. The information is interlinked through sequential information hash and therefore it cannot be generated or edited unidirectionally by the network's participants. Participants require a private key for generating a signature underlying every Blockchain transaction initiated by them. The signature allows for confirming the origin of the transaction and it prevents anyone in the network to alter information once issued (Tasca, P., & Tessone, C. J., 2019).

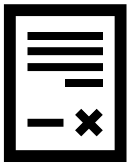
Immutability

Records contained in a Blockchain network cannot be repudiated and reversed. In other words, once a piece of information is recorded in the digital ledger, no one in the network can alter the information in secrecy from the whole network, making thus all records manipulation-free. This is possible thanks to hashes stored within the blocks. Each block contains information from the previous's blocks' hash, thus generating a chain of blocks.

The immutability of information varies in Blockchain networks and it depends and relates to the complexity characterizing the alteration of the transactions' chronology and history. This means that the proof-of-work mechanism upon which the information hash is built can be very complicated or very simple. In a private Blockchain network, for example, Blockchain can be validated only once signed by a set of pre-validated participants or when the information meets certain pre-conditions. In such a situation, a participant would need the private keys of all these participants to back engineer the information chain (Tasca, P., & Tessone, C. J., 2019).

Smart contracts and automation

The features so far described can be organized in such a way for stipulating, issuing and managing contracts between the blockchain's network participants. The



advantage is that these processes can be undertaken without the need for human interaction and verification. Information conflicts are autonomously reconciled by the system and valid transactions are added to the digital ledger only once, thus avoiding the creation of duplicates.

These forms of contracts, also named smart contracts, are revolutionary because in a Blockchain network these can be coded with specific algorithms which allow them to be self- executed/enforced/verified and constrained, thus allowing for rapid and multi-level negotiations and agreements to occur simultaneously without generating conflicting information (Clack, C. D., Bakshi, V. A., Braine, L., 2016).

Storage

The primary storage functionality of a blockchain network is to store the data structures underlying the network and the information log. Usually, Blockchain networks have some data size limitations to avoid clogging the system. However, Blockchain networks can be structured on different data layers and also integrated with private cloud or public databases. This allows the utilisation of the Blockchain network as an intra-database data carrier (Tasca, P., & Tessone, C. J., 2019).

Blockchain technology is composed of several elements and sub-elements which can be configured and operated together in flexible and countless ways, depending on the desired outcome and operational tasks demanded from the system. Nevertheless, Blockchain is oftentimes exclusively associated with Bitcoin, which is just one of the countless applications of Blockchain technologies.

An important constituent of Blockchain technology is the "Distributed Ledger Technology" (DLT). The basic functioning of DLT is to allow for transactions to occur among a distributed network of users without the need for validation from a third party such as a bank or authority and to log these transactions in an immutable database or ledger (Tasca, P., & Tessone, C. J., 2019).

The ledger is simply the transaction's recording which in the case of blockchain, and more specifically DLT, can be organized in a distributed manner without centralized consensus, thus overturning the old ledger technologies adopted by centralized institutions like banks (Davidson, S., De Filippi, P., Potts, J., 2016).

DLT and governance structures

Societies and economies are structured and organized around ledgers, and the organizational layout and configuration of modern economies are strongly interdependent on how ledgers are structured and managed (such as for governments, different strata of bureaucracy and corporations). For this reason, DLT is currently regarded as a "general purpose technology" and a "Disruptive technology" because it can ideally be adopted in a variety of sectors and for a variety of purposes, leading to a deep transformation of the current organizational layout of society and the mechanics of economy (Davidson, S., De Filippi, P., Potts, J., 2016).

Ledgers are very ancient, even older than the double-entry bookkeeping invented in the 15th century. Ledgers are as old as commerce and as numbers and their key functionality is and was to accounting and track consensus about ownership, transfer and value of assets (Davidson, S., De Filippi, P., Potts, J., 2016).

Ledgers are always been characterized by the following qualities: clarity/legibility, consistency, consensus and recording of ownership and asset value. But another fundamental quality that characterizes ledgers is trust in their records and in whom controls them. Trustful ledgers lead to low transaction costs in the economy (Nooteboom, B., Six, F., 2003). So far governments, banks and other auditing authorities have been put at the centre of modern economies, exactly because of the need for a high level of trust in ledgers. This is also why modern capitalism requires efficient and non-corrupted institutions for increasing them and consequently in the ledgers they manage (Davidson, S., De Filippi, P., Potts, J., 2016).

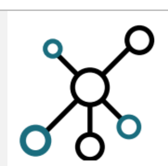
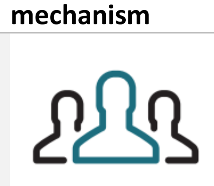
From the beginning of the 20th century and with the advent of personal computers, many ledgers have been digitalized, but still managed under centralized control (Atzori, M., 2017). The advent of Blockchain can lead to a redesign of the layout of modern economies, requiring smaller interventions and auditing power of central authorities such as governments, banks, and insurance companies (Davidson, S., De Filippi, P., Potts, J., 2016) (Evans, D. S., 2014).

As also discussed in the introduction of this chapter, this transformation process is already occurring in the financial sector where new digital currencies are allowing for decentralised financial operations. The transformation is slowly but steadily reaching out to other markets and industries (Davidson, S., De Filippi, P., Potts, J., 2016).

Characteristics of DLT and Smart contracts

A DLT is a set of **ledgers** encrypted through **cryptography**, composed of **validated** transactions which **occurred** and were **replicated** by and **distributed** through a **peer-to-peer** (P2P) network of users who reached a **consensus** about the transaction itself (Tasca, P., & Tessone, C. J., 2019). Despite its flexible application and configuration, DLT is widely recognized for its characteristics which make the ledger, after consensus is reached, **transparent**, **decentralized**, **immutable**, **secure** and **non-manipulable** (Tasca, P., & Tessone, C. J., 2019).

DLT is therefore characterized by the components illustrated by (Hileman, G., & Rauchs, M., 2017):

Cryptography	**P2P Network**	**Consensus mechanism**	**Ledger**	**Validity Rules**
				
Application of cryptographic techniques for securing information, access and management of the network.	Network for sharing and accessing data	An algorithm that governs transactions assuming participants might not be honest	Transactions/Data are linked together through a chain of encrypted blocks. Thus forming a Blockchain.	Rules that determine what transactions are considered valid and how the ledger is managed.

Due to the flexible configuration of Blockchain, DLT and Smart Contract, it is complicated to describe such a system in a simplified way. The following chapter presents, therefore, the building blocks of DLT and Smart Contracts, their interaction and how these could theoretically be operated and applied in the built environment (assuming a DT between PAT and DAM). For the sake of analysis, DLT and its functionalities are presented into hierarchical layers and sub-layers (see Figure 50) which are, in fact, complementary and operated in full synergy (Hileman, G., & Rauchs, M., 2017). The structure of the paragraphs that follow will reflect these layers. It is important to mention that the DLT is extremely versatile and can be arranged and operated in a variety of ways, making it thus difficult to define a static blueprint. The objective of the next paragraph is to provide the reader with a basic understanding of DLT and how it can be related to asset management in the built environment.

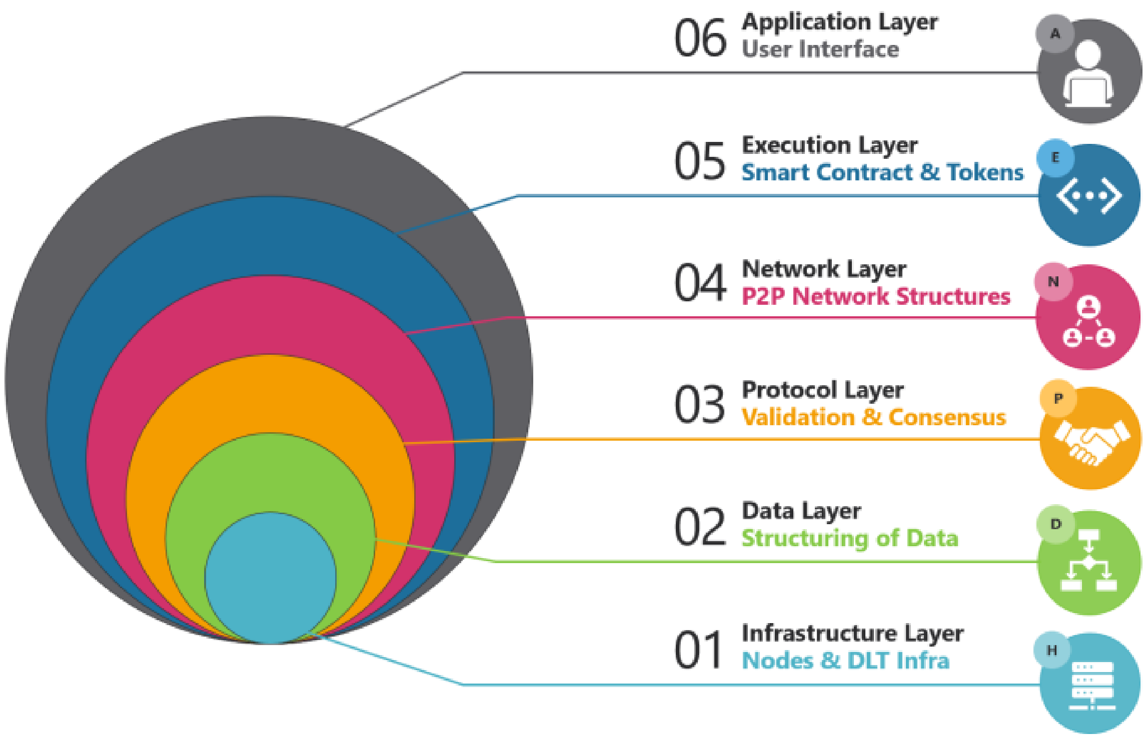


Figure 50 - DLT hierarchical structure and layers (source (Van Groesen, W., 2020))

01- Infrastructure Layer

Accessing a simple article online is possible thanks to servers that store and globally make accessible data. When accessing a web article, your device requests specific data from servers through your internet connection. This flow of information depends primarily on the server architecture adopted for hosting data and for connecting the servers (Tasca, P., & Tessone, C. J., 2019). The most widely adopted architecture is the Client-server architecture which allows users to access and retrieve data, through its user interface such as google news, from data centres located all over the globe (Van Groesen, W., 2020). In this case, the structure is built around centralized servers.

Nodes

Unlike the widely adopted client-server architecture, DLTs are usually distributed on a network of decentralized peers. These peers are individual computers (or servers) connected to each other. The difference here is that, because peers are connected through a shared network, they can process, exchange, store and retrieve data without the need for a centralized server but rather directly through their shared network (Van Groesen, W., 2020) (Tasca, P., & Tessone, C. J., 2019). The innovative aspect of DLT is that it acts as a decentralized database of information/data where each part of the network has (potentially) a replica of the whole database encrypted into a chain of blocks called Blockchains (Tasca, P., & Tessone, C. J., 2019).

The users/participant of the network act as nodes/peers and the exchange of information/data/transactions that occurs between them is defined as a peer-to-peer (P2P) network (Tasca, P., & Tessone, C. J., 2019). Blockchain technologies and architectures (for more details see Appendix I) allow for different types of nodes. For example in **thin nodes,** the full copy of the digital ledger is not stored on the device and the node stores only enough information (cache information) for verifying the execution of the transaction, **full nodes**, on the other hand, store a copy of the whole digital ledger and can actively participate in the consensus process and in validating transactions (Van Groesen, W., 2020). The way nodes communicate with each other is governed by a process called **gossiping** (Tasca, P., & Tessone, C. J., 2019). This process can be either **local** or **global**, with direct impacts on system performance and the security of the system (see Gossipping chapter for more info) (Tasca, P., & Tessone, C. J., 2019).

A DLT is also capable of keeping track of the state of each node/user (account state) taking part in the network and also of the DLT as a whole (world state). Account states concern the balance of an account, transaction histories, fees and so on, while the world stat is the collective state of all accounts at a certain point in time (Van Groesen, W., 2020). The account and world state are updated whenever transactions are executed between nodes and/or smart contracts.

Because the world state of a DLT can change at multiple points in the network, nodes have sometimes an internal sandbox where they run the transaction and change their state in an isolated way. Only if the transaction is verified the new state is deployed to the network, otherwise it is discarded and the world state is not affected (Van Groesen, W., 2020) (Tasca, P., & Tessone, C. J., 2019).

All these aspects are relevant to the correct functioning of DLT because its objective is to allow for information to be transmitted in an autonomous and decentralized way without the need for central authorities. To add information (in the form of a transaction or other forms) to the DLT, special nodes (also named mining nodes or minders) need to mine the transaction. Mining is the act of adding transactions/data into a block and to the DLT after all nodes have reached a consensus about the specific information/transaction. Consensus is reached when the information added to the block is coherent with the information so far stored in the whole DLT. After the mining process, the new block is added to the Blockchain and this is distributed throughout the full network, thus updating the information contained in the digital ledger (Hileman, G., & Rauchs, M., 2017) (Tasca, P., & Tessone, C. J., 2019)

To summarize, the infrastructure of a DLT entails the following elements and sub-elements:

- Network of nodes (full, thin, mining) capable of validating transactions, carrying out consensus and preserving copies of the full distributed ledger in a P2P network (Tasca, P., & Tessone, C. J., 2019).
- Record of all transactions and the capacity of assessing the account/world state of the DLT. This implies having information about balances, smart contract executions, transaction fees and much more information at a specific point in time.

02 Data layer

The previous section illustrated the difference between an account and a world state. While account states represent information about the specific account/node/user, the world state represents the state of all accounts that are present on the Blockchain network at a given point in time (Van Groesen, W., 2020).

This subsection outlines the mechanisms underlying data exchange and transfers within DLT. In general, world and account states are dynamically updated for each transaction (transfer of funds/information/data) occurring within the DLT. In other words, the transactions occurring on the Blockchain network will alter the targeted account state (affecting its balance) and consequently the world state of the Blockchain as a whole. The states are therefore affected by transaction-based changes. While transactions, once verified, are permanently stored in the Blockchain and such data is qualified as permanent data. Account and world state, due to their dynamic nature are instead considered to be ephemeral data which are not stored directly in the Blockchain information (also called off-chain information) (Van Groesen, W., 2020) (Tasca, P., & Tessone, C. J., 2019).

To effectively and securely deal with both, ephemeral and permanent data, DLT stores and manages these separately through tree-like structures called **tries** (Tasca, P., & Tessone, C. J., 2019) (Van Groesen, W., 2020).

Tries differ per state and per transaction, the main tries utilized on DLT are hereafter presented.

- ***Storage trie***: contains account states (each account has one)
- ***World and account state trie***: contains information of all storage tries in the DLT
- ***Transaction trie***: contains transaction-related information which is added to the block (each block has 1 trie)
- ***Receipt trie***: contains post-transaction information (in the form of receipts) of all transactions that occurred

Merkel & Patricia trie structure (Storage trie)

The Merkel & Patria trie (MPT) are discussed separately in Appendix I In this case the two tries are described together as currently operating on the Ethereum Blockchain system which is considered to be the most mature one in the Blockchain panorama (Van Groesen, W., 2020).

These tries are well known in the cryptography environment as variants of the hash tree. Hash functions are algorithms which allow comprising arbitrary-sized data into fixed-sized data, the benefit is that large-sized data can be reduced to manageable-sized data (usually 128-bit sized) without compromising the integrity of the information (Van Groesen, W., 2020). Hashing, in other words, ensures that encrypted information is authentic and preserved and employing MPT allow the verification of heavy data sets securely.

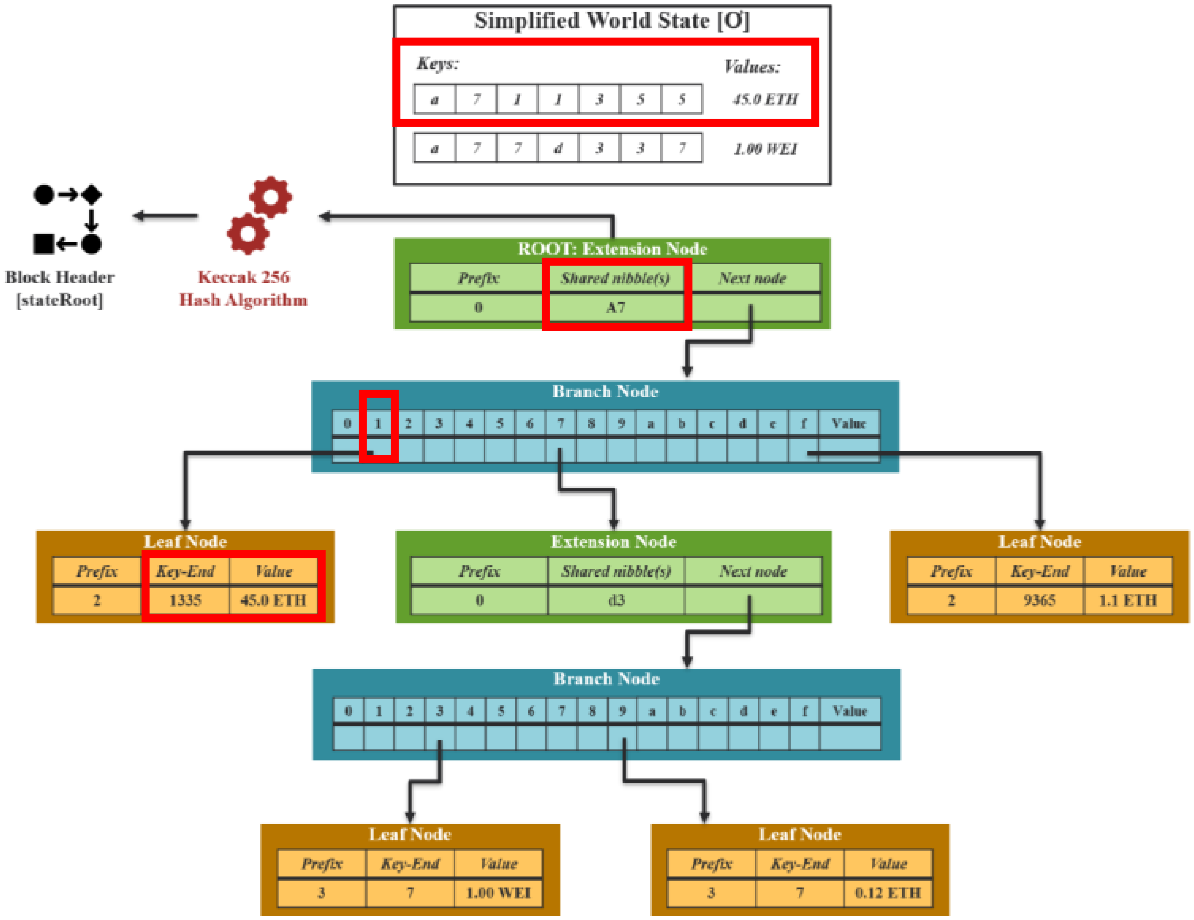


Figure 51 - Hybrid Merkel & Patricia trie utilized on the Ethereum Blockchain network (Van Groesen, W., 2020)

As illustrated in Figure 51, MPT is composed of the following elements and sub-elements:

- Extension nodes: which are composed of a prefix, shared nibble and next node (up to 16 child nodes) which is a branch node
- Branch node: consists of an array of branches, and a node value
- Leaf Nodes: key-end, value and prefix which constitute the hash of a block of data

As illustrated above, all nodes do eventually merge into a Root extension node which contains a unique hash encrypting the hashes of all hashes in the subsequent nodes. When a transaction occurs, the information (and the hash) associated with a specific node changes, and due to the dependency and interconnection between nodes, as illustrated in Figure 51, the final hash of the root node follows suit. This implies that the root nodes have an encrypted record of the information stored in all individual nodes, and consequently of the data structure as a whole (Tasca, P., & Tessone, C. J., 2019) (Van Groesen, W., 2020).

The hashed data within nodes are also named key-value stores which can be employed for mapping an information path taken in the MPT (Wood, G., 2014). The path is represented in a set of keys and values as illustrated in the world state (see Figure 51; Figure 52).

Figure 52 - Simplified world state. Snapshot of MPT (adapted from (Van Groesen, W., 2020))

For example, if we analyze key "a711355" (red square) it is possible to determine:

- <u>**a7**</u>11355: describes the nibble of the root node
- a7<u>**1**</u>1355: describes the branch of the relative branch node
- a711<u>**355**</u>: describes the key-end on the leaf node and its value in ETH

Finally, the information of the world state is stored in the block header (here referred to as **stateRoot**). The difference between a stateRoot at t=o and a stateRoot at t=1 is the transactions that occurred between t=0 and t=1. This approach allows Blockchain technologies to deal with ephemeral data and store them not permanent blocks (Wood, G., 2014) (Van Groesen, W., 2020).

Account and World state trie

The structure and architecture of the account and world state trie are illustrated in Figure 53. As mentioned previously, account and world states are interdependent and complementary as the world state represents the sum of all account states. The same is true for the storage trie and the state trie, which are both not stored in the Blockchain. The sub-elements of the account trie are the leaf nodes which are composed of a specific key and value. Each account on the DLT has allocated a unique address (key) (e.g. 0x70e5d2C6d8eH45039cHL5482addfdDDFJT) and a value. The leaf nodes that contain a full mapping of key and value pairs of all accounts in the network are ultimately connected to a root node (StateRoot) which is connected to the account state trie. The same structure is replicated for the world state trie. The State trie does therefore have information on the state of the entire network and so does the world state trie.

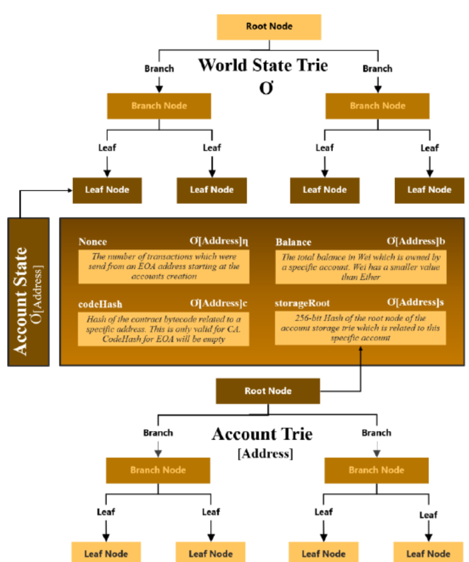


Figure 53 - World and Account trie (source (Van Groesen, W., 2020))

Transaction Trie

Figure 54 illustrates the transaction trie, its structure and the values that are utilized in the transaction hash.

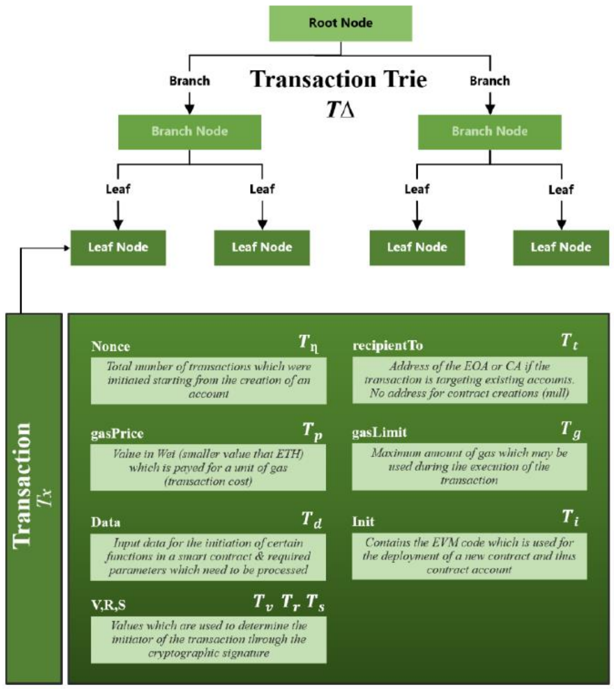


Figure 54 - Transaction trie (Van Groesen, W., 2020)

As outlined previously, the world state is reflected in the StateRoot and what the transaction process does is lead to the generation of a new StateRoot, thus updating the world state (Wood, G., 2014). The transaction process leading to the updating of the world state from an old to a new status is presented in Figure 55.

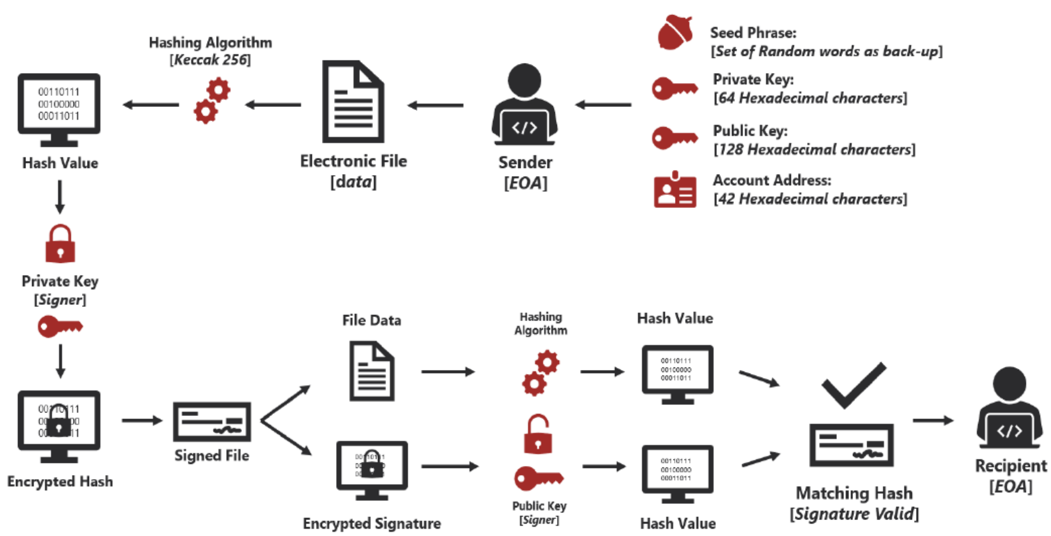


Figure 55 – Generic transaction process (source (Van Groesen, W., 2020))

The transaction, which must be initiated by an account, is signed with a private and public key and an account address. Both accounts (sender and receiver) must also generate a seed phrase composed of random numbers as a backup key. This also leads to the coupling of both accounts with a private key. The private key is employed by the sender for creating a unique signature of the transaction while the public key (retained by both sender and receiver) can be used by the receiver for revealing the transaction and its content (Wood, G., 2014) (Van Groesen, W., 2020).

The validation process of the transaction is carried out by the node/account receiving it. The process entails (ConsenSys, 2018) :

- Verification of the transaction information against the account and world state information
- Check whether the digital signature matches the account address of the sender
- Verification of whether the funds embedded in the transaction are available in the sender's balance

If these elements are validated, an ID is linked to the transaction and this is subsequently released to the whole P2P network (Van Groesen, W., 2020).

Receipt trie

The release and broadcast to the P2P network are not immediately added to the Blockchain. These must undergo a mining process first. Validated and broadcasted transactions are first gathered and stored in a transaction pool and are then evaluated against pre-determined conditions by a so-called mining node. Next, a miner can select a group of transactions which can be handled within a block (due to size limitations) and initiate the validation process. Through the validation process, two additional tries are constructed, namely a **transaction** and a **receipt** trie (see Figure 56). Their respective roots are the elements that will be added to the block. In this case, the transaction trie comprises the key-value pairs of not just a single transaction but of several ones (Wood, G., 2014) (Van Groesen, W., 2020).

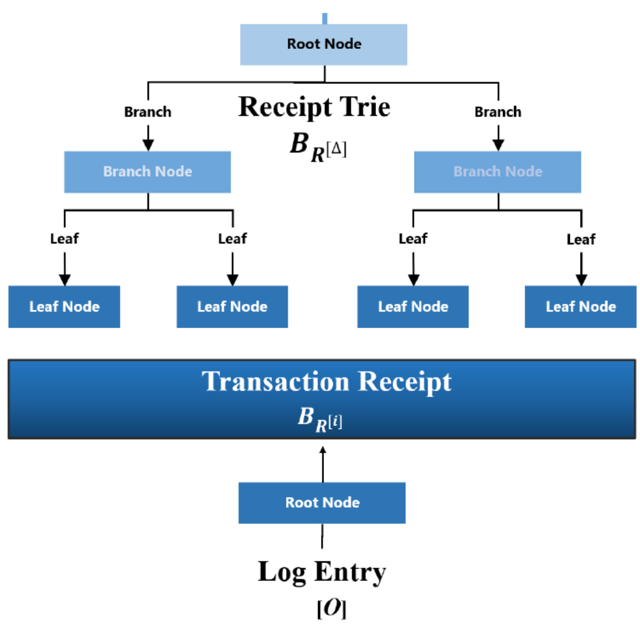


Figure 56 - Receipt trie (source (Van Groesen, W., 2020))

Once the information (from all tries) is merged into the block (see Figure 57) the block can be considered to be created. The addition of the block to the Blockchain will occur only once the mining node successfully runs and solves a **consensus algorithm.** This implies that the nodes need to solve a sort of cryptographic puzzle which will prove to all other nodes in the network that the newly added block is valid (Wood, G., 2014) (Tasca, P., & Tessone, C. J., 2019). This consensus algorithm varies in Blockchain architectures and can have different logic. After solving the consensus algorithm, the newly created block is attached to the preceding block within the node's local copy of the distributed ledger and is then broadcasted to the whole network, thus updating the distributed ledger as a whole (Wood, G., 2014) (Van Groesen, W., 2020). The information contained within newly created blocks is illustrated in Figure 57.

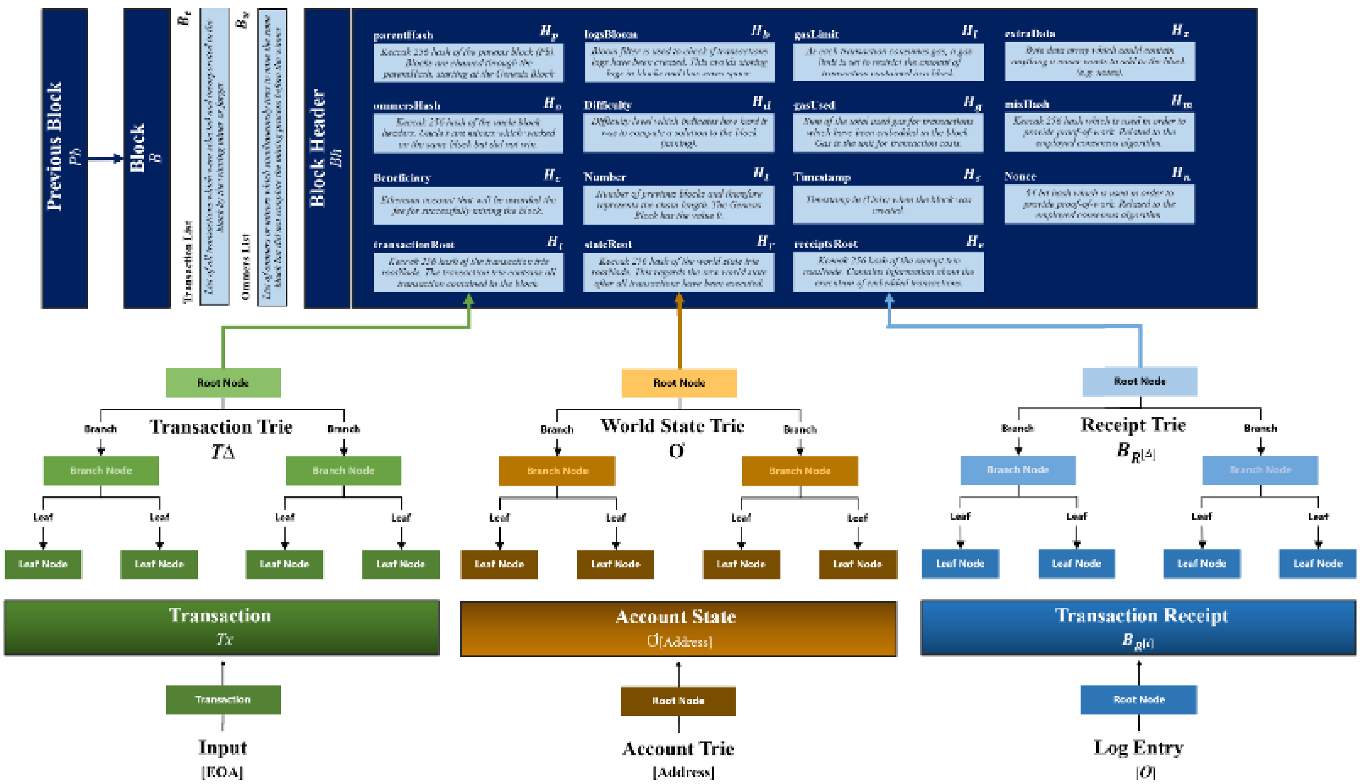


Figure 57 – Block's information and relation with tries (adapted from (Van Groesen, W., 2020)))

03 Protocol and Consensus Layer

The consensus algorithm was already mentioned in the previous chapters as an important element of the mining process. Here the topic is illustrated in more depth as this mechanism plays a pivotal role in the correct functioning of a Blockchain network. One of the many reasons for having a consensus algorithm is to prevent double-spending-related issues to occur within a Blockchain network. Double-spending means that due to the lack of a control mechanism an account can spend the same unit of funds multiple times, without proving that the funds are even available (Van Groesen, W., 2020).

In centralized institutions such as a bank, this issue is prevented by the fact that the governance structure is vertical and centralized, and data flows (such as transactions) are controlled and verified by a single entity that retains the authority to do so. On the other hand, Blockchain technology poses a higher degree of complexity because the governance structure is decentralised and distributed in which the transfer of funds occurs simultaneously between countless accounts. This implies that a user must put trust in a multitude of unknown parties rather than in a single one like a financial institution. In this perspective, the consensus algorithm allows for a distributed governance that certifies the validity of all transactions occurring among countless accounts (nodes) (Tasca, P., & Tessone, C. J., 2019) (Wood, G., 2014).

The mechanisms underlying the consensus algorithm are very complex and can have different architectures that will be briefly illustrated in the next paragraph. In general, consensus algorithms combine specific procedures and architectures aimed at determining whether the transfer of data (such as a transaction), embedded within newly created blocks (see Figure 57), will result in a new and valid world state of the whole distributed ledger (Baliga, A., 2017).

As explained in the previous paragraphs, the consensus algorithm is carried out by the mining node but then verified but other nodes before the new block (containing the new information of account status etc..) is attached to the Blockchain and the transaction is regarded as successfully executed (Baliga, A., 2017). The outcome of such a mechanism is to produce consensus, transparency, trust, agreement and a single source of truth within a distributed network of unknown users (Baliga, A., 2017) (Van Groesen, W., 2020) The most known consensus algorithm architectures employed for Blockchain technologies are hereafter resented.

Proof of Work (PoW)

This architecture is the most common and it requires validators in the form of minors for reaching a consensus. The newly created block is only attached to the Blockchain when miners can collective solve mathematical puzzles which are the combination of encrypted (hashed) data within the new block and the block header onto which this block needs to be attached. Once the mathematical puzzle is solved, the solution is broadcasted to other nodes who are responsible for verifying that the solution is indeed correct. The miner is then rewarded and the new block will be part of the Blockchain (Baliga, A., 2017) (Van Groesen, W., 2020) (Tasca, P., & Tessone, C. J., 2019)

This architecture presents some limitations. Specifically, it requires an exorbitant amount of computational power leading to an energy-intensive process which is still characterized by a very low execution speed. Additionally, Blockchains based on this architecture can be manipulated by parties who can manage to gain 51% of the computational power/mining capacity present in the network (also named 51% attack) (Baliga, A., 2017) (Van Groesen, W., 2020).

Proof of stake (PoS)

The first difference of this architecture is that miners are called forgers and they are rewarded (for the validation process) with part of the transaction fee. The block generation is the same as described previously but the main difference is that the mathematical puzzle is solved in a restricted environment and consequently the energy required in the process is lower and the execution speed significantly higher. The main characteristic is that forgers can invest/bet a certain amount of cryptocurrency on the block (staking) and the selection criteria for a block to be forged is directly proportional to the number of resources the forger has invested. The transaction fee a forger is rewarded with is also proportional to his investment/bet. Hence, forgers do not require computational power but rather a personal wallet to invest in the operation. If a transaction is regarded as invalid (due to manipulation for example) the investment/bet is affected. This implies that acting honestly in the network is more profitable than being dishonest (Van Groesen, W., 2020) (Baliga, A., 2017).

The negative aspect of POS is that forgers with a large number of cryptocurrencies in their wallets can potentially manipulate the information in the Blockchain by betting large amounts on manipulated blocks (Baliga, A., 2017).

Delegated proof of stake (DPoS)

DPos is very similar to PoS in how forgers/miners can run the consensus algorithm. The main difference is that forgers/miners can elect and delegate the activity of investing/betting and verifying blocks to other miners/forgers. In any case, the voting power is directly proportional to the amount of wealth owned by the forger/miner. The benefit is that elected miners/forgers can be punished for untrustful activities, thus increasing security within the network (Van Groesen, W., 2020) (Baliga, A., 2017)

The negative aspect of this architecture is that voters form alliances thus leading to a centralization of the consensus process and leading to the 51% attack problem outlined previously (Baliga, A., 2017).

Proof of authority (POA)

This system is mostly adopted in private Blockchain networks and it is primarily based on the reputation of miners. Unlike the preceding mechanisms, where the validation is allocated based on wealth and/or election, here the validation process is allocated to miners/forgers regarded as authoritative and trustful. It is widely adopted in private Blockchain networks because the miners can be defined upfront and can therefore be regarded by the network as trustful. This aspect has also a positive effect on the scalability of the network because the validation process is not hindered or slowed down by the size of the network itself. For instance, PoA consensus algorithms are regarded as a good fit for logistics and for compliance tracking where tokens/currencies are not required (Tasca, P., & Tessone, C. J., 2019) (Van Groesen, W., 2020) (Baliga, A., 2017).

04 Network & governance layer

The most common feature associated with Blockchain networks is its open, decentralized and permissionless system which allows users/nodes to read, update (write) and verify (committing resources) data within a distributed ledger (Hileman, G., & Rauchs, M., 2017). Other types of Blockchains are also adopted in industries. These alternative types can limit the possibility of nodes/users reading, updating and/or verifying the data in the distributed ledger. Such types of Blockchain networks are termed private or consortium-based blockchains (Van Groesen, W., 2020).

As described previously, the consensus algorithm determines how nodes can participate in the validation process of new transactions within the distributed ledger leading to the addition of new blocks to the Blockchain and thus updating the state of the distributed ledger. Whether a Blockchain is regarded as private, public or consortium-based is determined by the committing, writing and reading authorization given to individual nodes and configured within the Blockchain network. To clarify the different configurations (Hileman, G., & Rauchs, M., 2017) provide a concise description of these types of authorization:

- **Reading authorization**: the who and the how of nodes in reading data within the distributed ledger (Hileman, G., & Rauchs, M., 2017) (Van Groesen, W., 2020)
- **Writing authorization**: the who and why of nodes in writing new transactions and broadcasting them to the P2P network (Hileman, G., & Rauchs, M., 2017) (Van Groesen, W., 2020)

- **Committing authorization**: why and how nodes are allowed to update the world state of the distributed ledger by adding blocks to the Blockchain (Hileman, G., & Rauchs, M., 2017) (Van Groesen, W., 2020)

These types of networks or governance structures are illustrated in Figure 58 and are hereafter discussed.

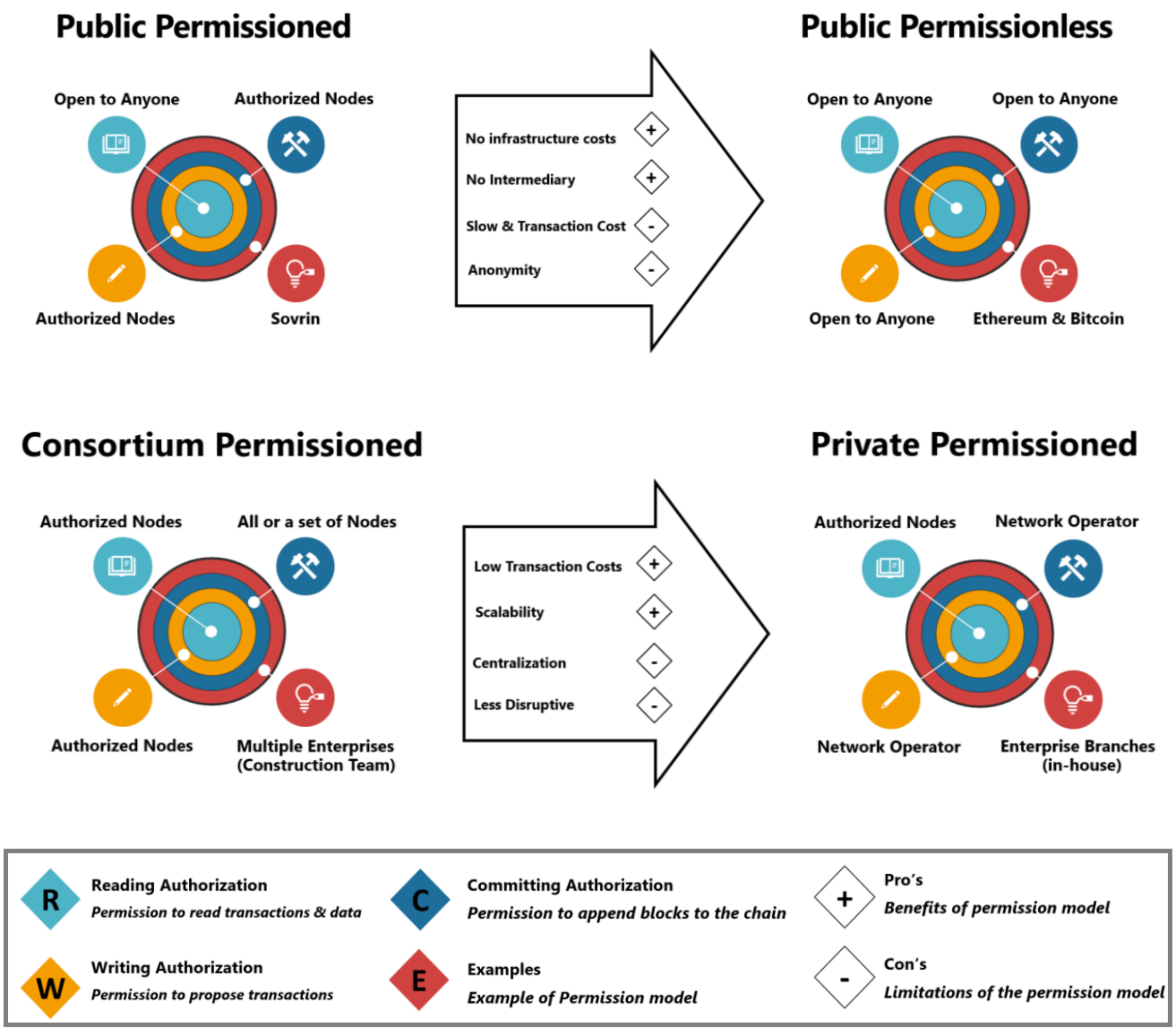


Figure 58 - Public and Private-based permission models with a legend (adapted from (Van Groesen, W., 2020))

The committing authorization of nodes is extremely close to the consensus algorithm topic outlined in the previous paragraph. While the consensus algorithm deals with how blocks are validated and added to the blockchain by either miners/forgers, the permission models outlined in Figure 58 describe the configuration of the network and, therefore, its governance structure (Van Groesen, W., 2020) (Hileman, G., & Rauchs, M., 2017). The permission models have a direct implication on the reading, writing and committing properties of the nodes within the network and can therefore be suited to different applications, based on the aim of the Blockchain network.

In **public permission-based** models, nodes/users can participate in the network anonymously and as consequence, the governance of the distributed ledger requires incentives (such as rewards) for honest participation. On the other hand, in **private permission-based** models, users/nodes are known to the network and honest participation is linked and related to their authority and reputation (Van Groesen, W., 2020) (Hileman, G., & Rauchs, M., 2017) Any dishonest activity carried out by nodes/users within this configuration can be punished as their identity can be known. In industrial applications, consortium or private models are prioritized because nodes/users are known to the network and reading and writing authorization can be limited and circumcised (Van Groesen, W., 2020).

Consortium-based models are very useful for industrial applications structured upon consortium-type so governance because the reading and writing authorization can be limited to nodes/users directly connected to the data (transaction) involved. In this model nodes/users can be selected and their authorization customized to mimic the governance structure that exists outside the Blockchain network. This has different advantages, starting from simplifying the development and operability of the Blockchain and ending with delivering the confidentiality in the data (transaction) flow that the industry demands and is accustomed to (Hileman, G., & Rauchs, M., 2017) (Van Groesen, W., 2020).

Private models are regarded to be more scalable than public ones because of the restriction in authorization that can be applied to nodes. The mining/forging process, which is the key process for validating and attaching new blocks to the Blockchain and thus updating the distributed ledger, is an energy and resource (computing) intensive activity. Therefore, limiting the committing, writing and readying authorization of nodes/users has a direct impact on the computing power, network traffic (flow of data) and speed of transaction execution of the Blockchain network (Hileman, G., & Rauchs, M., 2017).

It can be argued that limiting the reading, writing and committing authorization to a set of nodes/users is a centralization of power that undermines the values put forward by Blockchain technology. But, as mentioned previously, extending the committing authorization to all nodes within a blockchain network can directly affect its scalability (see Figure 59). There is no polarization on the matter because blockchain can be adapted and configured for meeting the needs demanded by the network. In general, if the needs are to guarantee trust, transparency, immutability and confidentiality within a distributed governance model, the literature indicates extending the committing authorization to all nodes, even though this might impact scalability. Additionally, it is suggested to extend the reading authorization to all nodes while the writing authorization should be restricted to nodes directly involved with the specific data (transaction), thus leading to a hybrid model that blends private and consortium-based models (Shojaei, A., Flood, I., Moud, H. I., Hatami, M., Zhang, X., 2019).

			Impact						
			Fundamental Properties						
Design Option	Comment	Examples	Immutability	Non-repudation	Integrity	Transparancy	Equal Rights	OVerall	Performance
Centralized	Central databases with a single or alternative providers	-	n	n	n	n	n	↓	↑
Private Permissioned DLT	DLT with permissions on both read & write-access	Hyperledger Fabric[1],Corda[1]	(y)	(y)	y	n	n		
Private Permissionless DLT	DLT with permissioned read-access & permissonless write-access	Holochain[2]	y	y	y	n	y		
Public Permissioned DLT	DLT with permissionless read-access & permissions for write-access	EOS[1]	Y	y	y	y	n		
Public Permissionless DLT	DLT with permissionless read access & permissionless write-access	Bitcoin[1], Ethereum[1]	y	y	y	y	y		

Figure 59 – Permission models, key characteristics and performance (source (Hunhevicz, J. J., Hall, D. M., 2020))

05 Execution layer

The **execution** and **application** layers presented in this and the following paragraphs are 2 interlinked layers because they represent the functionalities offered by and the operation interface through which the Blockchain network can be operated. The application layer is considered the front-end view of the system while the execution layer is the back-end view (Van Groesen, W., 2020).

The two are connected via specific and customized scripts in **smart contracts** which in this perspective can be regarded as mediating and controlling components. In other words, the execution of activities (such as the initiation of a transaction) is initiated by the user through a specific interface which is then translated into a specific code within the smart contract that will trigger a specific sequence of actions and thus of outcomes within the Blockchain network (Van Groesen, W., 2020) (Hileman, G., & Rauchs, M., 2017).

Smart contracts are, in other words, a set of codes able to perform specific functions (trigger a payment, reserve a material, book a transport and so on) once it is triggered by an event or input (Hileman, G., & Rauchs, M., 2017). For example, a smart contract configured on a distributed ledger technology can automatically trigger the payment from user A->B once the asset is transferred from user B->A without the need for manual, centralized and manipulation-prone procedures. The advantage of smart contracts in DLT is that they can be employed for automating countless inter-dependent/-connected operations occurring between countless stakeholders or entities. Because the relationship between input and output can be coded and configured based on the needs, the execution of smart contracts is certified (cannot be manipulated) and the outcome can be verified and audited by the Blockchain's network participants, thus guaranteeing transparency and generating trust (Hileman, G., & Rauchs, M., 2017).

The current issue characterizing the implementation and execution of smart contracts is that they allow using computer code for generating binding contracts outside the traditional legal framework. However, this is also their main objective. Namely, to allow the full replacement of traditional contracts by allowing them to be generated by computer codes according to pre-defined triggers and conditions, thus reducing the possibility of disputes, and the need for law enforcement and simultaneously accelerating the bureaucratic aspects of business operations (Shojaei, A., Flood, I., Moud, H. I., Hatami, M., Zhang, X., 2019).

06 Application layer

As outlined previously, the application layer represents the front-end layer of the distributed ledger. In this layer, the user (can be human as well as a third-party software) provides the input that triggers a cascade of actions that are governed through rules and conditions defined within the smart contract. For example, a user can book a specific asset contained within the distributed ledger and once the world state of the Blockchain changes, due for example to the availability on the market of that specific asset, the asset moves from a "bookable" to a "Purchasable" state and the smart contract mediates and forces the exchange of funds between user A (who booked the asset) and B (who owns the asset). The Blockchain network certifies and validates this exchange by adding the information to the distributed ledger, creating thus an **immutable record of the transaction** (Shojaei, A., Flood, I., Moud, H. I., Hatami, M., Zhang, X., 2019) (Van Groesen, W., 2020) (Tasca, P., & Tessone, C. J., 2019).

It is also possible to connect the application layer with external third parties software able to provide secure and reliable data that can be fed into the smart contract thus complementing its input data. This software is called Oracles and can provide countless types of data, ranging from sensor data (geographic location) to market data (prices of materials, resources etc). In this way, the smart contract can ideally be initiated by the input of a user and complemented with the information provided by Oracles, or the other way around. Oracles that offer a user interface and operate in a decentralized manner are also called decentralized applications (dApp) (Shojaei, A., Flood, I., Moud, H. I., Hatami, M., Zhang, X., 2019)

Recap

As illustrated in the preceding paragraphs, Blockchain technology is composed of different elements and layers which can be customized based on the needs and the desired outcomes. In general, a Blockchain is a decentralized consensus, data, process and asset management system in which any sort of exchange managed and performed through it is verified, executed, recorded and auditable by all network's participants (Tasca, P., & Tessone, C. J., 2019) (Van Groesen, W., 2020) (Saadatmand, M., Daim, T., 2019)

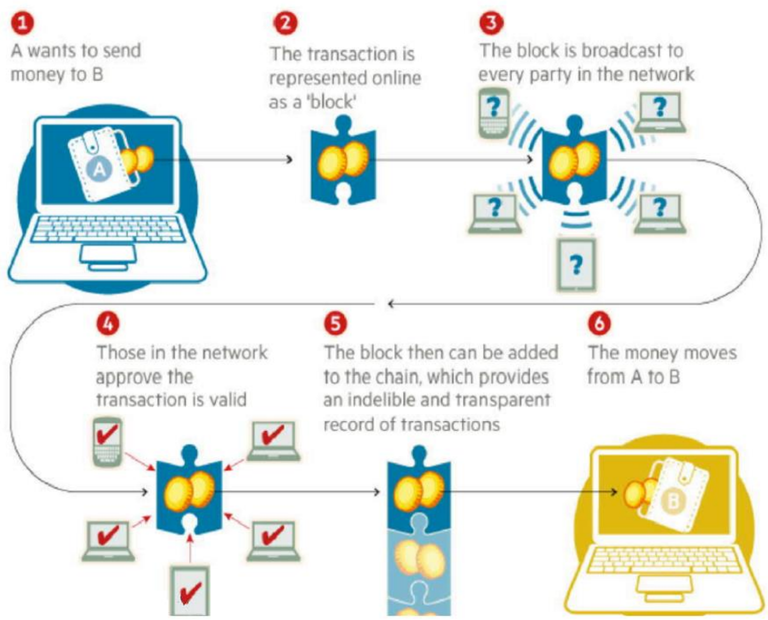


Figure 60 - Blockchain technology applied to financial transactions (source (Saadatmand, M., Daim, T., 2019))

Figure 60 provides a simple schematic of how Blockchain technology is currently operated for financial transactions. Information is stored and carried over in the system within blocks and, depending on the specific architecture, the Blockchain as a whole contains a full record of all transactions. Each user stores either a full copy or a part of the same Blockchain information, and their database is synchronized and updated with all other individual databases. When a new transaction occurs, members participate in the verification process (the how and the degree of participation depends on the architecture) and if successful the new block is added to the Blockchain and can thus no longer be manipulated or erased, making the full transaction record traceable, transparent and fully reliable (Tasca, P., & Tessone, C. J., 2019) (Van Groesen, W., 2020).

The fact that Blockchain technology is fully customizable and adaptable makes its use extremely versatile. For instance, the adoption of smart contracts allows define conditions and dependencies that allow full decision-making processes to be carried out without the need for human interaction and contractual agreements. Additionally, complex and multi-stakeholder processes that depend on multi-level data exchanges can be coded and carried out with the use of Blockchain without the need of knowing and certifying the authority and honesty of the stakeholders involved in the exchange. The innovative aspect is that the users in the Blockchain network do not require an intermediary that certifies and validates the information and the exchange of services, as it happens with financial institutions with the transfer of money. Blockchain technology replaces intermediation with cryptographic proof and allows the management of conflicting information (see double counting described previously). Because all blocks are interlinked cryptographically and new transactions need to undergo a verification process, it is extremely complicated for an external intruder to enter the digital ledger and manipulate the information (Tasca, P., & Tessone, C. J., 2019) (Saadatmand, M., Daim, T., 2019).

To conclude Blockchain technology can help with the self-execution of digital contracts (smart contracts), asset management through the cloud and multi-stakeholder governance activities with decentralized, autonomous and/or participatory decision-making without the need for human action (Wright, A., Primavera, D. F., 2015).

The application of Blockchain, DLT and Smart contracts in the built environment

The following paragraph outlines some case studies, grouped into 7 use categories in which Blockchain has been applied. These include (1) Smart Energy, (2) Smart Cities & the Sharing Economy, (3) Smart Government, (4) Smart Homes, (5) Intelligent Transport, (6) BIM and Construction & Demolition Management. Case studies from 1 to 5 can be found in Appendix XI.

Application in the C&D industry

(Succar, B., 2009) has pointed out that the wide adoption of BIM within the C&D industry is a progressive process which will require an increased maturity and capability across a variety of technologies, as well as process management and policies. The integration of Smart contracts and DLT with BIM and IoT are expected to provide a significant impact on C&D activities as well as facility management practices. This is extremely significant where mapping and tracking construction elements are paramount and where activities are duplicated. Thanks to the employment of IoT technologies in the form of PAT devices, specific data about the location of a construction element or a specific process can be automatically collected and the DLT can be updated accordingly (Heiskanen, A., 2017).

DLT is also regarded as beneficial for addressing those challenges which have so far slowed down the adoption of BIM. These challenges include limited collaboration, data and information sharing, trust and accountability. For example, in the case legal issues arise due to a shared access BIM model, the DLT can make every action undertaken in the model traceable and transparent, thus clearly outlining responsibilities, liabilities and rights on the intellectual property (C. Kinnaird, M. Geipel, 2018).

The World Bank has also endorsed the combination of DLT and Blockchain as a way of overcoming issues relating to trust and transparency (Natarajan, H., Krause, S., Gradstein, H., 2017).

(Li, H., Arditi, D., Wang, Z., 2015) has outlined how the integration of smart contracts, BIM and DLT could dramatically reduce cost and increase efficiency associated with construction projects. Specifically, the removal of third parties can reduce costs associated with contract drafting, negotiation and compliance tracking. On the other hand (Love, P., Davis, P., Ellis, J., Cheung, S. O., 2010) have investigated the impact that such a widespread transformation would have. For instance, several firms rely on the current state of the art as they operate as a middleman in the certification of contracts and settling of disputes.

(Mason, J., 2017) suggests that BIM and DLT will be the enabler for smart contracts to operate in future C&D projects. Most likely, semi-automation will be the preferred approach due to intrinsic limitations in BIM and smart contract technologies as well as the need to have human intervention in construction projects (Mason, J., Escott, H., 2018). (McNamara, A., Sepasgozar, S. M., 2018) indicate that smart contracts on a DLT can lead to the security of payments, reduced financial delays, as well as historical tracking of transactions due to immutable records stored in the ledger.

Several studies outline and support how the integration of Smart Contracts, DLT and BIM can help in improving supply chain activities thanks to asset tracking, payment automation, auditing of data and immutability of records (Mathews, M., Robles, D., Bowe, B., 2017) (Zheng, Z., Xie, S., Dai, H., Chen, X., Wang, H., 2017).

(C. Kinnaird, M. Geipel, 2018) investigated the combination of BIM, Smart contract and DLT concerning facility management. This integration can facilitate the sharing of the "as is" state of the building to its respective BIM model. This can in turn help with performance optimisation, assessing the lifespan of elements as well as providing extensive information before and during the demolition stage.

(Ye, Z., Yin, M., Tang, L., Jiang, H., 2018) proposes the use of BIM together with Blockchain and IoT for the creation of a decentralized autonomous organization (DAO) focused on fully automating the maintenance system of buildings.

(Li, J., Greenwood, D., & Kassem, M., 2019) discussed an even more disruptive approach in which all intermediaries are removed from the supply chain. The C&D industry is characterized by having numerous contracts acting as intermediaries between the project commissionaire and other parts of the supply chain which creates a dependency on the flowing of monetary resources. The removal of intermediaries can contribute by accelerating the flow of these resources.

Nevertheless, the implementation of DLT, Smart contracts, IoT and BIM does not come without challenges. Firstly, a substantial amount of IoT devices should be installed in buildings and the up-front costs might be extremely high for a construction and/or demolition firm. Also, the C&D industry is a very conservative industry and a slow adopter of new processes and technologies. Lastly, the potential benefits of adopting DLT and smart contracts in this industry are not widely known, making its adoption scattered within the industry (Heiskanen, A., 2017) (Li, J., Greenwood, D., & Kassem, M., 2019).

The integration of Blockchain, DLT, Smart Contracts and BIM can in general benefit the C&D industry in 3 ways through connecting, sharing and facilitating collaboration. (Oyedele, L. O., Ajayi, S. O., Kadiri, K. O., 2014) has highlighted the difficulty for architects and designers to incorporate reusable construction elements in new buildings because the required information is oftentimes missing. (Tam, V. W., Tam, C. M., 2006) indicate that the key functionality of any digital platform and configuration must primarily act as an information broker between the supply and demand of resources. (Rose, C. M., Stegemann, J. A., 2018) have studied how pre-demolition analysis of the material composition of a building could be handled through such digital platforms and the act of information brokerage between the demolition and the construction firm would be facilitated. As discussed previously, (see DAM chapter), BIM can centralize building information throughout its entire lifecycle and in this way enable collaboration between stakeholders (Huang, B., Gao, X., Xu, X., Song, J., Geng, Y., Sarkis, J.,Nakatani, J., 2020). Such collaboration is enabled and facilitated from the design to the EoL of construction projects. This is because the adoption of BIM can result in the generation of a complete material passport containing all specifics of the construction elements contained in the building. This can allow an asynchronous sharing of information between stakeholders involved at different stages of the building's lifecycle. construction firms could assess recovery potential, while demolition firms could effectively plan dismantling activities and optimize the demolition process. Blockchain, DLT and Smart Contracts would partially automate this process. (Munaro, M. R., Tavares, S. F., Bragança, L., 2020) (Chileshe, N., Jayasinghe, R. S., Rameezdeen, R., 2019)

The integration of Blockchain, DLT, Smart Contracts, BIM and IoT for tracking construction elements and contract compliance

The following paragraphs present a specific case study in which the integration of Blockchain technology, DLT, Smart Contracts, BIM and IoT has been conceptualized and tested. The concept was developed by (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019) while the simulation of the model was carried out as part of a PhD research developed by the Politecnico di Milano (Bolpagni, M., 2018).

This model represents an interesting blueprint for the development of this research. The model that will be described hereafter is operated to perform a specific objective. Nevertheless, as stressed in the previous paragraphs, Blockchain architecture can be structured in different ways, depending on the final objective. This model is interesting because it entails all the constituent elements (PAT, DAM and contract agreements) for providing a preliminary analysis of how the Blockchain network can be adopted.

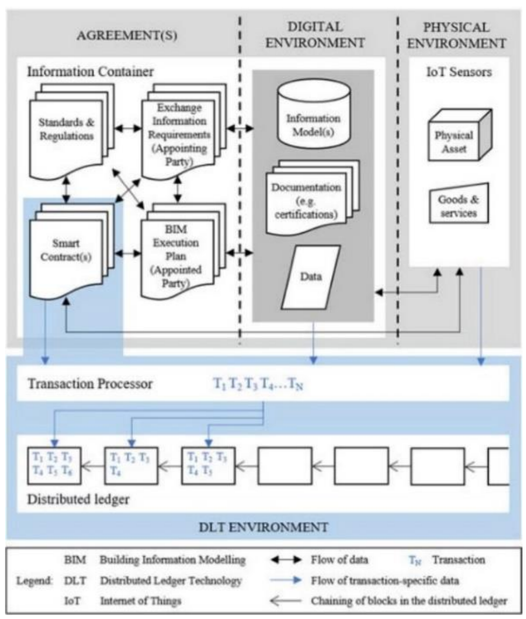


Figure 61 – Blueprint framework integrating DLT, BIM, IoT and Smart Contracts (source: (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019)

The model illustrated in Figure 61, was built within the context of the UK's construction sector and the terminologies employed (e.g. exchange information requirements, information container, appointing party) fall under the ISO [19650-1:2018] standards terminologies. Although terminologies and processes might be different in the Netherlands, the following analysis tries to illustrate the working principles of the model generically.

The first step in the procurement process is to compile the so-called exchange information requirements (EIR) which include technical, management and commercial details (software employed, level of accuracy, processes to be tracked in BIM, information exchange parameters etc.) (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019) All the contract clauses and requirements must be digitalized and coded in such way that the DLT and smart contract can recognize them. These must include the asset information requirements as defined in ISO 19650-1:2018 as “information requirements [...] in relation to the operation of an asset” (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019).

Contractors and distributors have to agree with the EIR developed by the project commissionaire (appointing party) and must then comply with the standards and conditions set in the BIM Execution Plan (BEP) (appointed party). The conditions and standards are clearly defined in the BEP contract. The conditions set in the EIR and BEP are converted first into digital deliverables outlined in the “Digital Environment” and then outlined in the “physical Environment”.

The final deliverable of the project is both digital (BIM, documentation and data) as well as physical (physical assets, goods and services) according to what is defined in the BEP and EIR. All data created and hosted within the digital environment are included in a so-called” information container” defined by the grey rectangle within the digital environment. BEP, EIR, Standards and Regulations and Smart contracts are contained within the “Agreements” section.

According to the model defined by (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019), the bi-directional information flow goes from the agreement section to the digital environment so that their outputs define the content of this environment. The one-directional arrow instead indicates transaction data that must be processed in the “transaction processor” and if the information is accepted by the nodes, the transaction is appended to the blocks within the distributed ledger.

The framework illustrated in Figure 61 is conceived for checking the development of the project against conditions set in the EIR and BEP. The checks are conducted through the transaction linked to smart contracts which in turn authorizes or denies payments based on the outcome of the check. The digital deliverables, as well as the transaction outcomes, can be linked to the distributed ledger in a “chained” way (meaning that the information of the deliverable is contained in the block) or in an “unchained” way (meaning that only fingerprints of the information are stored, not the whole dataset).In the approach presented here, the team opted for an unchained method. For instance, the link between the “DLT environment” (blue area) and the “Digital environment” only entails transaction data that are then copied into the distributed ledger. A chained method could allow more direct links between the two environments. The model also proposed a connection between the physical and the DLT environment. In this case, the IoT devices can be employed for assessing whether site activities are following the plan outlined in the EIR and BEP and send input information to the smart contract which will then trigger or not the payments, according to the agreements. The same information can also be used for updating the digital twin within the digital environment and tracking assets during the operation phase (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019).

The model is structured upon performance-based contracts which means payments are performed only if pre-defined performance and standard agreements are met. For example, the construction element must be installed within a specific date and with a specific quality. The limitation of this approach is the fact that traditional construction contracts entail a certain degree of flexibility which is difficult to include in smart contracts as of yet (Sklaroff, J. M., 2017). The human eye could recognize certain imperfections that, for example, are difficult to detect and asses solely with IoT technology, despite their accuracy (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019).

Simulation of an installation activity

The simulation hereafter illustrated presents how the installation of an insulation system can be automated with the adoption of a smart contract together with DLT, BIM and IoT devices. The simulation goes through the coding process of the smart contract in the DLT environment and illustrates its cohesion to the BEP and EIR within the digital environment (see Figure 61). The auditing of the installations' quality and performance within the physical environment are verified through a smart contract which authorizes or denies the payment accordingly (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019).

The quality assessment of product installation is usually conducted manually and there is currently no international standard that defines what the installation steps are. Therefore, to perform the simulation, the steps were conceived and computed with specific values within the smart contract. Without having the pre-conditions coded in a smart contract, it is not possible to review and audit performance against the requirements set in the EIR. Therefore, the simulation requires to code the information contained in the EIR to create a smart contract, monitor the installation process and link the smart contract to the distributed ledger (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019) (Clack, C. D., Bakshi, V. A., Braine, L., 2016).

Theoretically, IoT devices could be employed for checking automatically the correct installation and then triggering the payment via smart contracts. According to (Mason, J., 2017), their limited use in the construction industry still affects the industry's trust and reliance on these systems. The simulation hereafter presented did not employ IoT devices for the checking process but rather employed random values (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019).

The simulation entails two separate but interconnected processes, the first is the check process and the second is the installation/application process. The former uses smart contracts to review if the standard and quality requirements defined in the BEP and EIR are met, while the latter whether the installation is proceeding according to the deadlines defined in the BEP and EIR. The step-by-step simulation hereafter presented focuses on the installation process only.

Step 1: Flatness of wall <6mm: To install the external thermal panel, the wall's flatness must be below 6mm. This value is measured (either manually or via a sensor) and then computed within the smart contract (see Figure 62).

```
import random

FLATNESS_LIMIT = 6

def get_flatness():
    flatness = random.randint(0, 20)
    print 'tolerance flatness value is: ' + str(flatness)
    return flatness

def check_flatness(flatness, limit):
    result = flatness <= limit
    if result:
        print 'flatness tolerance is within limits'
    else:
        print 'flatness tolerance is outside limits'
    return result

def step1():
    while True:
        flatness = get_flatness()
        if check_flatness(flatness, FLATNESS_LIMIT):
            break
```

Figure 62 – Verify flatness function in the smart contract (source: (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019))

If the flatness is within the pre-defined limit of 6mm, the smart contract prints “flatness tolerance is within limits” allowing to go ahead with step 2, otherwise it returns a “flatness tolerance is outside limits” print and the process must be stopped.

Step 2-3: Installation of sensors and adhesives on the external thermal panel: This activity is not tracked in the smart contract

Step 4: Installation on wall of external thermal panels: This activity is not tracked in the smart contract

Step 5: Offset of External thermal panel is above/equal to 25cm: The external thermal panel is expected to have an offset from the wall of at least 25 cm. This value can be measured manually or via photo/videogrammetry and then computed in the smart contract. The smart contract verifies if the value is within or outside the required value (see Figure 63). Based on the outcome the next step can be pursued.

Step 6: Check for openings (doors/windows): This activity can be performed manually or through sensor technology. The information is then computed in the smart contract (see Figure 63).

Step 7: Installation of L profiles where openings occur: This activity is not tracked in the smart contract

Step 8: Check the presence of L profiles where the opening occurs: In case of openings the panel must include an L profile. This value can be measured manually or via photo/videogrammetry and then computed in the smart contract (see Figure 63).

Step 9: Flatness of external thermal wall is <6mm: Similarly to Step 1, the flatness of the wall must be below 6mm. This is measured (either manually or via sensor technology) and computed in the smart contract (see Figure 63).

Step 10: Installing anchors: Anchors are used for fixing the panels to the wall. This activity is not tracked in the smart contract

```
import random
from Step1 import get_flatness, check_flatness

def get_panel_offset():
    result = random.randint(0, 100)
    print 'panel_offset: ' + str(result)
    return result

def check_opening():
    result = (random.randint(0, 100) % 2) == 1
    if result:
        print 'there are openings'
    else:
        print 'there are no openings'
    return result

def check_l_profile():
    result = (random.randint(0, 100) % 2) == 1
    if result:
        print 'there are L profiles'
    else:
        print 'there are no L profiles'
    return result

def check_fibre_mesh_presence():
    result = (random.randint(0, 100) % 2) == 1
    if result:
        print 'there are fibre meshes'
    else:
        print 'there are no fibre meshes'
    return result

def get_fibre_mesh_overlap():
    result = random.randint(0, 100)
    print 'fibre_mesh_overlap: ' + str(result)
    return result
```

Figure 63 – Verify panel offset, openings profile and fibre meshes in the smart contract (source: (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019))

Step 11: Check anchor pattern: According to the BEP and EIR, the anchor should follow a pre-defined T or W schema. This can be assessed manually or via photo/videogrammetry and then computed in the smart contract (see Figure 64). If the pattern is wrong these should be re-applied, otherwise, the next step can be pursued.

```
def check_anchor_pattern():
    result = (random.randint(0, 100) % 2) == 1
    if result:
        print 'the pattern is correct'
    else:
        print 'the pattern does not follow the project'

def check_anchor_position():
    result = (random.randint(0, 100) % 2) == 1
    if result:
        print 'the position is correct'
    else:
        print 'the position is not correct'

def step2():
    while get_panel_offset() < 25:
        print 'panel offset is outside limits'
    if check_opening():
        while not check_l_profile():
            print 'add L profiles'
    else:
        pass
    while not check_flatness(get_flatness(), 6):
        print 'fix the flatness of the panel'
    while not check_fibre_mesh_presence():
        print 'add fibre meshes'
    while get_fibre_mesh_overlap() < 10:
        print 'fibre mesh overlap is outside limits'
    while check_anchor_pattern():
        print 'change the anchor pattern'
    while check_anchor_position():
        print 'change the anchor position'

```

Figure 64 -Verify anchor pattern and position (source: (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019))

Step 12: The position of the anchor has aligned with the surface of the thermal panel: The smart contract is now able to check and determine whether the pattern and the position of anchors are according to the project specifications and requirements (see Figure 64). In case of a wrong position, these should be reapplied or replaced.

Step 13-14: Application of protection layer and fibre mesh: This activity is not tracked in the smart contract

Step 15: Check fibre mesh: Fibre meshes should be applied in a specific way to reinforce the panel. This can be assessed manually or via photo/videogrammetry and then computed in the smart contract (see Figure 63)

Step 16: Overlap between fibre meshes is equal to 10cm: Like the positioning, the overlap of fibre meshes should be at least 10cm. This can be assessed and then computed in the smart contract (see Figure 64). The smart contract conditions assess if the value complies with the standard and quality requirements.

Step 17: Application of protection layer: This activity is not tracked in the smart contract

Step 18: The thickness of the protection layer is equal to 4mm: Similarly to Step 1, the thickness of the protection layers is equal to 4mm. This is measured and computed in the smart contract as indicated in Figure 62, but with different values.

Step 19-20: Application of primer and final coating: This activity is not tracked in the smart contract

Step 21: Final check of wall's flatness: The flatness of the final wall must be below 6mm after completion of all preceding steps. This is measured (either manually or via sensor technology) and computed in the smart contract as illustrated in Figure 65.

```python
from Step1 import get_flatness, check_flatness, FLATNESS_LIMIT

def step3():
    flatness = get_flatness()
    result = check_flatness (flatness, FLATNESS_LIMIT)
    if result:
        print 'the flatness is correct'
    else:
        print 'the flatness is not correct'
    return result

```

Figure 65 – Verify the final flatness of wall (source (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019))

If the smart contract returns a "flatness is correct" message than the process moves onto the final step which involves the assessment of payment permission (see Figure 66).

```python
from Step1 import step1
from Step2 import step2
from Step3 import step3

import sys

if __name__ == '__main__':
    step1()
    step2()
    if step3():
        print 'payment authorised'
        sys.exit(0)
    else:
        print 'payment not authorised'
        sys.exit(29)

```

Figure 66 – Payment permission steps (source (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019))

At this point, the smart contract verifies all the conditions and performance requirements, as outlined in the EIR and BEP, and if the final value returned by the code equals "0" then the payment is authorized (see Figure 67) and the transaction is recorded in the Blockchain. Instead, if it returns any other random value which is not "0", it means that the performance requirements were not met and the payment is denied (see Figure 68).

```
tolerance flatness value is: 6
flatness tolerance is within limits
panel_offset: 26
there are no openings
tolerance flatness value is: 15
flatness tolerance is outside limits
fix the flatness of the panel
tolerance flatness value is: 2
flatness tolerance is within limits
there are fibre meshes
fibre_mesh_overlap: 33
the pattern is correct
the position is correct
tolerance flatness value is: 0
flatness tolerance is within limits
the flatness is correct
payment authorised

Process finished with exit code 0
```

Figure 67 – Authorized payment (source (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019))

```
tolerance flatness value is: 3
flatness tolerance is within limits
panel offset: 34
there are no openings
tolerance flatness value is: 9
flatness tolerance is outside limits
fix the flatness of the panel
tolerance flatness value is: 5
flatness tolerance is within limits
there are fibre meshes
fibre mesh overlap: 100
the pattern does not follow the project
the position is correct
tolerance flatness value is: 20
flatness tolerance is outside limits
the flatness is not correct
payment not authorised

Process finished with exit code 29
```

Figure 68 - Denied payment (source (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019))

In the scenario simulated by (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019), the smart contract did not authorize the payment as the flatness of the wall exceeded the performance requirements. The performance criteria coded in the smart contract as well as the methods for assessing these can be defined based on the requirements. For example, it is also possible to connect the smart contract to public databases for either retrieving information (instead of manual inputs) and /or for defining performance criteria or thresholds based on national standards. The application of a model as the one illustrated in Figure 61, is extremely versatile and it can be adapted to different scenarios. In other words, it can represent a simplified model blueprint for utilizing BIM, DLT, Smart contracts and IoT in the construction industry. But the design options strongly depend on the objective of its use.

Reflections

The C&D industry is currently facing several challenges concerning circularity. These include, but are not limited to limited regulation and compliance frameworks, an ecosystem of distrust, inadequate collaboration models, non-coordinated data management strategies and slow payment practices (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019) As illustrated in the previous paragraphs, the combination of Blockchain, DLT, Smart Contracts and BIM can enable transparency, the immutability of data and information, security and automation (van Groesen, W., Pauwels, P., 2022). The digitalization of the C&D demolition industry, together with the advancements in BIM, DLT, Smart Contracts and IoT is being investigated by academics as a potential solution to the problems outlined above. Nevertheless, the novelty of the technologies and the lack of experience in merging and operating them together results in implementation challenges that must be addressed. The simulation carried out by (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019) has in any case illustrated that the integration of these technologies can be adopted for assessing and verifying performed work against contract agreements and automatically processing payment authorizations. In this case, the input of work status was conducted manually, but ideally, conditions in the physical environment (delivery, work status etc.) can be detected via IoT and/or image recognition technologies. Data could also be automatically fed into the smart contract from databases and data sources provided by third parties (for example material passports or BIM models). Several challenges must still be addressed by the industry. These include a lack of legislation and regulation for the management and enforcement of smart contracts, limited skills in the process of coding complex legal requirements in smart contracts and finally security concerns (Li, J., Kassem, M., Ciribini, A. L. C., & Bolpagni, M., 2019).

From a ***regulation*** point of view, smart contracts still need to gain legal validity equivalent to traditional contracts. Regulatory institutions will have to outline and enforce how smart contracts can be operated and assessed. Also the **implementation** of smart contracts, DLT and BIM will require a cultural advancement in the C&D industry. To operate these systems effectively, all stakeholders operating throughout the supply are required to adapt their processes and collaborate in a synergic way. This is because coordination and alignment of processes and data management practices is an important precondition for enabling PAT and DAM practices as illustrated in figure x. The last point is the **technological development** of Blockchain technology required for enabling its industry-wide adoption well as better integrating and interoperating different databases and software (van Groesen, W., Pauwels, P., 2022) (Shojaei, A., Flood, I., Moud, H. I., Hatami, M., Zhang, X., 2019).

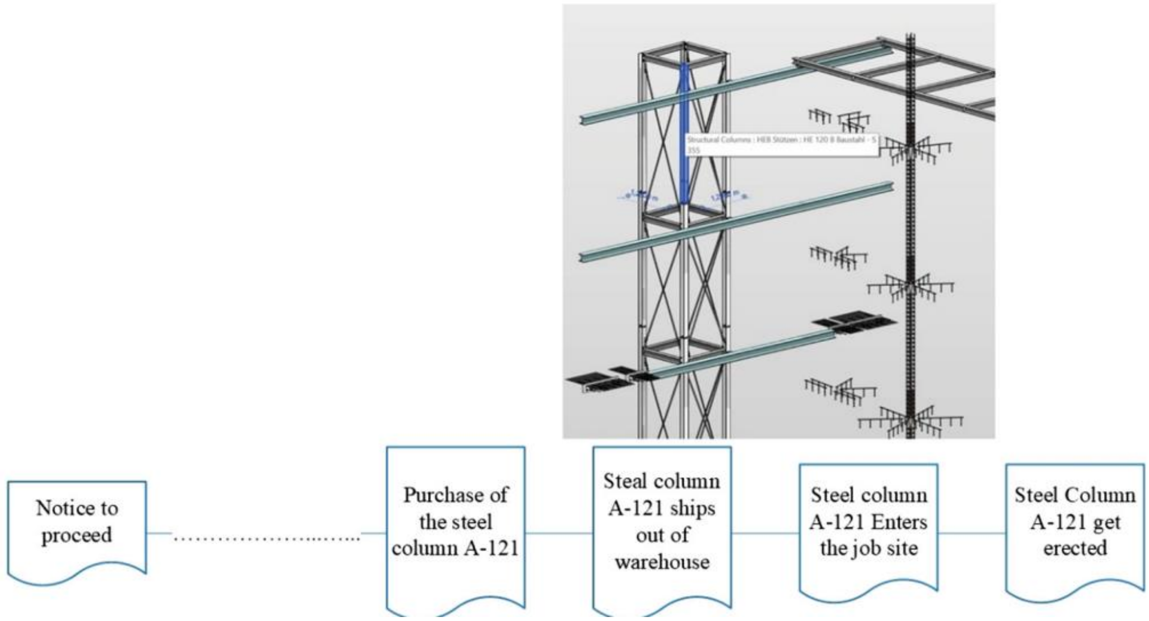


Figure 69 – Integration of processes through Smart Contracts, DLT and BIM (source (Shojaei, A., Flood, I., Moud, H. I., Hatami, M., Zhang, X., 2019))

Research methods

The following chapter presents the research design employed for collecting and processing data to answer the research questions investigated in this study.

Research Design

The objective of this study is to map the challenges that are characterizing and limiting the recovery and reuse of construction elements within the C&D industry in Zuid-Holland. The research is carried out as part of the Interdisciplinary Thesis Lab: Circular Building Materials and (re)Manufacturing Hub organized and managed by the Centre for Sustainability Leiden-Delft-Erasmus University.

The project was initiated by the active participation of the Municipality of Leiden, the municipality of Alphen aan den Rijn, Economic Development Board Alphen, Bouwend Nederland and the province of Zuid-Holland (LDE Centre for Sustainability, 2022). The objective of this project is to investigate potential opportunities and approaches for boosting circularity in the C&D industry in Zuid-Holland through the investigation of Circular Material Hubs. Specifically, the research group is interested in understanding what a circular building hub is, what can be expected from it and what are potential design requirements. Other sub-questions are derived from these.

This research focuses primarily on understanding and mapping what are the challenges that are characterizing circular (specifically material recovery and reuse) practices in the C&D industry in Zuid-Holland and make a preliminary assessment on whether Blockchain (in its current forms through DLT and Smart contracts technologies) can be a suitable solution for addressing these. The amount of research and proof-cases where Blockchain has been adopted in C&D are limited and are mostly focused on processes for automating and authorizing payments, not directly on circularity practices such as reuse and recovery (Li, J., Greenwood, D., & Kassem, M., 2019).

The decision of focusing on recovery and reuse practices is intentional. According to the waste hierarchy illustrated in Figure 11, reuse strategies are the first strategies (in terms of hierarchy) that should be favoured for circularity. Also, reuse practices require more technological and socio-technical advancements than other practices. Therefore, solutions that can address and tackle the challenges that characterize reuse practices can ideally also be applied further down in the waste hierarchy.

The research was conducted in different interconnected. First, a literature study was conducted to understand the theoretical background of the topic of circularity in the C&D industry, Blockchain and its application in the built environment together with PAT and DAM practices. Qualitative research (in the form of a semistructured interview) conducted with construction, and demolition firms, as well as architects operating in Zuid Holland, was carried out. The objective was to understand first-hand and with practical examples what are the challenges these firms are currently experiencing concerning the recovery and reuse of construction elements. Finally, the framework developed by (Hunhevicz, J. J., Hall, D. M., 2020) was used for assessing whether Blockchain can address the challenges identified in the previous phases.

The research was initiated at the end of February 2022 and is expected to be concluded in October 2022.

Research boundaries

The research was conducted within pre-defined boundaries. These are illustrated hereafter.

1) The research was focused on light buildings, such as residential buildings and offices, only.
2) The construction and demolition firms selected for the qualitative research had to operate primarily in Zuid-Holland. These were identified with the support of Bouwend Nederland
3) The focus of the research was to gain a first-hand perspective on the subject matter from firms operating in this sector. Due to time boundaries, the research was limited to a set of interviewees which cannot guarantee the statistical relevance of the findings.
4) The analysis of the adoption of Blockchain is limited to a conceptual level based on the framework developed by (Hunhevicz, J. J., Hall, D. M., 2020). The research does not investigate the technical, social and legal requirements as well as the specific architecture that the Blockchain system should adopt.
5) The findings are tailored to the situation in Zuid-Holland and might not hold for other provinces, regions and countries.

Research process

The research process was divided into 5 interconnected phases. These are presented hereafter.

Phase 1 - Orientation: Literature study on key subjects was designed and conducted to build the theoretical background for providing the reader with sufficient background information about the subject. The topics were structured hierarchically, starting from a high-level analysis of the C&D industry, to a specific analysis of Blockchain technology

Phase 2 - Mapping: Qualitative research in the form of a semi-structured interview was used for identifying from experts in the C&D industry what are the challenges currently hindering material recovery and reuse in construction and demolition projects.

Phase 3 - Data interpretation: The scattered information provided by the interviewee was analyzed and categorized through an open coding technique.

Phase 4 - Assessment: The challenges identified in Phase 2 and Phase 3 were fed into the Blockchain decision framework developed by (Hunhevicz, J. J., Hall, D. M., 2020) to determine whether this technology can, in principle, address the challenges.

Phase 5 - Evaluation and correlation: The final phase was to evaluate and relate the findings of Phase 2-3-4 with the literature study conducted in Step 1 and provide additional points of reflection for future studies.

Literature study

The objective of the literature study was to present all the key topics that are relevant for providing sufficient background information to the reader as well as structuring the outline of the research.

The research of literature was conducted primarily through *Google Scholar*. The keywords used during the research included words of the key topics in different arrangements. The selection of literature was based on the following hierarchical criteria: *date of publication*, the geography of study (European countries were prioritized to reflect the socio-technical structure of the C&D industry in the Netherlands), and type of study (peer-reviewed academic papers were prioritized over grey literature).

The type of literature study opted for this research was a "narrative" type of review as outlined by (Becker, S., Bryman, A., Ferguson, H., 2012). The objective was to outline and connect the literature into a coherent narrative that can provide the theoretical basis for understanding the research and its implications.

The key topics investigated were: Construction industry and its supply chain, Circularity in the built environment, material recovery and reuse in the C&D industry (current practices and challenges), Blockchain, DLT and Smart contracts (key principles and current adoption in the C&D and other industries).

Qualitative Research (semi-structured interviews)

The qualitative research was conducted in the form of semi-structured interviews. A part of the questions was pre-determined to create a coherent structure and a common thread throughout the interview.

The reason for opting for a qualitative type of research is its suitability for this specific research. Although a large mole of literature about circularity in the C&D sector is present, the latest events (the COVID-19 pandemic and the Ukrainian war) have brought about significant socio-economic variations that might have changed the perception of challenges and opportunities from those outlined in the literature. Also, because the scope of this research is focused on a specific region of the Netherlands, it was important to understand what are the challenges that characterize this region specifically.

The advantage of semi-structured interviews is their flexibility and the possibility of having follow-up questions that can help to identify certain aspects more in detail and if needed, go more in-depth about these together with the interviewee. In other words, the flexibility allows asking open-ended, spontaneous and context-specific questions that were not foreseen, allowing to have a more natural conversation and not limiting the outcome of the interview to a pre-defined and stiff script (Kovalainen, A., Eriksson, P., 2015) (Flick, U., 2017)

The pre-defined questions used during the semi-structured interview can be found in Appendix III. The questions were structured to understand and map the following:

Question 1-2: Profile the interviewee

Questions 3-4: What material/construction elements are regarded as relevant and what is the rationale behind this interest

Question 5: Understand the current company-specific process undertaken for recovering and reusing construction elements

Questions 6-7: What are the data/information needed now and in the future for optimizing/enabling the process

Question 8: open-ended question(s)

Interviewee selection criteria

The minimum number of interviewees to be included in this study was agreed upon with the project supervisors at the planning stage of the research. A number between 6-8 was deemed sufficient for collecting adequate insights on the subject matter within the time boundary of the research in mind.

According to (Boddy, C. R., 2016) the number of interviewees should be determined based on the level of saturation in terms of data acquisition, meaning that the information provided by any new interviewee is redundant and repetitive. Saturation can be determined between 6 and 12 interviewees.

In this research, 7 interviews (3 construction, 1 architect and 3 demolition firms) were conducted and these were sufficient for achieving saturation in terms of data acquisition. Thus the number was assumed to be sufficient for finalizing the research.

The interviews were conducted via online meetings (GoogleMeet) and lasted averagely between 30-60min. The selection process was undertaken in conjunction with Bouwend Nederland. Together we have identified construction, demolition firms and architects that have experience with the reuse and recovery process and who are actively trying to expand this type of activity. The objective was to identify at least one large and one small company for each category. This was important for levelling out the differences that might exist in terms of innovation and resources allocated to R&D within the firms.

The respondent, acting as a representative of the chosen firms, was not selected by the research team. Therefore the type of respondents was heterogeneous throughout the research, ranging from project managers to sustainability specialists. In any case, all of the interviewees covered roles within the company that made them the most (or among) knowledgeable people on the subject matter.

The firms which took part in the qualitative research are outlined in Table 6. The names were substituted with codes for guaranteeing their anonymity

Table 6 – Overview of semi-structured interviews

	C1-A	**C2-B**	**C3-W**	**A1-S**	**D1-B**	**D2-N**	**D3-V**
Date of interview	26/04/2022	05/05/2022	08/06/2022	12/03/2022	17/03/2022	10/06/2022	01/03/2022
Duration of interview	1:12 h	0:58 h	0:42 h	e-mail exchange	0:52 h	1:13 h	1:34 h
Sector	**Construction**	**Construction**	**Construction**	**Architect/ Design**	**Demolition**	**Demolition**	**Demolition**
Size							
Nr of employees	NL: 1700 / ROTW:3500	NL: 14000	NL: 14	NL:12	NL: 450	NL:25	NL: 150 *400 with self-employed people
Small/Medium/Large* *Benchmarked against Dutch standards	Medium	Large	Small	Small	Large	Small	Large

Data analysis

All meetings were recorded (by prior agreement with the interviewee) and manually analyzed. The content of the meeting was transcribed in English and grouped under the specific question that generated the answer.

To guarantee the integrity and reliability of the transcript, these were submitted to the interviewee for feedback and adjusted if certain sentences were miss interpreted or not correctly reflecting the interviewee's perspective.

The transcripts were analyzed and associated with the research questions through an Open coding technique as described by (Corbin, J., & Strauss, A. , 2014). The following process was undertaken:

1) All transcripts were merged into a single document "coding.xlsx" and grouped under the firm's category (construction, architect or demolition).
2) The transcript was analyzed and key concepts that were useful for answering the specific sub-research question were highlighted in red and labelled with a quote number [Quote: xx]. The quote was then mentioned during the answering of the sub-research questions 1 and 2.
3) For sub-research questions 3-4 instead, the quotes were collected in a separate table and analysed once more for identifying similarities and differences, as well as identify macro categories and themes helpful for presenting the results. The resulting analysis outlined in the results chapter (3-4) mentions the quotes that support the statement, while the quotes selected for the analysis were grouped in two distinct tables (see Table 24 and Table 25).

Data management and protection

The research involves humans and had therefore to follow the standards outlined by Delft University of Technology's Human Research Ethics Committee (HREC). The research was labelled as "minimal risk" according to the HREC's standards and framework.

All interviewees were required to accept and sign an Informed Consent form according to the HREC's standards (see Appendix IV).

Additionally, all information shared during the interviews was made anonymous to protect the firm's as well as the participant's privacy. The firm's name was substituted with codes, construction firms (Initials: Cx-x), architect firms (Initials: Ax-x), and demolition firms (Initials: Dx-x).

Each interview has therefore a recording of the meeting, a transcript and a consent form which are safely stored on the researcher's laptop (with a password). These will only be shared with the research supervisors.

From an ethical perspective, (Sanjari, M., Bahramnezhad, F., Fomani, F. K., Shoghi, M.,Cheraghi, M. A., 2014) outlines some important aspects that must be guaranteed when conducting qualitative research. These values are anonymity, secrecy, and informed permission. All 3 of these values were met throughout the conduction of this research.

Blockchain decision framework

To determine whether the challenges outlined in sub-research questions nr 3-4 can be addressed by the adoption of Blockchain technology, the research has relied on a decision framework conceptualized and developed b (Hunhevicz, J. J., Hall, D. M., 2020). This is illustrated in Figure 70

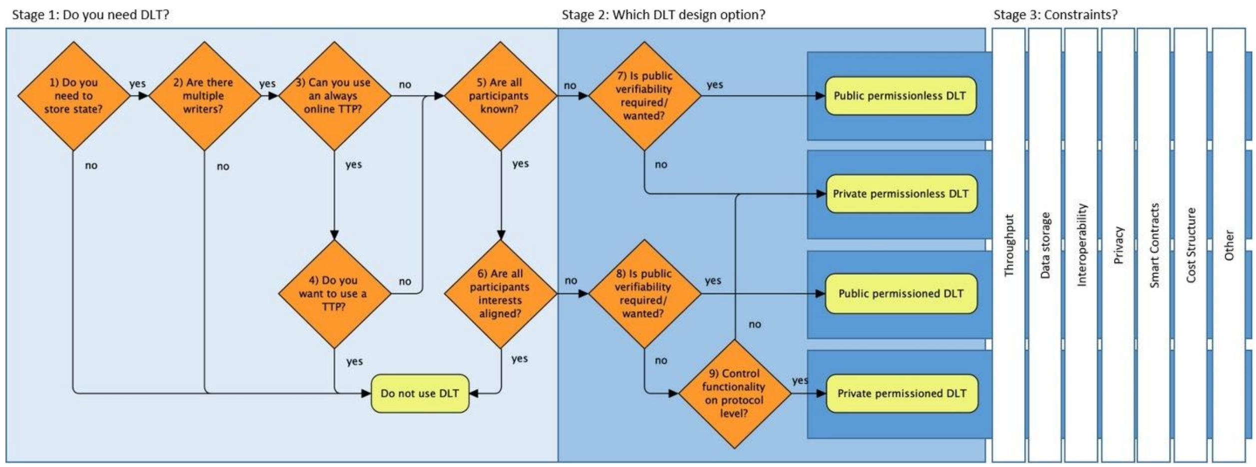


Figure 70 - A combined framework to decide on a DTL design option in three stages (source (Hunhevicz, J. J., Hall, D. M., 2020))

The reason for opting for a decision framework, and this one specifically, are several.

First, as illustrated in the paragraphs concerning Blockchain technology, the technology is extremely versatile its architecture can be structured in countless ways. Its architecture can be conceived and modelled depending on the necessities and the objective of its employment. For this reason, a peer-reviewed decision framework provides an objective assessment of whether the technology is useful or not for addressing specific challenges. Without such a framework, the assessment would be purely speculative.

Second, the adoption of a framework can be helpful for other cases in the future. Testing its applicability to diverse situations can strengthen its reliability.

Third, the decision for selecting this specific framework, among several others, has to do with the novelty of its conception as well as the way it was conceived and designed. For instance (Hunhevicz, J. J., Hall, D. M., 2020) have analysed 8 of the best and most reviewed decision frameworks (illustrated in Table 7) and has identified their weakness and strength points. Based on these, they have developed an integrated framework that overcomes the limitation and integrates the strength of all these frameworks.

Table 7 – Blockchain decision framework used as the basis for developing the framework by (Hunhevicz, J. J., Hall, D. M., 2020)

Source	**Type**	**Inputs**	**Outputs**
(Peck, M. E., 2017)	Sequential Framework	Seven questions: Participants, Likelihood of Attack, Trust, Possibility of Third Party, Privacy, Updateability of Data.	Three options: No DLT, permissioned DLT, public DLT.
(Turk, Ž., Klinc, R., 2017)	Sequential Framework	Eight questions: Possibility for Traditional Database, Trust, Alignment of Interests, Possibility of Third Party, Control of Functionality & Privacy, Type of Consensus.	Four options: No DLT, public DLT, hybrid DLT, private DLT.
(Xu, X., Weber, I., Staples, M., Zhu, L., Bosch, J., Bass, L., Rimba, P., 2017)Xu	Sequential Framework	Trusted authority, Ability to Decentralize Authority, Various Technical Configurations, and Other Design Decisions	DLT, Traditional Database
(Mulligan, C., Scott, J. Z., Warren, S., Rangaswami, J. P., 2018)	Sequential Framework	Eleven questions: Possibility of Traditional Database, Technical Limitations, Relationship of Participants, Trust, Control of Functionality.	Five options: No DLT, not ready for DLT applications, further research needed, private DLT, public DLT.

(Wessling, F., Ehmke, C., Hesenius, M., Gruhn, V., 2018)	Four steps	Step 1: Identify participants. Step 2: Trust relations. Step 3: Interactions	Step 4: Derive system architecture by overlaying trust and interactions.
(Wüst, K., Gervais, A., 2018)	Sequential Framework	Six questions: Database Type, Participants Known & Trusted, Alignment of Interests, Need for Public Verifiability.	Four options: No DLT, private permissioned DLT, public permissioned DLT, and permissionless DLT.
(Hunhevicz, J. J., Hall, D. M., 2019)	Mapping Based on Trust Proxy	Three questions to determine the proxy "level of trust" in a use case. Table with fundamental properties of the DLT design options for the mapping.	Four options: Fully centralized, private DLT, public permissioned DLT, and public permissionless DLT.
(Li, J., Greenwood, D., & Kassem, M., 2019)	Sequential Framework	14 questions	Five options

The framework developed by (Hunhevicz, J. J., Hall, D. M., 2020) and illustrated in Figure 70 is divided into 3 stages, each one entailing some questions.

Stage 1: Do you need DLT?

The first stage is intended to evaluate whether a DLT is preferred over a traditional database. The questions that are included in this stage are:

1) *Do you need to store state?* State refers to the totality of transactions (can contain part of the information or all information) contained within the DLT.
2) *Are there multiple writers?* If multiple users will apply changes to the status by initiating transactions
3) *Can you use an always-online trusted third party (TTP)?* TTP are third-party databases that can be employed for verifying the trustfulness of information triggering a smart contract and/or transaction.
4) *Do you want to use a TTP?* Is it important for achieving the required objective or level of performance to employ third-party databases?
5) *Are all participants known?* Is it known who will be part of the Blockchain system, as writer and reader.
6) *Are all participants' interests aligned?* Is the interest of the Blockchain participants aligned.

Stage 2: DLT design option

Through this stage, the best-suited design for a DLT is selected. This is based on the need for employing a Blockchain system. The trust setup plays a key role in determining DLT's design option. The key functionality and property of DLT are to manage and simply trust relations through the exchange of certified data. The questions aim at determining whether a permissioned (needs to receive permission for reading/writing on the Blockchain) system is preferred over a permissionless (does not need permissions for reading/writing) one and if these should be public or private. Figure 71 illustrates the different possibilities in terms of trust setups and their implications concerning the fundamental properties (immutability, non-reputation, integrity, transparency, equal rights) of Blockchain (Xu, X., Weber, I., Staples, M., Zhu, L., Bosch, J., Bass, L., Rimba, P., 2017).

Design Option	Comment	Examples	Immutability	Non-repudiation	Integrity	Transparency	Equal Rights	OVerall	Performance
			Impact						
			Fundamental Properties						
Centralized	Central databases with a single or alternative providers	-	n	n	n	n	n	↓	↑
Private Permissioned DLT	DLT with permissions on both read & write-access	Hyperledger Fabric[1],Corda[1]	(y)	(y)	y	n	n		
Private Permissionless DLT	DLT with permissioned read-access & permissonless write-access	Holochain[2]	y	y	y	n	y		
Public Permissioned DLT	DLT with permissionless read-access & permissions for write-access	EOS[1]	Y	y	y	y	n		
Public Permissionless DLT	DLT with permissionless read access & permissionless write-access	Bitcoin[1], Ethereum[1]	y	y	y	y	y		

Figure 71 – Trust setups and performance implications (source (Hunhevicz, J. J., Hall, D. M., 2020))

The fundamental properties are briefly described in Table 8.

Table 8 - Fundamental properties of Blockchain trust setup (adapted from (Hunhevicz, J. J., Hall, D. M., 2020))

Fundamental property	Meaning
Immutability	The ledger cannot be manipulated after transactions were added.
Non-repudiation	Each transaction is added only once to the ledger.
Integrity	Data can be verified to be complete and as initially written to the ledger.
Transparency	Transactions and data are visible to everyone.
Equal Rights	Everyone can read and write transactions.

There is a direct correlation between enabling the fundamental properties of a Blockchain system, how public the overall system is and its performance. Increasing the permission to read and access the system reduces its performance because more nodes and more consensus algorithms are needed for securing information. Also, public DLT might have issues with on-chain information as this is harder to encrypt and protect. The only property that is never affected by the type of permission of the system is ***integrity,*** as this is always guaranteed through the cryptographic hash functions adopted in DLT.

Public permissionless DLT is the only design that delivers the highest level of trust while still enabling all fundamental properties of Blockchain.

Public permissioned DLT limits the right for writing as well as for setting up new nodes, thus the ***equal right*** property is affected.

Private permissioned DLT limits the possibility to read the information in the DLT and thus it reduces the ***transparency*** outside and within (if you do not have the right permissions) the network.

Private permissionless DLT in this case permissionless ledgers can be adopted for exchanging and validating specific data. **Non-repudiation** and **immutability** are only guaranteed for the shared data but not for the private data included in the private ledgers. The permissionless structure guarantees equal rights while transparency cannot be fully guaranteed as this one is only certified for the shared data and not the private data contained in the private ledgers.

In general, permissioned and permissionless architectures have an impact on the immutability and the repudiation of data. Depending on the governance structure (public or private) adopted within the DLT this has a more or less strong impact on the assurance that outsiders have about the fact that the DLT has never been modified by the majority of the nodes. This issue is more prominent with the private permisssioned DLT structure.

The questions that are entailed in the framework for determining the best-suited DLT design are :

7-8) *Is public verifiability required/wanted?* Public DLT allows everyone to see information on the ledger, while private DLT can set permissions on visibility and accessibility.

The last question regards whether participants can have control functionality on the protocol level. Data can be kept private in the private permissioned as well as in the permissionless DLT, but the first one has an additional control level. Therefore, private permissioned DLTs need to be operated on a completely autonomous network, while private permissionless DLTs can operate on existing networks.

9) *Control functionality on protocol level?* Permissionless can substitute permissioned systems if strict control is not needed.

Results

The following chapter presents the results obtained from the qualitative research. The results are structured and presented under the research and sub-research questions underlying this research.

Profiling of companies involved in the research

The companies included in this research are outlined and profiled (in an anonymous form) in Table 9. These include 3 construction companies (Initials: Cx-x), 1 architect firm (Initials: Ax-x), and 3 demolition companies (Initials: Dx-x).

Table 9 - Profile of companies involved in the research

	C1-A	C2-B	C3-W	A1-S	D1-B	D2-N	D3-V
Activities							
Construction				*very specialized in reused materials	*very specialized in material harvesting	*very specialized in material harvesting	
Design							
Advice/Consultancy							
Execution (Material procurement/planning/execution)	*sometimes material procurement			*externalized			
Demolition							
Design		*externalized	*externalized				
Advice/Consultancy		*externalized	*externalized				
Execution (Material mapping/extraction /sorting/selling)		*externalized	*externalized				
Renovation							
Design							
Advice/Consultancy							
Execution (Material procurement/planning and execution)				*externalized			
Size							
Nr of employees	NL: 1700 / ROTW:3500	NL: 14000	NL: 14	NL:12	NL: 450	NL:25	NL: 150 *400 with self-employed pp

Small/Medium/Large* *Benchmarked against Dutch standards	Medium	Large	Small	Small	Large	Small	Large

All 3 construction companies have as part of their core activities the design of buildings and the consultancy/advise service to private clients and public institutions (e.g.: Provinces/Municipalities). This implies that all construction firms have a dedicated architect department within the company. On the other hand, only 2 out of 3 companies execute construction projects, the third (C1-A) externalises this activity because its core business is to carry out consultancy services to other construction companies. As mentioned by the interviewee:

"(…) we are not project developers. We work for other companies. We work for project developers (…) our job is to do quality checks on the soil and stuff like that. We are a consultancy firm in all stages of spatial projects you can think of " [Quote 1.0]

A similar situation applies to renovation activities, while companies C2-B and C3-W execute all sub-activities included in the renovation, company C1-A does neither carry out nor externalize the activity to other firms.

In terms of demolition activities instead, the 3 companies differ significantly in their activities. C1-A does neither carry out nor externalize the execution of demolition activities but does provide consultancy/advise and design activities. C2-B on the other hand externalizes all sub-activities involved in demolition. C3-B, instead, does neither carry out nor externalize any of the sub-activities. The size and the unique value proposition of the companies might have an impact on this aspect. This was however not investigated in the research.

The only architect firm included in the research was intentionally selected among many companies operating in Zuid-Holland. The architect firm is specialized in the reuse and recovery of building materials. As mentioned by the interviewee:

"We are an architectural office that focuses mostly on architectural design, and secondary also urban design, research, advice and mediating in the use of circular building materials" [Quote 1.1]

The firm provides design and consultancy/advice to construction/renovation companies but does not internalize the execution phase of them. The company provides also advice/consultancy to demolition companies concerning interesting materials that can be recovered, but does neither design nor execute the recovery part.

All 3 demolition companies were quite aligned in their activities. None of them includes construction or renovation sub-activities.

Interestingly renovation sub-activities are limited to construction firms and partly to the architect firm. Demolition companies do currently not see the value of having these types of a project commissioned to them. To the question " do you only do this (demolition and material recovery) for demolition projects or are you also extending this to renovation projects" D2-N answered:

" For now only demolition because renovation is a whole other specification. Also in renovation, there is a little amount of material that you can harvest/dismantle. With the demolition, you have all the materials of the building, and these are the ones that have the highest footprint and impact on the environment" [Quote 1.2]

While D1-B mentioned that:

" (…) we have a recycling company which recycles only on construction and deconstruction waste" [Quote 1.3]

Sub-question 1: What are the construction elements/materials of interest with regard to recovery and reuse and why?

The following paragraph presents the construction elements that are regarded as interesting for reuse purposes by the companies that participated in this research. The content is divided for each interviewee and it outlines the top materials of choice as well as the reason for regarding these as relevant for reuse and recovery purposes. The motives are sometimes material specific and other times generic to the unique value proposition of the company itself.

Construction (C1-A)

Table 10 summarizes the findings for interviewee C1-A.

Table 10 - Relevant reuse and recovery construction elements/building materials indicated by C1-A

Construction Element / Building material	Insights	Notes
Sand	"Sand is easy to rearrange, and that happens a lot." [Quote 1.4]	
Bricks	"(…) for bricks, well that is relatively easy to get out from the building and to reuse it." [Quote 1.5]	
Asphalt	"Whereas asphalt or concrete are more based on CO2 motives/reasons." [Quote 1.6]	*Not reuse but recycling (up/downcycling depending on final application)
Concrete		

As illustrated in Table 10, C1-A regards sand an bricks as interesting materials to be reused. The motives, as illustrated in [Quote 1.4] and [Quote 1.5], relate primarily to easiness in recovering them during demolition activities an reemploying them for new constructions. Additionally, the interviewee highlighted (See *[Quote 1.7])* how increasing prices for commodities is becoming the leading factor in pursuing reuse and recovery practices and how this is becoming somehow more important than sustainability-related motives.

"The price is something I am starting to notice more and more, especially in the last year. Prices for commodities are getting higher and higher. If before it was more for circularity and idealistic arguments like CO2, now it is also because of economic necessities. People want to build but there are not enough materials. The pandemic and the war make it even more urgent. We are not used to such limitations. We are used to buying what we want."
[Quote 1.7]

Asphalt and concrete were also mentioned by the interviewee but these materials are not recovered and reused, but rather downcycled as secondary raw materials for new roads and/or recycled concrete.

Construction (C2-B)

Table 11 summarizes the findings for interviewee C2-B.

Table 11 - Relevant reuse and recovery construction elements/building materials indicated by C2-B

Construction Element / Building material	Insights	Notes
Concrete	"Because we reuse the concrete in the new concrete pre-fab materials. We grind them and we put them into the new prefab materials. We cannot reuse it directly due to specs and dimensions who do not fit. We only reuse it in prefab materials, not in liquid concrete made on site." [Quote 1.8]	*Not reuse but recycling (up/downcycling depending on final application)
Asphalt	"In asphalt we have even a recycle percentage of 70-80%. This is also common knowledge. We started with 20% but in the last 10 years we reached almost 80%." [Quote 6.9]	*Not reuse but recycling (up/downcycling depending on final application)
Steel	"Steel is going back to the remanufacturing process and make new frames out of it." [Quote 1.9]	*Not reuse but recycling (up/downcycling depending on final application)
Wood	"Wood is something different. Sometimes we use it for furniture, sometimes for plates. We crash it and make some plates out of it. Also in playgrounds and horse pavements employ these wood plates. But not for new construction elements." [Quote 2.0]	*Not reuse but recycling (up/downcycling depending on final application)
Window (frames)	" (…) same about window frames. We put them apart and we mould them once more for new frames." [Quote 2.1]	*Not reuse but recycling (up/downcycling depending on final application)
Copper cable	"Same goes for piping and cables. Basically all recycled." [Quote 2.2]	*Not reuse but recycling (up/downcycling depending on final application)
PVC piping		

As illustrated in Table 11, all elements/materials indicated by the interviewee are not recovered to reuse them in new projects but are instead recycled (up/downcycling depending on final application) by externalized companies.

This observation has naturally led to the following question: "**None of these elements is reused as they are. You always reprocess them. Right now you have little material that you reuse directly?**"

The interviewee provided the following answer

“ (…) maybe 1 or 2 % of the recovered materials. Maybe if you are very lucky. (…) little fits in the new construction and that is why (reuse) this is limited right now.”
[Quote 2.3]

Hence, this specific construction firm is sporadically recovering (through externalized firms as illustrated in Table 9) and reusing construction elements in new projects, and this activity is not part of their regular/standardised construction processes.

Construction (C3-W)

Table 12 summarizes the findings for interviewee C3-W.

Table 12 - Relevant reuse and recovery construction elements/building materials indicated by C3-W

Construction Element / Building material	Insights	Notes
Bricks	“ When we have to renovate we have to reuse old bricks so the facade is the same. When we use the construction skeleton (more the facade). We did this in a recent project. Some parts are demolished and others will be reused. Some bricks from the demolition part are used for another project.” [Quote 2.4]	
Window (frames+glass)	“Windows is a bit difficult. This is one of the things (…) when we give to an architect some windows and we need to reuse them. The architect can employ them in the new constructions.” [Quote 2.5]	
Steel	*No full sentences to quote. It was just listed	

As illustrated in Table 12, C3-W is focused on recovering (with the aid of externalized demolition companies [see Table 9]) and reusing bricks, window frames and steel profiles. The motives include the advantage of maintaining certain structural elements such as brick facades. For the windows frames, for example, the construction firm has deliberately chosen to do so and has involved the architect in designing the old windows for new projects (see Quote 2.5)

The interviewee was asked the question: “Currently how much (%) material do you reuse?”.

The interviewee has outlined that:

“ (…) we are around 1-2 %.”
[Quote 2.6]

Architect (A1-S)

Table 13 summarizes the findings for interviewee A1-S.

Table 13 - Relevant reuse and recovery construction elements/building materials indicated by A1-S

Construction Element / Building material	**Insights**	**Notes**
Windows (frame + glass)	"(…)they are used a lot in transformation of old buildings to get light in." [Quote 2.7]	
Doors	" (…) to make new arrangements possible in existing buildings." [Quote 2.8]	
Facades	*No full sentences to quote. It was just listed	
Structural elements (wood/steel)	*No full sentences to quote. It was just listed	

A1-S is an architectural firm specialising in designing new buildings (and renovating old ones) with either reused or recycled materials. As highlighted in Table 13, windows (both frames and windows) and doors are quite common elements that are reused, as well as complete facades and structural elements such as wood beams and steel profiles. The motives for focusing on these elements were not explicitly outlined by the interviewee. Being reuse and recovery-based design an integral part of their core business, it is very likely that these elements are interesting from an offer and demand perspective.

Demolition (D1-B)

Table 14 summarizes the findings for interviewee D1-B.

Table 14 - Relevant reuse and recovery construction elements/building materials indicated by D1-B

Construction Element / Building material	Insights	Notes
Concrete	" (…)concrete is very actual at the moment. They used to be mixed with all the other debrief. And now more and more companies are using on recovering concrete for making new one. Huge volumes and huge demands." [Quote 2.9]	*Not reuse but recycling (up/downcycling depending on final application)
Carpet tiles	" (…)But carpet tiles are quite regular in supply (…)" [Quote 3.0]	
Doors	" (…) doors, (…) you can take out quite easy (…)" [Quote 3.1]	
Glass panels (room division in offices)	" you have systems with wood and other with glass. (…) these are quite common and you see them in all offices. We renovate offices quite often and the materials (..) are quite new and easy to reuse (…)" [Quote 3.2].	
Toilet/Sink	"sinks, toilets (…) you can screw out can be reused and is interesting.	

	Especially for the quality of the material” [Quote 3.3]	
Steel beams	“these need often refurbishment, an extra fire resistance coting or need for measuring the structural quality” [Quote 3.4]	*Not reuse but refurbishment
Glass wool insulation	“ (…)glass wool insulation is currently being removed for reuse, however demand for this is still low” [Quote 3.5]	

Most of the materials outlined by D1-B can be reused in new construction or renovation projects. Only concrete and steel beams (according to their experience) need to be either recycled into new concrete or refurbished for meeting specific quality standards. Recoverable and reusable materials/construction elements are considered interesting due to the easiness of removing and reusing them (see Quote 3.1 / Quote 3.2 / Quote 3.3) or due to the regularity in supply and demand (see Quote 3.0 / Quote 3.2)

In general terms, the assessment criteria for including certain materials/construction elements in the recovery and reuse processes are determined by the facility of recovering them and market demand. The following quote outlines these quite clearly.

“ (…) 2 things are very important.

1. *Easy to take out screws instead of glue and cement.*
2. *And of course can we find someone who wants to have it.*

(…) our circular advisor he checks all the properties where we work on in advance to see what we will take out and what not. And he is also responsible for selling those items. That way he learns first-hand what is interesting to take out and what not. (…) toilets are something that you can quite easily to take out but no one wants to buy them.”

[Quote 3.7]

D1-B is a demolition company specialising in circularity and the reason for actively focusing on recovery and reuse practices is determined by costs as well as fulfilling customers’ sustainability requests. As stated by the interviewee:

“ (…) decision to dismantle for reuse can come from two ways:

1. *It is beneficial in costs, by safely dismantling it, more profit can be made and the deconstruction can lower the total bill for demolition – often this is added in the bill as a discount.*
2. *Landfilling/recycling/incineration costs are becoming more expensive, so this motivates to reuse the product in another format.*

Lastly also sometimes a client finds it important to do, this also helps to dismantle products for reuse. Also most clients just want to demolish the building as fast as possible, which is a shame, because then potential reusable products will be recycled.”

[Quote 3.6]

This demolition firm is also interested in circularity because it will provide them a competitive advantage in the future and the experience in conducting selective demolition can have an impact on the final costs of the project. The following quotes make this point quite clear.

“In a tender I preset myself including all the circular innovations I can offer. So because of that I would like to invest in circular innovation because the more I do so, the more I can offer in the tender process and the more I can win these tenders. If I have exactly the same innovation as my competitors and then we have to present ourselves in the tender, we will not have a competitive advantage on each other. Then the only thing you can win on is labur costs and price.”

[Quote 8.9]

“*what you see when you compare a circular demolition compared to a traditional one is that costs that of circular project is much higher, especially in taking out materials because when you take out a sink it takes you 30 minutes while by smashing it takes 1 minute. So the costs are higher but also the revenue is higher because you can sell it instead of paying for its demolition.*

So we started seeing a shift especially with all virgin material costs going up. So it pays more now to actually take a circular approach instead of a traditional approach in demolition. This is not always the case. When time is critical, then the traditional way is better. You destroy, separate and then pay for the treatment.”

[Quote 8.8]

“The ROI is very similar right now. Of course it changes per project but the demolition companies that do all in the traditional way are still doing fine and actually making large amounts of money with no problem. Because we like to invest in circular projects, even if sometimes we make less money doing in the circular way, we see this as a long-term investment. We work for most big construction companies and most big real estate developers. They all want us to work circular, They all want us to work sustainably and safe. They call us because they know we work as circular as possible. So talking about ROI it is less interesting to do it circular than the traditional way. But still, companies doing it circular are anticipating the increase of prices and also legislation. They will be ready when this will become the norm. (…) I am really convinced that our customers are our customers because we work with this attitude. Sustainability is huge and very important. Especially for the big companies. So they want to gather partners who work as sustainable as possible. As long as it does not cost them too much.”

[Quote 9.0]

Demolition (D2-N)

Table 15 summarizes the findings for interviewee D1-B.

Table 15 - Relevant reuse and recovery construction elements/building materials indicated by D2-N

Construction Element / Building material	Insights	Notes
Facades (Aluminium/Steel)	“lot of companies looking at outer part of the building (aluminium/steel).” [Quote 3.8]	
Windows (Frame + glass)	“ Some companies have a circular solution for recovering glass panels surrounded by an aluminium frame. If these elements have a lot of corrosion they can reuse them with a new colour or design in other building.” [Quote 3.9]	

Concrete	"(…) materials that have most emissions like cement, concrete, bitumen, gypsum, bricks, wood. I think those are the main ones and also **steel**. And you have also a lot of aluminium.." [Quote 4.0]	*Not reuse but recycling (up/downcycling depending on final application)
Bitumen		*Not reuse but recycling (up/downcycling depending on final application)
Gypsum		
Bricks		
Wood		
Steel		
Aluminium (cable tray)		

Also in this case most of the materials outlined by the interviewee can be recovered and directly reused in new constructions or renovation projects. However, concrete and bitumen are not reused, but rather recycled and employed as secondary raw materials.

D1-B is a demolition company specialising in circularity and the recovery of construction elements/materials. This is evident by the number of construction elements/materials listed in Table 15. The motives that drive this company to focus on circularity and recovery practices are illustrated hereafter.

The first motive for D1-B relates to sustainability and has the objective of reducing the environmental impact of the industry while tackling challenges that might arise soon. The following quotes highlight these points.

"The big bulk materials. Once again you come back (from renovation) to demolition and construction. (…) Those are the most impactful on the environment and also the ones with the biggest revenue"
[Quote 4.1]

"The point is that the use of virgin material in the world will become a big problem. The same relates to other materials."
[Quote 4.2]

" (…) the materials that have the most impact on the environment will be the frontrunners right now and will be the most important and developed ones. Within 2030 and 2050 we have to be 50% and 100% carbon neutral so I think these materials will be in scope."
[Quote 4.4]

A second motive is the standardization of designs and materials employed in Dutch residential buildings. This has also an implication for regularity in supply and demand.

" we build all buildings with wood or concrete. Only construction plants are made with steel. But steel is already recycled quite well. (…) until 5-6 years ago we did not have any good way of reusing concrete or a lot of wood in some sort of ways. (…) still at this moment we do not have the knowledge and regulation on how to reuse wood"
[Quote 4.3]

The third motive, which can be related to the first and the second point, relates to the importance of driving innovation and being frontrunners and pioneers in the industry.

"you need to expand the scope as a constructor and use different processes and materials and try them out. Because if you start in 5 years you are going to be too late. I think there are a lot of companies at this moment who will not exist after 2030 because they will not keep up with other companies. Many think that 2030 is too far away and it is not important to focus on the work right now. I think that these companies will be out of business by 2030 because they cannot keep up with innovation, regulations and do not know how to change their business model because they do not make the right choices right now"
[Quote 4.5]

The last element relates to costs and material prices.

"(…) Everything is going in inflation and prices are increasing significantly. Construction companies are struggling very hard and do not know how to stay in business. In any kind of ways there are getting these prices increase coupled to the yearly inflation. In bigger projects the scope is the same but it only costs more. The issues, and dynamics are similar but more complex"
[Quote 4.6]

Demolition (D3-V)

Table 16 summarizes the findings for interviewee D1-B.

Table 16 - Relevant reuse and recovery construction elements/building materials indicated by D3-V

Construction Element / Building material	Insights	Notes
Glass wool insulation	" (…) reuse you have insulation, getting to become more worth (…)" [Quote 4.7]	
Wood (beams)	"Wood is a big one because prices for it are going up" [Quote 4.8]	
Iron	"In the recycle way you have iron and copper" [Quote 4.9]	*Not reuse but recycling (up/downcycling depending on final application)
Copper		*Not reuse but recycling (up/downcycling depending on final application)
Doors	"Doors and windows are difficult because houses need a sort of energy classification and the glass is usually too thin and old. People want to save in energy and therefore they want products that guarantee good isolation. If you take it from a new building then yes it makes sense and it is interesting. You have thin glass or doors with a draft. Therefore these are not reused in new projects. Sometimes we reuse them in renovation because there it is interesting" [Quote 5.0]	
Windows (frame + glass)		

D3-V operates in the demolition sector for decades and is now focusing more on recovery and reuse practices. As illustrated in Table 16, several materials such as doors, windows, glass wool insulation and wood beams are efficiently recovered and reused. Copper and Iron are also recovered but are recycled by externalized companies.

The motives that drive D3-V to focus on sustainability, specifically on recovery and reuse practices are hereafter listed.

The first motive is innovation. In other words, the demolition company sees a window of opportunity in complementing current demolition practices with sustainability. This can be inferred from the following statements:

" (…) we always do selective demolition because this is the way things work."
[Quote 5.1]

"demolition company is obliged to bring this apart. You cannot put everything in a container and bring it to incineration. You are forced to put glass, iron, concrete in different containers. In small portions, you can. But you need to make sure things are apart."
[Quote 5.5]

"First you need to reuse and then recycle stuff. When you are on an excavator you need to get clean concrete out of it so you need to make sure that concrete is clean and not polluted with other materials so you do selective demolition in that sense."
[Quote 5.2]

" (…) for example wooden beams you would get them out because there is demand in our network and it is not difficult to get out."
[Quote 5.3]

The second motive is material price and additional revenue streams that can be generated with recovery and reused practices. The following statements are indicative of this.

" The price of a new product is going up. Wood is becoming more expensive. Reused wood is more interesting. Why would you buy a new wooden beam if you can buy a reused one for cheaper? This is the same for insulation. When the price for new goes up, then people things that reused is better."
[Quote 5.4]

"If I see 10k of stuff I can sell, my demolition price goes down by 10k for the customer."
[Quote 5.6]

Summary

Table 17 provides an overview of all construction materials/elements regarded as relevant by the research participants. In green are the materials that were mentioned by the interviewee, in yellow are the ones that were mentioned but do not fall into reuse/recovery practices and in red are those elements that were not mentioned by the interviewee. This table provides a concise overview of divergencies and similarities existing between the firms involved in the research.

Table 17 - Overview of Construction Element / Building material of focus and Motives/Rational/Driving factors

	C1-A	C2-B	C3-W	A1-S	D1-B	D2-N	D3-V
Construction Element / Building material of focus							
Sand							
Bricks							
Asphalt*	n.a	n.a					
Concrete*	n.a	n.a			n.a	n.a	
Steel		n.a	Profiles	Profiles	n.a	Profiles	
Wood		n.a		Beams		Beams	Beams
Windows		Frames	Frame+ glass	Frame+ glass		Frame+ glass	Frame+ glass
Copper		Cables					Cables
PVC piping		n.a					
Doors							
Facade							
Carpet tiles							
Glass panels							
Toilet/ Sink							
Glass wool insulation							
Bitumen*						n.a	
Gypsum							
Aluminium (cable tray)							
Iron							n.a
Motives/Rational/Driving factors							
Easiness in recovery/reuse	x		x		x		
Supply/demand factors				x	x	x	
Increasing material/processing costs	x				x	x	x
Sustainability aspects				x	x	x	
Additional revenue stream				x	x	x	x
Client's demand				x	x		
Innovation and new business model				x	x	x	x

The first interesting aspect is that construction firms have very little material/elements which are currently reused/recovered in their projects. Bricks for example were mentioned by 2 out of 3 companies while sand, steel and windows were only by 1 out of 3.

One company (C2-B), on the other hand, is more specialized in recycling practices than reuse practices. All materials mentioned by this interviewee do not fall under reuse/recovery practices but are instead recycled by externalized companies.

Looking at the demolition firms, a different situation can be seen. While 1 out of 3 companies focuses on bricks, entire facades, steel profiles, carpet tiles, glass panels and toilets/sinks; 2 out of 3 companies focus on wood beams, windows (frame + glass), doors and insulation (glass wool). Although none of the listed materials/elements was mentioned by all demolition firms, more similarities (than among construction companies) can be observed among them. Besides the sheer number of materials/construction elements, the demolition companies seem to be more adapted to reuse and recovery practices than construction companies.

The architectural firm, on the other hand, has a very similar specialization as the demolition firms. This might indicate that the materials that are both listed by the demolition and architect firm are currently the favourite ones concerning reuse/recovery practices.

Interestingly, only bricks, steel profiles and windows are regarded as important by all 3 categories of firms. This implies that, despite all operating in Zuid-Holland, the companies involved in the research are most likely not collaborating in recovery and reuse practices. More insights will be presented in the following paragraphs.

The lower part of the table presents also interesting elements.

The first observation is that the demolition firms and the architect firm have multiple motives/driving factors that lead them to consider reuse and recover practices as important for their business.

There seems to be a correlation between these drivers and the sheer number of materials of focus (listed in the upper part of the table). All construction firms have mentioned, so to say, exogenous driving factors rather than endogenous and purpose-driven ones.

For example, innovation and sustainability-related motives were never mentioned by the construction firms involved in the research. These are, for instance, endogenous types of drivers because part of the long-term innovation strategy of the company.

While 3 out of the 7 interviewees have mentioned sustainability and 4 out of 7 innovation as an important driving factor, 4 out 7 have mentioned that additional revenue streams are characterizing reuse and recovery practices. Thus indicating that new market opportunities for recovery and reuse are there.

The positioning along the supply chain of demolition firms might have also an implication on the larger capacity of these firms to adapt to recovery and reuse practices. For instance, demolition firms are at the end of a material's life cycle and this can facilitate the choice to selectively recover certain construction elements/materials that are characterized by supply shortages in the market.

Construction companies, on the other hand, have technological and process lock-ins that require more time to be overcome. Many other challenges hinder the transition toward recovery and reuse practices by construction companies and these will be investigated in the next paragraph.

Sub-question 2: What is the step-by-step decision-making process for reusing and/or recovering construction elements/materials adopted by construction, architect and demolition firms in Zuid-Holland?

The following paragraph outlines the reuse and recovery processes currently undertaken by construction/renovation and demolition companies in Zuid-holland. The process flow diagram, outlined in Figure 72, is a generalized flow that applies to all the companies involved in this research. Therefore, company-specific processes were compared to the ones undertaken by the other companies involved in the research and differences, if too significant, levelled out while similarities were maintained. Standardized steps, currently undertaken in the C&D industry (see Figure 3), were used as the basis for developing this specific flow diagram.

The interviews and the relevant quotes (summarized in Table 24), together with information retrieved on the company's website, and documentation provided by the interviewee (see Appendix VII) helped in tailoring a process flow diagram that describes the main aspects of current reuse and recovery practices for lightweight buildings. The analysis presented hereafter does not put much emphasis on the steps that are already described in Figure 3, but rather on the relevant steps that help to better understand the characteristics and logic of the reuse and recovery practices carried out in Zuid-Holland. Renovation is not presented as a self-standing process because it does replicate the steps and processes entailed during construction and demolition.

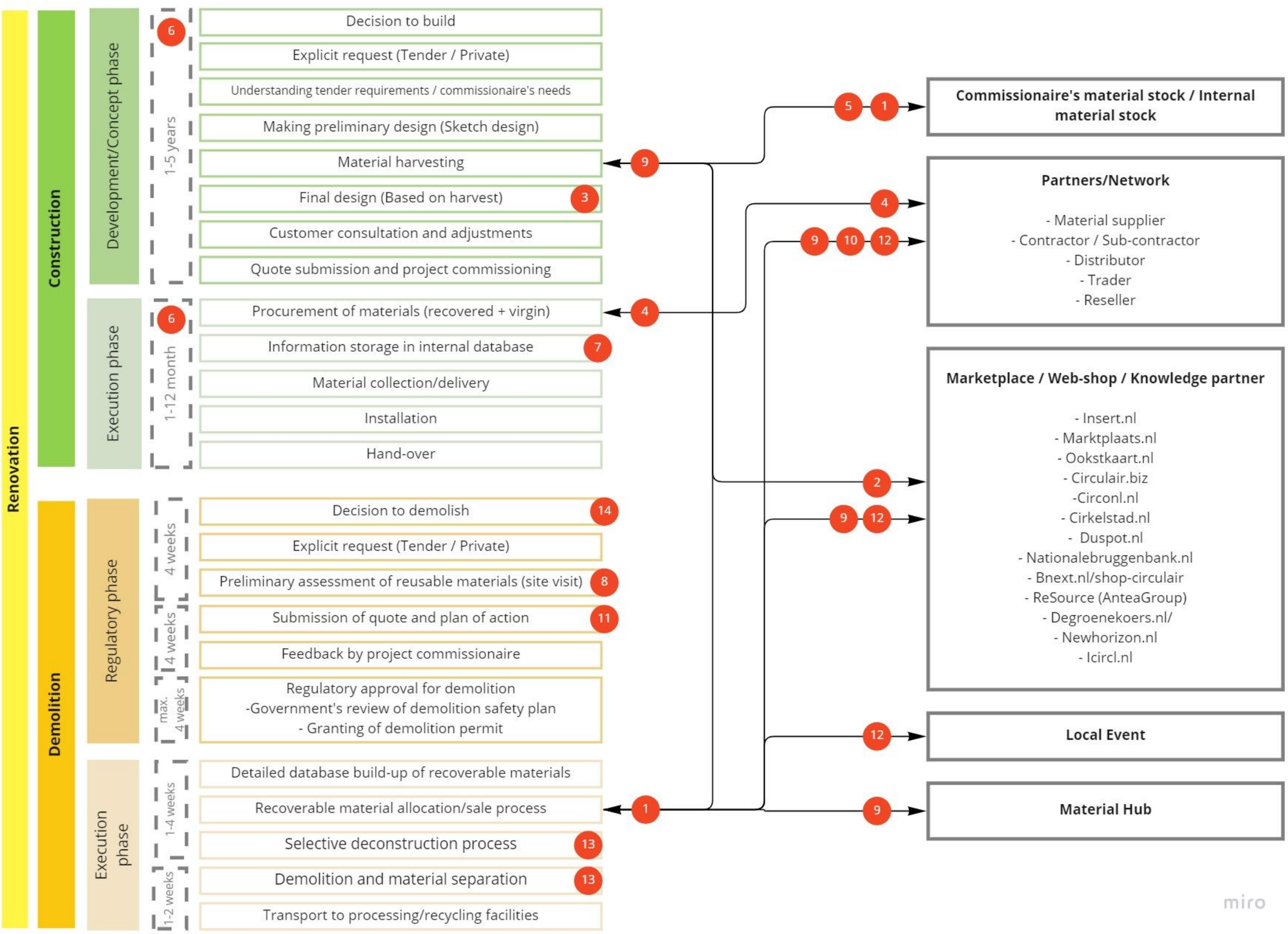


Figure 72 - Process flow diagram of construction/demolition practices in Zuid-Holland with focus on material reuse and recovery

Construction

The construction phase is subdivided into the **development/concept** and **execution** phases. The former has the objective of understanding/interpreting the requirements of a tender or a private customer's, converting these into a tangible design, developing and presenting a price quotation to the client and if successful, getting the project commissioned. The latter has the objective to prepare the construction site, getting the material delivered on time and executing the design developed by the architects and engineers.

The **development/concept** and **execution** are either managed by the same firm or externalized to contractors (see Table 9). Some are specialized in managing the development/concept phase for projects commissioned by the Dutch government (or public institutions) but externalize the execution phase to contractors (see Quote 5.7), while others internalize both processes (see Quote 7.2 / Quote 10.2). The whole construction process can last several years (see 6 in Figure 72) and due to the multitude of stakeholders involved in the process, coupled with conditions exogenous to the project itself (e.g. weather, licenses, plot conditions) the overall construction phase can be affected by strong delays (see Quote 6.6 / Quote 6.7)

Development/concept phase

The development/concept phase starts with the **interest** of a private person or a public institution (hereafter named: commissionaire) to build a lightweight building. The commissionaire makes then an **explicit request**, either through a public tender or by contacting construction companies directly, in which the criteria for the new building are defined and presented to the construction firm. At this point, the architect/engineers start developing a **preliminary design** that reflects these requirements. If the commissionaire accepts (or it meets the tender's requirements) the preliminary sketch is used as a basis for starting the **material harvesting** process.

Distinct approaches have been identified in this phase. None of the construction companies (only the architect firm) has mentioned Approach #1 as their current approach, while Approach #2 was mentioned by 2 out of 3 construction firms.

Material harvesting (Approach #1)

(see 1 and 2 in Figure 72)

This approach is mostly adopted by A1-S, which is specialized in working with circular materials in their new projects.

In this step, the architects manually prepare and send via e-mail a "shopping list" to the demolition companies with whom they have established a partnership (see Quote 7.7). Based on the preliminary sketch, the shopping list outlines the type and number of construction elements required and their characteristics. The demolition company sends back a list with pictures and specs of the construction elements (more info is given later) that can be recovered from current demolition projects. If the construction elements look interesting and meet the requirements, a site visit for assessing their status is scheduled by the architect. If the construction elements meet all the criteria, these elements are booked (not purchased) and included in the final design. In parallel (see Quote 7.8) the architect browse through the different marketplaces/webshops/ knowledge partners and undertakes the same process of looking into the specification of available materials. Figure 73, Figure 74 and Figure 75 below illustrate how the information is organized on these marketplaces/web shops.

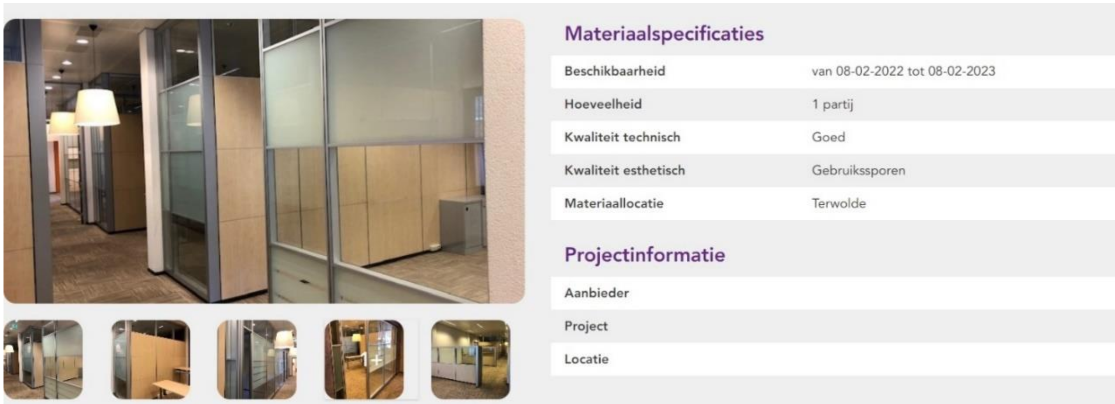


Figure 73 - Example #1 of construction element on the marketplace (Insert, n.d.)

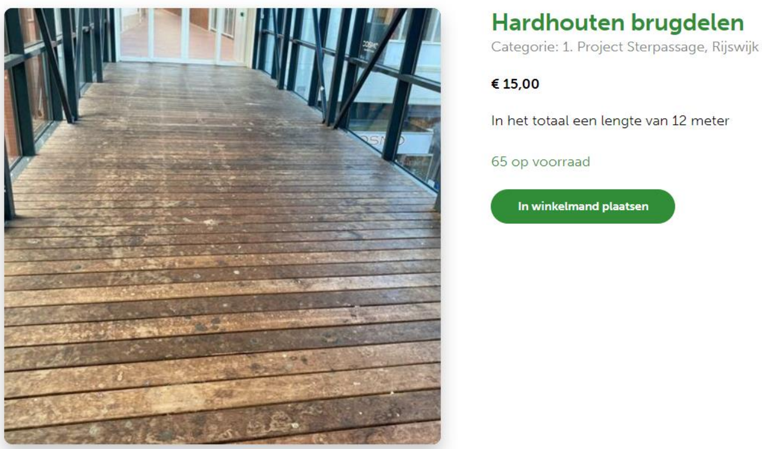


Figure 74 - Example #2 of construction element on marketplace (Bnext, n.d.)

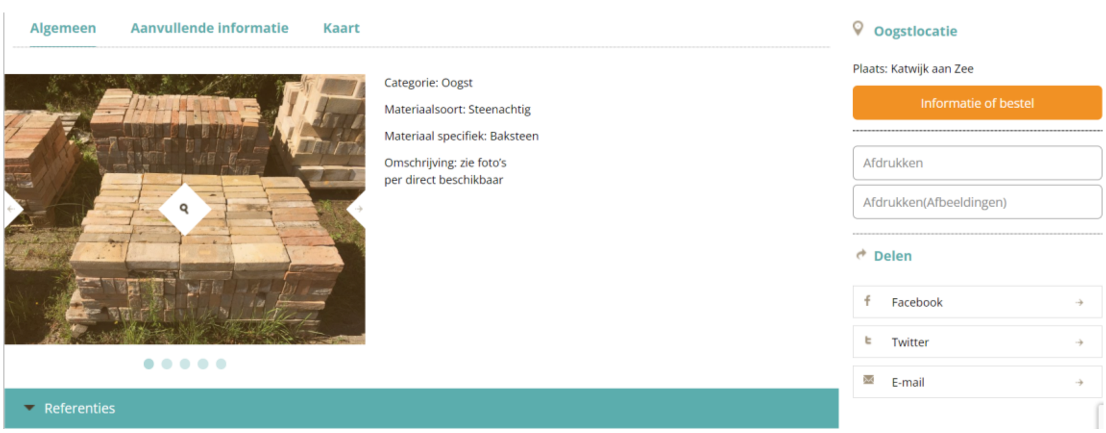


Figure 75 - Example #3 of construction element on marketplace (Oogstkaart, n.d.)

When the project involves a renovation, the architects do also run this harvesting process within the commissionaire's building material stock. In general, the harvesting process is a material-driven process in which the architect considers construction elements for which they have a direct application. According to their experience, their demand is lower than the supply (see Quote 8.0)

Material Harvesting (Approach #2)

(see 5 in Figure 72)

In this approach, architects of the construction firm try to harvest and include in the final design construction elements that can be recovered from the commissionaire's building or from the material stocks of other buildings that are undergoing renovation or demolition (see Quote 6.3). However, this is a very rare case. None of the construction companies has mentioned the browsing of marketplaces/webshops/ knowledge partners for harvesting materials.

According to these construction firms, recovery and reuse of materials are only feasible when the process is undertaken on-site (so to say from the same building) or when the construction firm has commissioned the demolition of multiple housing complexes and similar ones need to be built as substitution (see Quote 6.4 / Quote 6.5 / Quote: 6.8). In one specific instance, the construction firm has reused many structural elements of the old building and integrate it with the new building (see Quote 7.3).

The materials retrieved in the material harvesting process are then merged into the final design. This is submitted to the project commissionaire who needs to **review** and suggest **adjustments** if desired. In the case of A1-S, a harvest map is complemented to the final design. The goal of the harvest map is to illustrate, visually and without technical specifications, to the commissionaire which reused materials will be included in the new project (See 3 / Quote 7.9). At this point, the commissionaire accepts and signs the final **quote** and the project is **commissioned** to the construction firm.

Execution phase

The execution phase starts with the **procurement** of the construction elements and materials. On one side the harvested materials that were previously booked are now ordered and the logistic is arranged with the material supplier, be this the demolition company or the marketplace/website. For virgin material instead, the construction firm makes the order directly to their contractors and sub-contractors/suppliers/distributors and resellers (see 4).

The focus of the **procurement** process is to minimize costs while delivering the construction quality agreed upon with the project commissionaire. According to the interviewees, the project development and procurement process in the Netherlands is quite standardized and primarily money-driven. Standardized because the materials employed in residential buildings are mostly the same ones and money-driven because the construction technology is being optimized and this, coupled with the standardization, allows to keep construction and material costs low with very large profits (see Quote 5.8 / Quote 6.2). An important driver in the allocation of tenders is the so-called "EMVI: economisch meest voordelige inschrijving" but now, with sustainability aspects becoming more relevant within the C&D industry, tenders require to calculate and maintain below a pre-defined threshold the construction's "MKI: Milieu Kosten Indicator" (see Quote 5.9). According to the interviewee's experience, the relevance that sustainability-related aspects have in a tender, depends largely on where the project is carried out in the Netherlands and what is the scope and objective of the project itself (see Quote 6.0). In general, cost abatement is still driving the procurement process. Construction firms focus on this aspect because, in their perspective, competitors will carry out the activity for less money. Some construction firms have sustainability as their unique selling proposition, but these are not very common (See Quote 6.1)

Once the procurement process is finalized, the architects and engineers **store** part of this **information** (design, material stock) in their internal databases (see 7). This process is specific and unique to every company. None of the research participants mentioned the active use of BIM as part of their modelling activities or material passport as part of their material stock tracking (See Quote 7.4 / Quote 7.5 / Quote 10.3).

Based on the procurement strategy and the project's timeline, construction elements are either **delivered** on-site or **collected** by the construction firm. These are then **installed** according to the final design and once finished, the building is **handed over** to the commissionaire.

Demolition

The demolition phase has a similar sub-division to the construction phase. In this case, the first is a **regulatory phase** whose objective is to design the demolition activity and quantify the costs associated with it. The **execution phase** instead focuses on carrying out the demolition plan.

Overall, the time required for carrying out both processes is significantly shorter than the time required for carrying out both phases of construction. In other words, demolition activities are faster than construction ones. Overall demolition activities can be carried out between 1-12 months, depending on the size and complexity of the project. Whereas, construction activities can last, from beginning to end, about 1 to 6 years.

In the reuse and recovery context, more time, compared to the traditional demolition process, is currently invested in mapping recoverable materials. This has an impact on the return on investment of the project, but the demolition firms see this as a long-term investment (see Table 9) and are in this perspective optimizing their processes for making the business case of selective demolition more sustainable and more profitable for the future (see Quote 9.0).

Regulatory Phase

This phase starts with the commissionaire **deciding** to **demolish** his/her old building. According to the interviewee, this step is not well planned by commissionaires and is left as the last step before initiating the construction project (see 14 / Quote: 9.8)

This is then formalized in an **explicit request** or in a tender (when the commissionaire is a public institution).

When the demolition firm receives this request or decides to participate in the tender, the first step entails making a **preliminary assessment of reusable materials** (see 8). Every demolition firm has a slightly different process for doing this (an example of a company-specific decision-making process is provided in Appendix VII), depending on their experience as well as the network and collaboration that they have established with other partners. But all the demolition firms organize a site visit (1-5 days max) in which a circularity specialist/project manager visually looks at the construction elements in the building and makes a preliminary assessment of their value, if partners can be interested in them and what could be the costs associated with the recovery (see Quote 8.1 / Quote 8.2 / Quote: 9.5 / Quote: 9.9). The assessment is purely based on the firm's experience and discretion. The specialist makes a very basic inventory including notes, pictures and estimated costs and revenues (see Quote 8.3). For big projects with a lot of valuable resources, some demolition firms invest in making a complete and detailed material passport. This can require 5 days of work and is currently only conducted a few times per year (see Quote 8.4). This step is extremely important because the recoverable material list is conceived as potential revenue and is therefore subtracted by the demolition costs that the demolition firm estimates for the remaining part of the building (see Quote 5.6). Oftentimes, the amount of material that needs to be recovered, is a precondition for winning the tender (an example of such tender conditions is provided in Appendix VI). Nevertheless, the demolition firm cannot have the guarantee of being able to resell the construction element that needs to be recovered (see Quote 10.1).

The next step is the formulation and submission of a **quotation** and a detailed **demolition action plan**. The project commissionaire has 4 weeks to provide his **feedback** and an answer to the demolition firm (see Quote 9.5). If the feedback is positive and the project is **commissioned** to the demolition firm, the next step is to undergo the **regulatory approval process** which entails a review of the demolition safety plan and the granting of the demolition permit (see BRL SVMS-007 certification). This process can take another 4 weeks.

Execution phase

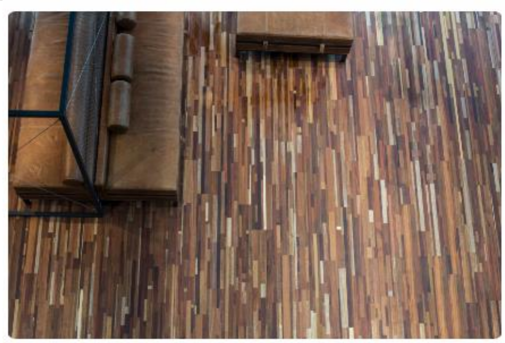
The moment the demolition firm is officially granted permission to demolish, the preliminary database drafted during the preliminary assessment is optimized and additional information is added to **compile a detailed database of recoverable construction elements**.

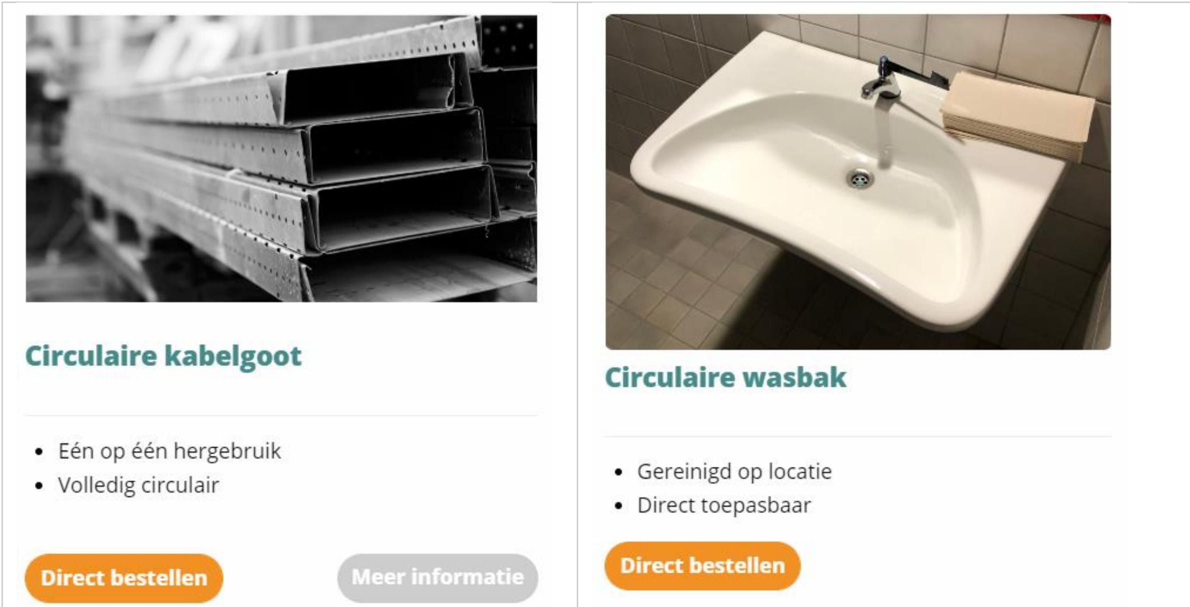
The next step is to start with **allocating/selling the recoverable construction elements** listed in the internal database by the circularity expert/project manager. The approach differs slightly between the demolition companies included in the research.

In the **first** case (see 9 and Quote: 8.5 / Quote: 8.6 / Quote 8.7) the circularity specialist/project manager replies to the "shopping list" shared by the architect firm, secondly it directly reaches out to (via phone or e-mail) to the partners within the company's network. All the construction materials are also posted on the marketplaces/web shop (see Figure 73, Figure 74, Figure 75). In the meantime, the deconstruction and demolition team starts with the **selective deconstruction** process and selectively recovers the construction elements. Ideally, the recovered construction elements are sold before being taken apart and can therefore be shipped directly to the buyer. Otherwise, the construction element is transported to the Material Hub owned by the demolition firm and is stored there until someone is interested in purchasing it.

In the **second** case (see 10 and Quote: 9.1 / Quote: 9.2 / Quote: 9.3 / Quote: 9.4) the demolition firm relies on a consolidated network of partners and does not directly adopt marketplaces/web-shops, and hubs and does not handle direct demands from architects. The firm has an established business case with each partner, meaning that each partner handles specific construction materials. The business case is supported by specific and binding contracts that oblige the partner to accept the construction element if it meets the quality and specification requirements specified in the contracts. The **selective deconstruction** process starts as soon as the demolition firm wins the tender or receives the commission for the project. The construction elements are selectively removed and carefully stored on site and the partners are responsible for picking these up, bringing them to their facility and selling them on the market (see Table 18). The secondary application of these materials depends on the quality of the recovered construction element. For example, wood is profiled in different quality categories (A, B, C) and based on these different partners and different applications are identified. Oftentimes, the construction elements are <u>not directly reused but are rather downcycled</u> and or <u>refurbished</u> by the partners. So far the demolition firm can guarantee a stable and continuous recovery flow for 15/20 construction elements.

Table 18 - Examples of construction elements sold by partners

 **CicloBrick** • CicloBrick bestaat uit 20% keramisch restmateriaal Op aanvraag · Meer informatie	 **Circulair balkhout** • Verschillende houtsoorten beschikbaar • Volledig circulair Direct bestellen · Meer informatie
 **Circulaire gipswand** • Circulaire gipswand • 25% CO_2-reductie Direct bestellen · Meer informatie	 **No Waste vloer** • Circulaire houten vloer • Op maat gemaakt • Iedere vloer heeft haar eigen verhaal Direct bestellen · Meer informatie



In the **third** case (see 12 and Quote: 9.5 / Quote: 9.6 / Quote: 9.7) as soon as the tender is won or the project commissioned, the demolition firm shares the detailed database containing all recoverable materials with their network of partners located in the proximity of the demolition site. Partners that are located too far from the demolition site are not contacted in this case. The demolition firm prioritizes partners over other solutions because of their reliability and commitment. Next, the circularity specialist/project manager manually uploads all the construction elements on the available marketplaces/web shops (see Figure 73, Figure 74, Figure 75). The last step is to contact local companies that might need construction elements. Sometimes the demolition firm organizes specific circularity events to which local companies are invited.

After the material allocation/sale process comes the **selective deconstruction process** (see 13). As mentioned previously some demolition firms start these processes in parallel because they rely on an established network of partners and/or on a privately owned material hub that allows storing the construction elements for a longer period. Others instead, start with the selective demolition only after some weeks from when the recoverable construction elements were proposed to the partners or posted on the marketplace/web shops. In this case, and as illustrated in the timeline in Figure 72, the demolition firm has a time window of 1-4 weeks before the actual demolition process is initiated. Thus, if the internal deadlines are not met, the project manager decides to start the **demolition and material separation process** and includes in the demolition also those construction elements that were put on sale (see Quote: 9.8 / Quote: 10.0 / Quote: 8.6 / Quote: 8.7). The execution phase concludes with all the separated containers with demolition material being **transported to** either **processing** or **recycling facilities**, according to the waste management criteria set in the province.

Sub-question 3: What are the data/information required for effective reuse and recovery practices and the challenges characterizing these practices?

Challenges are identified based on clear statements by the interviewee, the comparison of data required and the current reuse and recovery practices and the state of the art in terms of information and construction practices. The interdependency between different challenges that arose from this research was not investigated. These are therefore based on clear and direct linkages that can be deducted from the findings. Quotes utilized in the analysis are summarised in Table 25.

Data/information required

Construction projects are strongly bound and dependent on time, and as outlined previously contract compliance is extremely important too. This implies that the C&D industry requires precision, and tight planning and operates in a space with little margin of error. Additionally, C&D are a resource and labour-intensive activity. Accurate and trustful information/data is required for preventing delays and for maintaining all cost forecasts under control, as well as tracking accountability and contract compliance.

All information/data there were highlighted and deemed by the interviewee as important and must be related to this aspect of precision and error prevention. From the perspective of reuse and material recovery, this is also a very important factor to take into mind.

Supply /demand (volume/time)

Schedule in C&D projects is extremely important and can have a repercussion on the overall planning and execution phase. In this perspective, material availability and deliverability need to fit tightly within both phases. The designer needs to have the certainty that a specific construction elemental will be (or is) available at the time the construction firm starts executing the job. This is important for making a correct cost estimation that is present in the customer's quote, aligning the customer's expectation with the final design as well as preparing all the documentation for obtaining the required construction permits. Also, the construction elements included in the final design are not purchased until the quote is signed. The certainty that specific construction elements are delivered on time becomes even more relevant when considering that the execution phase is carried out in a few weeks and it can do so because it heavily relies on very specific and tight planning activities defined during the planning phase. Because of this, the material allocation must be integrated into the planning phase and cannot be carried out during the execution phase. The same principle applies to the volume of construction elements.

At the same time, the demolition firm needs to have a clear understanding of which construction elements need to be recovered, what the costs associated with selective demolition are, where will these be employed and consequently how much can the final demolition quote be reduced for the final customer. As for construction firms, the planning phase is extremely important because it allows them to carefully and correctly estimate what, how much and how specific construction elements can be recovered. Also, demolition firms need to clear the demolition site within a pre-defined deadline.

In this perspective, the planning phases of construction and demolition activities are strongly interdependent and the supply and demand-related information are relevant in this specific phase, not in the execution one. At the current stage, reuse and recovery practices are not aligned.

Currently, the construction firm has more information, about timing and volume (and therefore about the supply and demand of construction elements), when the demolition relates to buildings that were built by them and when the construction (both planning and execution phase) is internalized. In this case, the construction firm deals with a material stock that is under their complete supervision and for which volumes and deliverability-related information can be easily handled.

Information about the demolition and construction activities of a building is bound to the decision taken by the commissionaire (be it private or public) to build and/or demolish the property. For public institutions, the decision is part of more long-term planning (like urban planning) activities, while for a private commissionaire the decision can be taken more or less suddenly. For example, Municipalities develop construction agendas for the next 5 years for their projects (like road maintenance) which clearly define the project's date and objective.

There is currently no platform or database available in the public domain that centralizes information about the construction and demolition dates of private and public projects.

(see [Quote 10.6] / [Quote 10.7] / [Quote 11.1] / [Quote 11.2] / [Quote 11.6] / [Quote 11.8] / [Quote 6.7] / [Quote 12.0] /[Quote 12.1] / [Quote 6.8] / [Quote 12.9] / [Quote 13.4] / [Quote 7.8] / [Quote 13.9] / [Quote 14.4] / [Quote 14.7] / [Quote 15.9] /[Quote 16.5] / [Quote 16.7] / [Quote 16.8])

Technical specifications & Material Passport

Following supply and demand-related information are the technical-related information.

To start with, a construction firm needs to assess during the planning phase whether the construction element fits the new design or not. To do this efficiently requires general and specific information or data. General information includes the brand name, supplier, year of production, composition, colour and dimensions. Specific information is for example performance related characteristics (thermal, fire resistance, sound dampening etc.).

All this information is extremely important for considering the reuse of construction elements in the new design. Without these, it is extremely complicated (if not impossible) for the architect to assess their applicability to the new design as well as to receive an objective evaluation by the customer about the final design. According to the interviewee, final customers are very selective and demanding when it comes to new constructions.

Required information includes also quality, design and building-specific information. These include strength characteristics (original and current) of the construction element, load distribution (in case of load-bearing elements), when was the original building designed and if renovation work was ever conducted in the building.

All the information is important to the architect and engineers because when it comes to load-bearing elements, for example, the engineer must be able to assess whether the construction element can still be employed in the new building or not. The construction firm is responsible for the structural integrity of the new building and can therefore not employ load-bearing construction elements that might be compromised.

According to the interviewee, material passports are a very important precondition for allowing for material recovery and reuse. The foreseen benefit is also extended to the government which can potentially have a better overview of the material stock on a national level as well as for building owners for facility and asset management activities.

What is evident from the different interviews is that material passports are deemed important, but only when the aspect of sustainability is relevant to the project’s outcome. Otherwise, the information is not regarded as relevant because the level of information is in any case too vague or not tailored to the processes specific to the ways activities are carried out within construction or demolition firms. Material Passport can also be used to show the final customer what materials have been employed for his/her project. This aspect is important for tenders where specific reuse and recycling volumes are set as pre-condition for winning the tender. Additionally, a material passport could level the demolition price during tender because companies would be prevented from making reusability claims that cannot be assessed and verified.

The large construction firms highlighted that for them reuse is simpler to apply when conducted on their projects because it allows investigating the internal database of available (or soon-to-be) material stocks. The format of the information is in this case already tailored to internal processes and therefore making the information trustful and actionable.

Interviewees also share that there is currently no standardization process for how material passports are compiled. This affects the relevance the material passport can have in reuse and recovery practices. Also, many old buildings do currently not possess a material passport.

BIM models containing detailed information about buildings' design and material stock are also deemed important as these can facilitate material recovery as well as maintenance activities. Also, in this case, BIM models are not standardised, not all construction firms adopt them and old buildings do not even possess a BIM model.

(see [Quote 10.7] / [Quote 11.1] / [Quote 11.5] / [Quote 12.1] / [Quote 12.7] / [Quote 12.8] / [Quote 13.4] / [Quote 7.7] / [Quote 13.5] / [Quote 14.0] / [Quote 14.2] / [Quote 14.7] / [Quote 8.1] / [Quote 15.3] / [Quote 15.6] / [Quote 9.1] / [Quote 15.7] / [Quote 16.0] / [Quote 16.1] / [Quote 16.5] / [Quote 16.6] / [Quote 16.7] / [Quote 11.0] / [Quote 11.7] / [Quote 6.8] / [Quote 12.6] / [Quote 13.2] / [Quote 7.8] / [Quote 14.3] / [Quote 14.4] / [Quote 14.8] / [Quote 15.1] / [Quote 15.5] / [Quote 15.9] / [Quote 16.8] / [Quote 17.1] / [Quote 17.3] / [Quote 9.4])

Construction year, construction techniques and design

An important element is also having access to the old and new sketch designs of the building. As highlighted by the architect firm, reusability is facilitated when the design of the old building is used as a basis (or reference) for the new one. This can in certain cases even allow to reuse of whole parts of buildings and not only specific construction elements. One interviewee presented a project in which the whole basement was preserved thanks to the designers who carefully designed the new building with this aspect in mind.

The design and year of construction are also extremely important information for both, construction and demolition firms. The coupling of this information can provide insights into the construction techniques applied (how were the construction elements put together) as well as potential risk factors (presence of asbestos) that must be considered during the demolition’s planning phase. According to the interviewee, dutch buildings were built with specific construction technique standards throughout the decades. This information allows assessing, with a certain degree of accuracy, how the buildings were designed and put together and to deduct (empirically) the material content as well as assess the recoverability of certain construction elements. This information is also very important to the demolition firm as it might impact the costs for selective demolition and the feasibility of recovering specific construction elements.

Both demolition and construction firms need to economically evaluate the costs of recovering and reusing construction elements. Therefore understanding the way these elements are put together is paramount for conducting effective cost & benefit analysis. This also includes the context in which the building is located. It has been shared a peculiar situation that describes this. During a demolition project, certain construction elements were feasible for reuse but the location required the renting of specialized equipment such as a crane which made the recovery cost soar significantly above the potential revenue, thus shifting the cost-benefit analysis to a negative figure.

An additional point, that directly links to the construction techniques employed, is the know-how concerning material recovery and dismantling. This knowledge is currently developed within the demolition firm. This information should be made accessible to other firms, and should not be segregated within the firm. New constructions should also highlight the way construction elements can be safely taken apart. This would allow for standardized ways of dismantling buildings.

Interviewees were highlighting the benefit of having a recoverability index in place. Old buildings were not designed with material recovery in mind but new construction techniques and modular ways of the building will make sustainability and material recovery easier and more cost-effective in the future.

(see [Quote 11.5] / [Quote 8.1] / [Quote 15.3] / [Quote 15.4] / [Quote 9.1] / [Quote 9.4] / [Quote 16.1] / [Quote 16.6] / [Quote 10.7] / [Quote 11.1] / [Quote 12.1] / [Quote 12.7] / [Quote 12.8] / [Quote 13.4] / [Quote 7.7] / [Quote 13.5] / [Quote 14.0] / [Quote 14.2] / [Quote 14.7] / [Quote 15.6] / [Quote 15.7] / [Quote 16.0] / [Quote 16.5] / [Quote 16.7] / [Quote 11.7] / [Quote 6.8] / [Quote 12.6] / [Quote 13.8] / [Quote 14.4] / [Quote 15.1] / [Quote 15.9] / [Quote 16.8] / [Quote 17.3])

Challenges

The challenges hereafter presented were identified through a comprehensive analysis of all interviews conducted in the research. Construction and demolition firms are currently operating in a linear fashion which implies how challenges regarding material recovery and reuse are perceived and put forward. Specifically, perceived challenges were mostly circumscribed to company-specific activities.

Because the objective is to assess the challenges from an industry-wide perspective, the challenges were segmented and categorized. Many are interdependent but a cause-and-effect nexus was not investigated.

Table 25 (see Appendix VIII) provides a list of all quotes employed in the analysis.

Compliance /Accountability/Tracking

One important challenge that is currently hindering reuse and recovery practices is the lack of trustful tracking systems and accountability mechanisms.

As outlined in the previous paragraph, for construction and demolition firms (as well as for regulatory institutions) it is extremely important to rely upon trustful and verified digital information. This is currently not the case in the C&D industry in the Netherlands.

The first aspect where this lack of verified data is clear is the material content of buildings. The need for material passports for boosting the transition toward circularity practices is clear and supported by literature, nevertheless, there is currently no standardized way for either compiling or tracking material passports. Softwares like Madaster offer the possibility of creating material passports but these might differ significantly when compiled by specialized firms or internally by construction firms, or even by the private owner. Demolition firms have all reported that the material passport they receive are oftentimes not accurate and therefore not trustful for them. They tend to make new ones for incoming demolition projects.

Additionally, maintenance and renovation work is not tracked at all. This implies that the material stock of a building can change throughout time and this information is not stored and therefore not retrievable. The fact that this information cannot be certified right now has a direct implication for the costs associated with the preliminary assessment of recoverable material and thus with the final costs associated with the selective demolition process. Having the certainty of finding expected materials and volumes in a building could enhance the cost-effectiveness of selective demolition. To conclude, there is no standardisation or obligation to compile and track material passports.

The second aspect is the accountability of reused construction elements. A construction firm is responsible for the safety and integrity of the building they bring together. Virgin products come with a quality certification (Komo productcertificaat) that is provided directly by the manufacturer. This does not exempt the construction firm from their accountability in case the building does not deliver the required quality standards (especially load-bearing elements). The issue with reused construction elements is that there is no process for verifying and certifying their status and quality (especially for load-bearing elements). For example, a wooden beam might still be perfect from an aesthetic point of view while its strength might be compromised. Demolition firms recovering the construction element cannot provide this guarantee to construction firms, thus delegating all the responsibility.

Experts, sensor technologies or specific tools might be able to assess the strength of the construction element but this information is currently not certified. This is slightly different for those demolition firms that have established partnership contracts and agreements with suppliers and resellers. In this case, the supplier/reseller treats the recovered material as a virgin and certifies its strength and quality (this is more of a refurbishing process). The issue of quality is more prominent for load-bearing construction elements because a wrong assessment might jeopardize the integrity of the building and put people's lives at risk. These issues are usually dealt with through compliance agreements and contracts. But at the current stage, there is no process in place that can replicate this for reusable/recoverable construction elements. Therefore there is an important information gap that prevents having compliance and accountability mechanisms in place. With all other construction elements (sink, door, gypsum panel etc.), the quality can be assessed visually instead.

The lack of established material tracking systems in the industry is also negatively affecting demolition firms during tenders. As highlighted previously, public institutions are making sustainability more important in tenders by adding reusability and recyclability volumes as pre-conditions for winning the project (Appendix VI). Demolition firms participating in this research have highlighted how, on several occasions, ghost companies were established and used as material dumping mechanisms. The demolition firm participating in the tender would claim that all the required volumes (as defined in the tender) would be recovered and either reused or recycled. Instead, they would "sell" these to the ghost company which would stream these materials to traditional processing facilities. The lack of a trustful tracking system makes it very hard to prevent and eventually punish such illegal dumping activities. Demolition firms that respect the tender conditions cannot compete with these companies on a price level because recovery and recycling/reuse activities require more labour force and thus more capital. Potentially, also construction firms can benefit from this lack of tracking mechanism because their claims of using materials with a certain quality or sustainability standards cannot be certified.

The last but important issue is the accountability of those stakeholders reserving construction elements from demolition firms who then do not show up when it is time to get the material recovered on-site. Also in this case demolition firms struggle to make these actors accountable for the reservation. As illustrated in the previous paragraph, demolition firms will reduce the final quote assuming that certain materials will not be processed but rather sold to third parties. To prevent this, demolition firms are working with only trustful partners who might be interested in a few material streams only, thus preventing other streams to be recovered, sold and reused.

(see [Quote 10.4] / [Quote 12.2] / [Quote 12.3] / [Quote 12.4] / [Quote 12.5] / [Quote 12.7] / [Quote 13.0] / [Quote 13.1] / [Quote 14.8] / [Quote 15.6] / [Quote 15.7] / [Quote 9.4] / [Quote 16.0] / [Quote 16.2] / [Quote 9.7] / [Quote 17.1] / [Quote 17.3] / [Quote 17.4] / [Quote 17.5] / [Quote 17.6])

Quality of products

The quality of construction elements has been mentioned in the previous paragraph. Fundamentally, the biggest issue is that construction firms have currently no way to determine upfront the strength-related status of construction elements. This can only be prevented by having a circularity expert/project manager go on-site and testing through NDT (non-destructive testing) methods the integrity of the construction element.

All interviewees, especially construction firms, have highlighted the compliance-related aspects of reusing load-bearing construction elements. This is an important factor hindering reuse practices. The architect firm, which is specialized in building with reused construction elements, does assess the strength and quality of construction elements with specific site visits and ad-hoc specialists. In this case, the activity is part of the core business and the value proposition of the firm. For the other firms, this is currently an additional cost to include in the quotation.

The aesthetic quality was not regarded as a hindering factor as long as the final customer was involved in the decision-making process. The reuse of construction elements has a significant impact on cost reduction and the rise in material prices can be regarded as an incentive for encouraging reuse.

(see [Quote 10.6] / [Quote 12.7] / [Quote 13.0] / [Quote 7.7] / [Quote 13.7] / [Quote 15.6] / [Quote 15.7] / [Quote 16.6])

Asynchronous/Misaligned project/process management

Reuse and recovery practices are regarded as more feasible when the objective of the project is clear from the beginning and when all stakeholders involved are coordinated and aligned. For example, the Werkspoorfabriek in Utrecht was built with reused (repurposed in this case) products. In this specific case, the planning and execution side of the construction project was carried out with complete synergy between the firms involved. But this is an exception.

Most of the time this is, according to the interviewee, not the case at all. It was reported that especially when the commissionaire is a private house owner, the planning and the execution phase can be handled by completely different parties. This generates quite some complexities concerning reuse and recovery practices.

First of all, construction firms have to procure materials and execute the construction project on final designs developed by other firms. This leaves little flexibility in terms of reusing construction elements that can be retrieved from the material stock of other buildings (or even the same) managed by the construction firms themselves. This has significant implications for the demolition firm as well. All interviewees have outlined that the current practice is that private customers reach out to the demolition firms only after having defined the final design and having signed the quote with the construction firm. Taking into consideration the current reuse and recovery practices outlined in Figure 72 it becomes evident the challenges for a demolition company to map the available materials, propose them to their network, sell and then recover them within a pre-defined timeline. This leads to other challenges that will be outlined in the next paragraphs.

In general, the issue that stems from this approach is that it hinders synergic collaboration between the demolition and construction firms. Involving demolition firms at the early stage of the project can allow them to work with the already existing construction elements and boost material recovery and reuse. This would consequently have a positive impact on procurement costs for virgin materials and transport costs.

The reason why construction firms or architects do not proactively suggest to the private commissioners the involvement of demolition firms at the beginning of the planning phase was not investigated. Nevertheless, some comments made by the interviewee shed some light on this matter. For example, the architect firm has clearly stated that construction firms are not so eager of working with reused materials and traditional architects are not very happy to work with reused materials either as this might hinder the creativity of their project. Nevertheless, the architect firm has several times presented partner demolition companies during tenders as material suppliers rather than as traditional demolition firms. This is an interesting approach and it indicates that the collaborations between complementary firms are not automated and require a proactive attitude by the companies involved. The same goes for data-sharing. The process requires active and direct collaboration.

The reason why private commissionaire does not involve demolition firms at the early stage of the project was also not investigated in this research. Interestingly, the economic advantage for a house owner in reusing construction elements would be significant as it would reduce costs associated with purchasing virgin materials. The suspect is that this relates to a lack of knowledge and/or concerns about the quality of the final project.

(See [Quote 10.5] / [Quote 10.6] / [Quote 7.0] / [Quote 7.1] / [Quote 7.3] / [Quote 13.4] / [Quote 13.8] / [Quote 14.4] / [Quote 14.5] / [Quote 15.1] / [Quote 15.3] / [Quote 16.7] / [Quote 9.8] / [Quote 16.8] / [Quote 16.9] / [Quote 17.0] / [Quote 17.1] / [Quote 15.2] / [Quote 16.0])

Discordant and inconsistent data management practices and governance practices

In general, the process of reusing and recovering construction elements is currently not established and consolidated in Zuid-Holland. Data storing and sharing, which is the basis for enabling material and reuse activities are carried out manually and there is no harmonized and automated process currently employed. This has a direct impact on the cost-effectiveness of current reuse and recovery practices, leading to large resources involved in collecting and sharing information as well as allocation of risks that are not optimal.

As illustrated in Figure 72 every party involved in this research is adopting a different process for assessing the feasibility and cost-effectiveness of reusing and/or recovering construction elements. Especially the demolition firms, all of them have different communication channels and different methods for collecting data and for selling reusable construction elements and rely mostly on a network of partners where the personal relationship is extremely relevant, if not key.

Reuse and recovery activities intrinsically need to align and coordinate processes and data management activities carried out by multiple stakeholders at multiple points in time and space. This makes reuse and recovery a multistakeholder governance process that relies upon the information/data collected, stored and made available by multiple parties. Nevertheless, the companies participating in this research are working in the opposite direction of this.

The first point is that all firms are adopting **local databases** and **data sources** for storing and retrieving their information. For example, construction firms are creating and storing BIM models and material passports within their databases. Some of the construction firms are not even adopting BIM models as a means of storing building-related information while others do this sporadically, depending on the size of the project. Old buildings do not have a BIM model or material passport readily available. There are specific nomenclature and design standards (see NEN-9116 or CE standards) that help with harmonizing the definition of construction elements and design, nevertheless, there is currently no harmonization in terms of data requirements for facilitating material management throughout their full life-cycle. Several of the demolition companies involved in the research have outlined that the material passport provided by construction firms (or specialists) are not specific enough for decision-making and for making material recovery activities cost-effective. On the other hand, construction firms struggle at considering the information provided in marketplaces (see Figure 73, Figure 74, Figure 75) sufficiently detailed for facilitating their decision-making process during the design phase. Some interviewees were not even aware these marketplaces/webshops existed in the first place. Therefore construction firms prefer to work on reuse activities when the data are part of their internal databases (in other words when they work on projects realized by them) and even consider this the only feasible way for conducting reuse and recovery practices.

This leads to the situation where countless databases (and potential data sources) are currently available in the industry but where these are not open source and the information contained in them is collected, stored and processed based on company-specific requirements and standards, and not industry-specific ones. The industry does **not have specific guidelines** on how **data** should be collected, **processed**, **stored** and **managed**.

As mentioned above, not all construction firms adopt BIM or generate material passports from their projects. At the same time, demolition companies take pictures and technical specifications and store these in excel sheets or public marketplaces, while others use mobile applications or prepare shopping lists for specific partners. It has been mentioned by the interviewee that the direct advantage of creating and managing their database is that data can be tailored to their company-specific needs and processes. This has led to the situation where almost every demolition firm has invested or relies upon multiple marketplaces/webshops for trying to sell recoverable construction elements.

In other words, data collection, processing, storage and data sharing practices are currently not harmonized making the interoperability of databases and data sources very difficult, if not impossible. Additionally, companies cannot fully trust the reliability and accuracy of the data/information provided by third parties. For example, the demolition firms have all mentioned that the material passports they receive are neither accurate nor reliable. Because of this, demolition firms prefer to make material passports from scratch.

Interestingly, none of the construction firms involved in the research has mentioned marketplaces/webshop as means of procuring reusable materials. This does not indicate that they are not aware of their existence, but it rather suggests that it is not a standardized way of procuring reused construction elements. Instead, the architects look either within their databases or contact demolition firms with whom they have an established partnership.

Another challenge relates to trust and the market value of data. Several demolition firms do not publish construction elements that can potentially be reused on open-source marketplaces/web shops because this information could potentially provide some market advantage to other competitors. Therefore the close network relationship outlined and described previously is a way to keep the information contained within controlled networks of actors. Some marketplaces have been completely dismissed because of this reason. None of the construction firms participating in this research has outlined this issue. Nevertheless, from the description of their current reuse process, it is clear they are not proactively sharing information with demolition firms or other construction firms. The interviewee mentioned that some competitors are browsing through these marketplaces/web-shop intending to assess what type of project their competitors are working on and in this way gain insights on prices and other information. The industry is very conservative and competitive, mistrust and privacy are how the current processes can be characterized. Also, every firm needs different types of data and so far no marketplace/webshop provides, according to the interviewee, all the required information.

Even though all parties involved in the research regard digitalization as an important step forward for sustainability, not all of them have tailored and adapted their activities and processes for sustaining this transition. As mentioned previously, many construction firms rely exclusively on digital floor plans and do not employ BIM at all. The main argument is that there is currently no national regulation/law forcing companies to either create BIM models or Material Passports. The choice of employing Material Passports and/or BIM models relates to the perceived advantage, both in terms of innovation and unique selling proposition. In other words, some firms are including digitalization in their activities while others do currently see this as an additional cost and do not perceive its added value.

To conclude, the C&D industry in Zuid-Holland sees the advantage of applying circularity principles to its industry but it still operates and thinks linearly. For instance, demolition firms would benefit significantly from having access to BIM and Material Passports. On the other hand, construction firms are not consistently adopting these systems as a standard way of storing and managing data. When they do, they prefer to keep this information in private databases. Therefore, there is an important process (and consequently data/information) gap that is hindering the transition towards circular practices. According to the interviewee, no one is leading the way and C&D firms are not sure where and how to initiate this digital transition. Many have tried to start small cooperations and consortiums between some parties, nevertheless, they have realized that to make a consistent impact for the whole industry, the whole industry must participate in the transition in a coordinated manner, with a clear and measurable objective.

Some among them are waiting for the government to give a clear indication and pathway. So despite understanding that making data management transparent and coordinated lies at the heart of making circularity work, many firms are still concerned about privacy and the market value that data has. In a context where collaboration is needed, companies are very much concerned with competition and apply business models that reinforce linear material management practices. Also, the C&D industry is very capital and resource-intensive meaning that the activities must always be framed within a limited budget allocated for innovation. All activities that require additional work will ultimately increase the final price of a project.

(see [Quote 10.8] / [Quote 11.2] / [Quote 11.4] / [Quote 11.9] / [Quote 11.8] / [Quote 6.6] / [Quote 7.1] / [Quote 7.8] / [Quote 10.3] / [Quote 7.9] / [Quote 13.7] / [Quote 14.4] / [Quote 14.3] / [Quote 14.7] / [Quote 15.1] / [Quote 15.4] / [Quote 16.0] / [Quote 16.2] / [Quote 16.3] / [Quote 16.4] / [Quote 16.5] / [Quote 9.7] / [Quote 16.7] / [Quote 9.8] / [Quote 16.8] / [Quote 16.9] / [Quote 17.0] / [Quote 17.1] / [Quote 17.2] / [Quote 17.3] / [Quote 17.4] / [Quote 11.3] / [Quote 11.6] / [Quote 7.0] / [Quote 12.5] / [Quote 13.6] / [Quote 13.0] / [Quote 7.4] / [Quote 13.2] / [Quote 13.3] / [Quote 14.9] / [Quote 15.0] / [Quote 8.9] / [Quote 15.6] / [Quote 15.7] / [Quote 15.8] / [Quote 16.6] / [Quote 17.5] / [Quote 17.6] / [Quote 12.3])

Unavailable and/or inaccurate information/data

A direct consequence of having multiple databases and data sources and no harmonization and standardization in data management practices is that information/data required for making reuse and recovery cost-effective are either not present or inaccurate and therefore considered as not reliable. All interviewees have mentioned that the lack of data is one of the most pressing issues characterizing and limiting reuse and recovery practices.

Information/data is important because it helps in assessing the cost-effectiveness of recovering and reusing construction elements if the construction element can fit the new design, what will the final design look like and also facilitate the matching of offer and demand.

Architects invest significant time to retrieve scattered information present on marketplaces/web shops or via the shopping list sent to the demolition firms. Also, the information is not always reliable and detailed enough to be actionable. The additional hours that must be invested in conducting this harvesting activity can have an impact on the final cost for the client. For demolition firms instead, the lack of information is translated into increased risks during the cost & benefit analysis.

The lack of information/data differs between old buildings and new ones. Demolition and renovation projects are currently focusing on buildings from the 70s-80s-90s which have no digital information available. The complexity, in this case, is that demolition companies must rely on old floor plans and must retrieve information about construction elements that are no longer manufactured. Also, renovation can have changed the materials tock of the building. In this case, the information is just not available and needs to be retrieved manually or via an empirical method. For example, one of the demolition firms has established agreements with material suppliers/distributors for specific construction elements such as gypsum walls, sinks and toilets. These construction elements are present in almost all buildings and can be quantified with empirical methods or with quick site visits. More complex construction elements such as wooden beams, windows, flooring and doors require some more specifications which cannot (or only partially) be assessed visually.

For new buildings instead, the issue is not perceived as of yet because they will be demolished 50-60 years from now. Nevertheless, the current lack of standardized digitalisation and data management practices will most likely lead to challenges very similar to the current ones. Information and data will not always be digitalized, when digitalized these will be present but scattered across multiple databases and in formats that will, according to the interviewee, still hinder material recovery and reuse.

(see [Quote 11.6] / [Quote 11.7] / [Quote 11.8] / [Quote 6.6] / [Quote 11.9] / [Quote 6.8] / [Quote 12.6] / [Quote 13.2] / [Quote 7.5] / [Quote 10.3] / [Quote 14.1] / [Quote 14.2] / [Quote 14.3] / [Quote 14.4] / [Quote 14.5] / [Quote 14.7] / [Quote 15.5] / [Quote 9.4] / [Quote 15.9] / [Quote 16.2] / [Quote 16.3] / [Quote 16.5] / [Quote 16.7] / [Quote 16.8] / [Quote 17.0] / [Quote 17.2] / [Quote 17.3] / [Quote 17.4])

The mismatch between offer and demand

C&D projects need to comply with specific and tight contract conditions. One of these is the project timeline. Material supply plays, therefore, a key role in respecting the project timeline. The challenges outlined so far contribute to another significant challenge which is the **matching of the offer** and **demand of** construction elements and the **asynchronous execution of construction and demolition activities.**

The duration of the demolition process (0-12month) is significantly shorter than the duration of the construction project (1-5 years). As illustrated in Figure 72 the design phase occurs years before the actual execution phase. During the design phase, the architect needs to harvest materials, make a final sketch with these materials, get confirmation from the customer (which requires detailed information about the quality and design of the recovered materials) and then if the customer confirms, the architect needs to reserve/purchase materials and get them delivered on-site by the time the execution phase starts. Every delay incurred during the execution phase makes the final cost of the project soar and sometimes the construction firm can incur fines (if defined in the contract). So the recovered construction elements must be there on time.

The demolition process, instead, is carried out in less than 1 year and all the potentially recoverable construction elements need to be mapped, sold and removed from the premises by the end of the demolition. Therefore, the demolition and construction processes, besides being at different stages of the building's lifecycle, have very different planning and execution period. And this strongly affects the matching of the supply and demand of construction elements.

The execution phase during demolition is relatively short (1-6 weeks). Within this time window, the project manager needs to make sure that the recoverable construction elements are recovered, sold and delivered to the customer. This however clashes with the time gap existing between the design and the execution phase in the construction process. In case the customer accepts the architect’s design with reused construction elements, the architect would then book/reserve the construction element for a couple of years. This would force the demolition firm to store the construction element somewhere for the time being. Some demolition firms are adopting a material hub for temporarily storing materials but are realizing that most of them are not sold and are, therefore, deciding to reduce the volumes of material stored in them. Their focus is right now only on standardized (sinks, toilets, cable) construction elements.

Because of this significant time gap between offer and demand, demolition firms take all the risk of “purchasing” assets that will maybe not be sold. This applies in both situations; if they store it in their material hub but also when they make a quotation to a customer with the expectation they can sell something. Sometimes the customer does not even show up and the demolition firm is obliged to demolish it.

Consequently, construction elements that might be of good quality and reusable do not find their way into new buildings because they become available when there is no direct/immediate demand. And are therefore discarded.

Information about future construction and demolition projects is oftentimes available but, because of the lack of standardization of information/data management, processes and governance outlined in the previous paragraphs, the information is not accessible and actionable. Actionable because knowing that a building will be demolished at a specific point in time, coupled with the material passport/BIM information would give more time to demolition and construction companies to match the offer and demand of construction elements. Ideally, the information on recoverable material should be available to both, the construction and demolition firm, 2-3 years before the actual demolition project is initiated.

Timely collaboration between construction and demolition companies could be easily initiated by the customer but, due to factors that were not investigated in this research, this is a very rare situation. All demolition firms have clearly stated that the customer reaches out to them at the last moment and they only look for the cheapest price. Sometimes architects commissioned by the client reach out directly to the demolition firms but, because they tend not to store construction elements, they need to be lucky in having the demolition firm working on a project from which valuable construction elements can be recovered at the time of the request.

So far the supply and demand are working efficiently only where the construction and demolition activities are coordinated and carried out in synergy between the involved parties (or by the same company (see

Quote 11.8)). Not only for better managing supply and demand but also for assessing collectively what construction elements are worth maintaining. A good example is the Bajes Kwartier project in Amsterdam (see Here) which resulted in recovering and reusing 98% of construction elements demolished or preserved from the old structure.

Right now the data/information available and the lack of standards in data management, connected to current construction and demolition practices, cannot sustain full autonomy and facilitate cost-effective reuse and recovery of construction elements.

(see [Quote 11.8] / [Quote 6.6] / [Quote 11.9] / [Quote 6.7] / [Quote 12.0] / [Quote 12.9] / [Quote 13.9] / [Quote 14.4] / [Quote 14.5] / [Quote 14.7] / [Quote 15.1] / [Quote 9.7] / [Quote 16.7] / [Quote 9.8] / [Quote 16.8] / [Quote 16.9] / [Quote 17.1] / [Quote 10.0] / [Quote 10.1] / [Quote 16.6])

Ownership of information/data about buildings' lifecycle

An important challenge that was observed during this research is the ownership of information/data connected to the building. For example, some construction firms create a material passport and BIM for the new construction which is so to say "attached" to the building and handed over to the final customer.

Nevertheless, according to the information provided by the interviewee, customers are not actively requesting this information and do neither keep this information up to date (for example after renovation work). Companies specialized in facility and asset management are, according to the interviewees' insights and experience, focused on the operational part (maintaining the heating system) only. These companies do usually maintain large housing complexes. They are not obliged by law to maintain material passports and BIM models up to date, and private customers are neither. So right now there is no evident incentive forcing these parties to invest resources in maintaining the information updated. Also, the investment for retrospectively making a material passport out of an old building is extremely high.

Despite this, building owners are legally responsible for the correct disposal of all materials embedded in their buildings. As outlined by the demolition firms, by the time they are required to demolish the building, they contact a demolition firm which takes care of dismantling and processing the waste. In all of this, the customer has no clear incentive for requesting and then maintaining a material passport or BIM model up to date.

(see [Quote 10.9] / [Quote 11.4] / [Quote 12.2] / [Quote 10.3] / [Quote 7.9] / [Quote 14.3] / [Quote 15.5] / [Quote 15.9] / [Quote 16.0] / [Quote 16.2] / [Quote 9.8] / [Quote 17.0] / [Quote 17.2] / [Quote 17.3] / [Quote 11.0] / [Quote 12.3] / [Quote 7.3] / [Quote 15.1] / [Quote 15.2] / [Quote 16.4] / [Quote 16.8] / [Quote 16.9])

Designing for circularity

A relevant challenge outlined by demolition firms is that old buildings were not designed with circularity principles in mind. Oftentimes the construction techniques employed in old buildings make it extremely complicated to recover a construction element that might be potentially recoverable and reusable. But the complexity and time associated with recovering and cleaning the construction element might make it not attractive for recovery.

Innovative construction concepts and technologies applied to new buildings are making circularity a more relevant factor, TinyHouse is a good example.

The demolition firms have also outlined how a sort of reusability/recoverability indicator applied to new materials and construction technologies could be interesting and relevant.

(see [Quote 10.6] / [Quote 13.8] / [Quote 14.5] / [Quote 16.1] / [Quote 17.0] / [Quote 17.3])

Lack of experience and standardized collective training

Another challenge that has emerged from this research is the limited experience that the industry has gained, as of yet, concerning material recovery and reuse. The architectural firm specialising in working with reused construction elements has pointed out that sometimes it is difficult to find construction firms that feel comfortable working with reused construction elements.

In the meantime, the demolition companies involved in this research are gaining more experience and are strengthening their skills in both, recognizing what construction elements are cost-effective to be recovered and also which ones are easier to sell. For example, the project manager responsible for compiling the list of recoverable materials needs also to assess the context the material is located in. If, for example, special equipment is required, or it is not possible to utilize the elevator, this is information that needs to be considered for evaluating the recovery process.

This type of knowledge is still very much owned by specific individuals within the company. The demolition firms do not have standardized training about recovery practices for employees, meaning that knowledge can be easily lost in case the specialized person/team leaves the company. This is even more important if we consider that the selling of recovered products is still very dependent on the network established by the specialized person/team.

(see [Quote 13.8] / [Quote 14.5] / [Quote 14.6] / [Quote 15.3] / [Quote 15.4] / [Quote 15.6] / [Quote 4.3] / [Quote 9.4] / [Quote 16.3] / [Quote 9.7] / [Quote 16.6] / [Quote 16.7] / [Quote 9.8] / [Quote 16.8] / [Quote 16.9] / [Quote 17.0] / [Quote 17.1] / [Quote 17.3] / [Quote 17.4])

Sub-question 4: Can Blockchain technology address and tackle these challenges and how?

The following paragraph investigates whether a distributed ledger technology (DLT) combined with a Smart Contract functionality is needed for addressing and tackling the data/information-related challenges identified in sub-question 3. The challenges will be fed into the framework to understand whether DLT technology can be employed and what is the best design option.

The framework requires answering specific questions that on one side might describe the current issue but that intrinsically require identifying a solution. The solution that is intrinsically connected to the answer is based on the requirements characterizing the C&D industry blended with the needs identified through this research.

What has been assessed through this research is that the C&D industry in Zuid-Holland currently operates in a decentralized and disconnected manner characterized by multi-level governance operated by cross-functional teams and involving multiple firms located in different geographical areas. Additionally, the supply chain is extremely complicated and fragmented, with company-specific data-management practices that differ from frim to firm, and sometimes from project to project. Construction and demolition projects are intrinsically complex and require trust for having solid consensus and information exchange.

The current recovery and reuse practices have highlighted other additional or complementary challenges. For instance (see sub-question 3 for more details), the challenges currently faced in Zuid-Holland are the lack of coordinated and agreed-upon methodologies for data management and an aligned vision on the most suitable circularity practices and transition pathways wich together lead to asynchronous project and process management practices. Practically, circularity is interpreted and carried out in different ways. This leads to the unavailability of data/information for making circularity cost-effective, the lack of coordinated efforts and actions, and firms pursuing and enforcing company-specific practices and not industry-wide ones. The lack of an industry-wide strategy leads to company-specific data management practices which in turn lead to fragmented databases, thus limiting the possibility of effective information sharing. In general, the industry is characterized by mistrust between firms wich results in firms collecting and managing data/information within closed databases and without standardized processes. This results in poor information sharing and difficulty in reaching a consensus about data.

An important aspect is that the decision-making process in C&D leaves little tolerance for errors. Minimizing risks is extremely important in this industry. Contract and compliance with these contracts are therefore extremely important. The information/data that is therefore employed for decision-making purposes must be accurate and certified.

With these aspects in mind, the framework's questions are answered one by one. The investigation is structured in 3 phases according to the framework.

Stage 1: Do you need DLT?

1) ***"Do you need to store state?" -> YES***

Relevant information that is required by the C&D industry for cost-effective reuse and recovery practices which is currently unavailable, inaccurate or missing are: ***Specifications of the construction element, quality of construction element, location within the building, geographical location of the building, date of supply/demand, volumes and prices.***

All this data/information can be considered as "states" that are either compiled by a stakeholder, retrieved from a database (ie. From a manufacturer's database), recorded by sensor technology or by multiple sources.

Therefore a state is simply put, a set of information that (be it physical, digital or both) describes the collective state of a system at a given point in time. For example, the state of a distributed ledger encompasses all transactions that have occurred on the ledger since its activation. This allows tracking of the flow of information (and consequently of a physical asset). As explained before, and illustrated in Figure 76, information can be stored off or on-chain, meaning that the transaction accounts (which are added to the blockchain) for only the exchange of a service/product or all information/ data about the construction element (such as specs. Volumes etc).

In the context of reuse and recovery practices in Zuid-Holland, it is evident from the findings that specific states must be stored and kept updated at all times. Right now physical and digital assets are not tracked, information regarding demolition construction states is not recorded and interdependent processes are not interconnected and need manual inputs and data sharing by the participating stakeholders. Often this data is not even present and can therefore not be shared.

As illustrated in the theoretical chapter, buildings keep transforming over time and the information required for decision-making (both on the construction and demolition side) needs to be correct, reliable and verified throughout the entire life cycle of the building. In this perspective, the system requires to store "state" in the form of element-specific information (as outlined above) but also in the form of input and output of construction elements and materials (transactions). A material passport compiled at the time of construction needs to be certified and kept updated at all times. If renovation activities are for example not correctly tracked, the BIM and material passport (digital environment) of a building might not represent correctly its physical status (physical environment). This situation could lead to the same challenges outlined in sub-question 3. Storing the state of the whole system is a fundamental prerequisite for enabling reuse and recovery practices and is therefore deemed an important characteristic.

If combined with sensor technologies, the system could also update the structural integrity of construction elements at all times. This again is a piece of information that should be verified and stored with a methodology that is considered reliable by the whole industry.

2) *"Are there multiple writers?" -> YES*

As identified and outlined in Figure 72 the construction and demolition industry in Zuid Holland involves multiple stakeholders at different points in time and different stages in the supply chain.

Each one of them can run a transaction that will change the status of the DLT. For example, the construction firm might run a transaction with the inclusion of a specific construction element within the new building, on the other hand, a demolition company might record the transaction about his removal. The same could happen during renovation work. Many other more specific cases can be outlined and presented, but the principle is the same.

In general, the C&D supply chain involves multiple stakeholders at multiple points in time and space. Each one can carry out activities that can affect the material composition of the building. All these activities can be regarded as "writing" activities because they trigger a change in the DLT and in the information that might ideally be connected to it.

3) *Can you use an always online trusted third party (TTP)?" -> YES/NO*

Right now there is no recognized or agreed-upon TTP in the Netherlands that could verify and certify all the data/information required by the C&D industry for enabling reuse and recovery practices (see sub-question 3).

Material passports and BIM models are currently elaborated in complete autonomy and at the firm's discretion, also there is currently no national database that collects and verifies this information. In other words, there is currently no database centralizing the construction elements that are embedded in buildings. Information about a building undergoing demolition, or about the initiation of a project is collected and retrievable on municipalities' websites, but there is currently no central database that presents this information.

On the other hand, the Stichting National Environmental Database ("Nationale Melieu Database") (NMD) was founded by the Dutch government to define and maintain an assessment method and an accompanying database for calculating the Energy Performance of Buildings (EPB). This database provides a very extensive list of construction elements with their relative environmental impact values. This can aid the construction and demolition industry with sustainable procurement practices and with assessing in a precise and certified manner, the environmental impact of the building and its relative energy performance. The database is accessible online and can be regarded as trustful (*Link*). But this database would not provide the required information. This information would instead be complementary and used for enabling performance assessment of buildings.

4) ***"Do you want to use a TTP?" -> NO***

The question regards the exclusive use of a single TTP for managing and updating the status of the DLT. As mentioned above there is no TTP in the Netherlands that collects and provides all the data/information required by the industry for cost-effective recovery and reuse.

The NMD provides very useful information and can provide a certification for the environmental aspect of construction elements. Nevertheless, it does currently not provide information about the demolition and construction state of a building, the quality of a construction element, supply and demand volumes and information about the geographical location of the construction element.

In this perspective, it is not possible to use a single TTP for updating the status of the ledger concerning the information flow that is required.

5) *"Are all participants known?" -> YES*

The participants (in this case the stakeholders that might take part in the Blockchain network and DLT) are all known. The reason is deducted from the interviewees' insights and the literature background information about the requirements for conducting construction and demolition projects.

First of all, construction and demolition firms are accountable for the health and safety resulting from their construction and demolition activities. Also, a construction and demolition firm needs to have the needed requirements and permits and must comply with specific laws and regulations for being able to operate in the Netherlands. Additionally, all interactions between construction, demolition firms, customers, suppliers, contractors and distributors must be managed and comply with specific contract requirements. In this perspective, construction and demolition companies must be officially authorized by the government and the participants of the network would by extension be always known and identifiable.

6) *"Are all participants' interests aligned?" ->NO*

As illustrated in sub-question 1, the stakeholders involved in recovery and reuse practices have currently diverse and most of the time-inconsistent interests. For some, the objective is to reduce operational costs, for others might be reducing the environmental impact and for others is to become a pioneer in the industry of material recovery. Even though the overarching interest of acting with environmental and financial sustainability is the same for all the firms, the day-to-day objectives and interests differ.

In this case, specifically, interest is referred to the objective of the action undertaken by the participant to the system and the expected outcome. This relates in other words to the activities that each stakeholder carries out within the supply chain and C&D projects. Some network participants will primarily deal with procurement activities while others with design-related activities. As mentioned in the theoretical background, asset management activities are structured around specific (or set of) objectives. In this case, the interests relating to asset management (be it physical or digital) will not be the same for all the stakeholders. Therefore, it can be stated that individual interests are not aligned.

Stage 2: Which DLT Design Option?

7) *& 8) "Is public verifiability required/wanted?" -> YES*

Public verifiability allows anyone to control and assess the correctness of the status of the DLT. Even though each transaction must be verified by miners, external (to the Blockchain network) users can check each state of the ledger and if the change occurred according to protocol. This has also an implication for the view that each observer can have of the ledger's status. In a centralized system, the observer needs to rely on and trust the central entity regarding the correctness of the data.

According to the challenges outlined in CHAPTER RQ4, private house owners, as well as facility and asset managers, have currently no direct interest in keeping track of and updating information about the material stock of the building. Nevertheless, it is in their interest to be able to review the status of the material stock at any given point in time. The same accounts for a potential buyer of a property or the government for auditing purposes. Such auditing activities can also be beneficial for assessing compliance to tender conditions such as recovering and reusing specific construction elements or employing sustainable materials.

In this perspective, the status of the ledger (for example the material stock of a house or the addition/removal of elements) should be verifiable by the public at any point in time.*

*This is based on the assumption that this information should be in the public domain. Can also be the case that due to data sensitivity or national strategies, this is not desired.

9) "Control functionality on protocol level?" N.a This question is skipped

This question is too specific at this point of the analysis and cannot be answered in detail. The answer provided to this question would affect the outcome of the results.

Stage 3: Constraints

This stage defines the final constraints useful for defining the DLT design options. Due to the conceptual analysis, multiple design options might be possible.

According to the answers provided in Stages 1 and 2, the most suitable DLT set-up is a **Public Permissioned DLT**. In this case, public means that the Blockchain does not necessarily rely on existing infrastructure such as Ethereum, but rather that the Blockchain system and architecture opted for this specific use case is public and not limited to a close circle of users. Permissioned DLT is characterized by a central entity that can provide the authority and permissions to parties participating in the writing operations on the Blockchain network. The reading permissions are instead granted to everyone. This is also the optimum set-up because writing permissions (such as recording the addition or removal of construction elements within a building) must be granted and limited to C&D companies which have the required permits to operate in the market. The reading permissions, instead, are important to be accessible because the information will ideally be important also for facility owners who will employ this information at a certain point in time.

Now it is relevant to outline the constraints and characteristics of the DLT. This part is speculative and based on the findings of the theoretical background and the available data recovered during the interviews. Being these elements are extremely context and system specific, an accurate evaluation can only be made once the objective and governance of the system are agreed upon.

a) **Throughput**: The throughput defines how many transactions/actions can be performed by the blockchain system in a given period. In this specific case no estimate on how many transactions would be needed. But assuming that the Blockchain will be limited to verifying the status of construction projects (in construction/ended/demolition/renovation) the range of daily transactions should not constitute a limitation for the system. Public Blockchain can, on average, handle between 3-20 transactions per second (Xu, X., Weber, I., Staples, M., Zhu, L., Bosch, J., Bass, L., Rimba, P., 2017)

b) **Data storage**: Storing too much information on-chain (within the block hash) can be costly and compromise system performance, and non-transactional data can usually be stored off-chain in databases connected to the DLT. A common practice which could be beneficial for this specific case is to store raw data off-chain (for example in individual databases) and to store on-chain meta-data (fragments and hashes of the raw data). Ethereum technology allows storing arbitrary data of any size, at an average cost of US$0.007 for 80 bytes of data (Xu, X., Weber, I., Staples, M., Zhu, L., Bosch, J., Bass, L., Rimba, P., 2017).

   As illustrated in Figure 76, the off-chain information can be collected and processed and then used as input for triggering the transaction in the Blockchain. Oracles are responsible for converting real-world data in useful data for the Blockchain network, and vice-versa (Nehai, Z., Bobot, F., 2019)

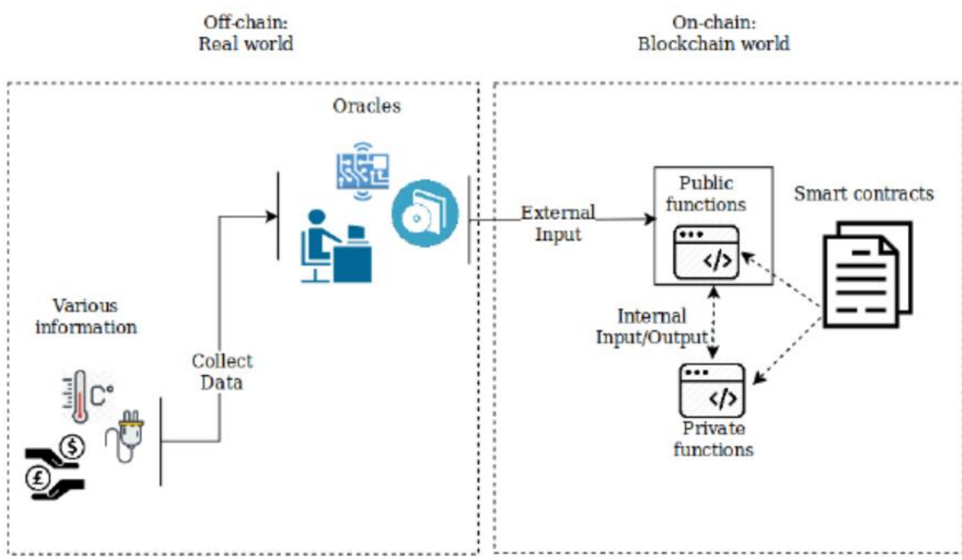


Figure 76 - Communication between off-chain and on-chain (source (Nehai, Z., Bobot, F., 2019))

The off-chain data can be stored and/or retrieved on/from private databases managed individually by each firm. An Oracle can be employed for translating data for the Blockchain network or the other way around can interpret the data from a Blockchain.

c) **Interoperability:** Interoperability is the capacity of the DLT to be connected with other technology stacks. The DLT allows interoperability by connecting smart contracts with Oracles and external interfaces for example. The scope of the DLT is to store data in a permanent and non-alterable way. But data need to be sourced from smart contracts and oracles, which can be triggered manually, via sensors or manual inputs.

   In this specific case, it is desired to allow for interoperability between the DLT, smart contracts , oracles and external databases. The objective is to use smart contracts for certifying the status of a building (whether it is going to be demolished) which updates the DLT and allows the oracle to identify which materials can be retrieved or are now stored in a specific building (more details in the next paragraph)

d) **Privacy:** This constraint needs to be defined based on national guidelines and the collaboration framework opted for by the participating firms. Nevertheless, it has been outlined the need to have secured and transparent data without disclosing who is the owner of these data and projects. In general, Blockchain can guarantee data privacy through encryption and cryptographic hashes as outlined in the theoretical background.

e) **Smart contracts**: As outlined in previous paragraphs, smart contracts can be employed for automating transactions based on specific conditions. In other cases, smart contracts can be used as triggers for more complex operations. Smart contracts are not necessarily linked to legal contracts.

   In this specific case, smart contracts should be employed in 2 ways:

   First, to certify the status of a building (in construction, demolition, renovation) and unlock construction elements within the BIM model.

   Second, when a construction element is chosen and purchased, the information relative to the purchase, price range and logistics is included in a smart contract which, after being accepted would update the DLT and through the Oracle, the individual databases with the final material stocks. A Turing (see Appendix I) complete scripting structure will allow the creation of customized and adaptable scripts. In this way, all databases would contain the same information about materials tocks of the buildings through the transactions recorded in the DLT.

f) **Cost structure**: With the adoption of public DLT (public as in already existing), users must pay a fee for each transaction. In private ones, the costs are only associated with the initial investment and not with transaction fees. In this case, it is expected to build a Blockchain network from zero and make it a Public Permissioned DLT. Therefore the costs associated with its operation would be related to the initial investment only.

A concept integrating Blockchain, DLT, Smart Contracts and BIM

The following sub-paragraph provides a first concept on how a Blockchain structure can be implemented in Zuid-Holland and thus address the challenges associated with the reuse and recovery of construction elements. The structure is based on the outcome of the previous paragraph.

One important premise is that Blockchain alone cannot solve all the data-related issues that characterize reuse and recovery practices in Zuid-Holland but it requires a coherent and structured integration with a digital asset management tool such as BIM. To make the integration between BIM, DLT and Smart Contracts technology work, level 3 in BIM (see Figure 32) should be reached. This is currently not the case in the Netherlands. This is further discussed in the discussion chapter.

The concept hereafter presented entails the adoption of a **Public permissioned DLT** which integrates Smart contracts, DLT, iBIM (integrated BIM) and Oracles. Being the Blockchain Public permissioned DLT, everyone with the right software can access and read the information in the DLT but needs permission for executing writing tasks (like initiating a smart contract). This is intentional. C&D is a high-risk industry and firms need to have the required permits to operate. Likewise, house or facility owners must be registered in the national cadastre. In this perspective, all stakeholders who are willing to access the Blockchain for writing purposes, need to be granted access and be attributed with a unique ID. Marketplaces and webshops as currently operated in the Netherlands are not included in the solution framework because information stored and handled within BIM is regarded to have a higher level of accuracy and allow for more collaboration between C&D companies. The main objective of combining these technologies is to interconnect C%D processes and allow for consistent data management practices and the sharing of data/information in a reliable but anonymous way. Figure 77 provides a graphic illustration of the Blockchain concept developed for this research.

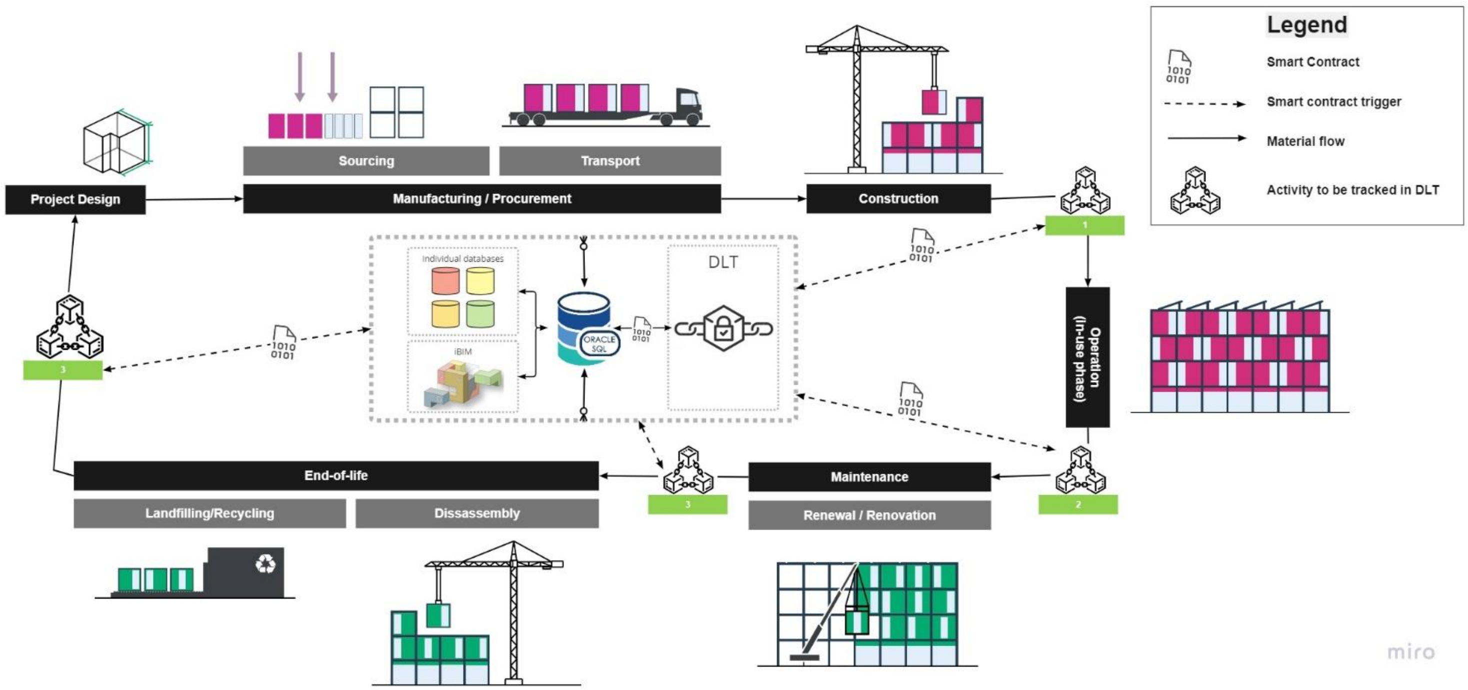


Figure 77 – Blockchain, DLT, Smart contract and BIM integration (concept diagram)

The structural information gaps identified in the literature (see Figure 21) are the same as the ones identified in this research. These information gaps are 3, between the **construction and operation phase**, between the **operation and maintenance phase** and lastly between the **end-of-life and project design** phase. The Blockchain configuration conceptualized and hereafter presented focuses primarily on addressing these issues. To simplify the presentation of the concept, the Blockchain processes are illustrated in a sequential way (1 -> 3) but these should be seen as processes that might occur simultaneously throughout the supply chain.

Process #1 Construction -> Operation

The first step (see Figure 78) focuses on storing the BIM-related information after the completion of the construction project. The firm should in this case generate a smart contract that contains the ID of the building (XXX) of the construction elements (W/C/D), their design arrangement (W3/C5/D8), together with all permits that certify the compliance of the construction with the construction regulations in place.

The smart contract would, with the aid of the oracle, verify against the databases that the information is correctly reported (ID of construction elements match and all permits are certified) and subsequently generate an additional smart contract to store the information in the form of a transaction in the DLT. The oracle could even retrieve information from the national "Nationale Melieu Database" and assess the Energy Performance of the Building (EPB). The DLT would only record a unique hash (**# WDC-12345-W1w2w3w5-xcvnbm #)** that identifies the construction elements in the different databases and the iBIM models and label their status as "In use".

The objective of this activity is to guarantee that the information stored in the collective iBIM models is certified and most importantly correct. The lack of certified data can be a limitation to circularity practice and pose risks in the decision-making process of C&D companies.

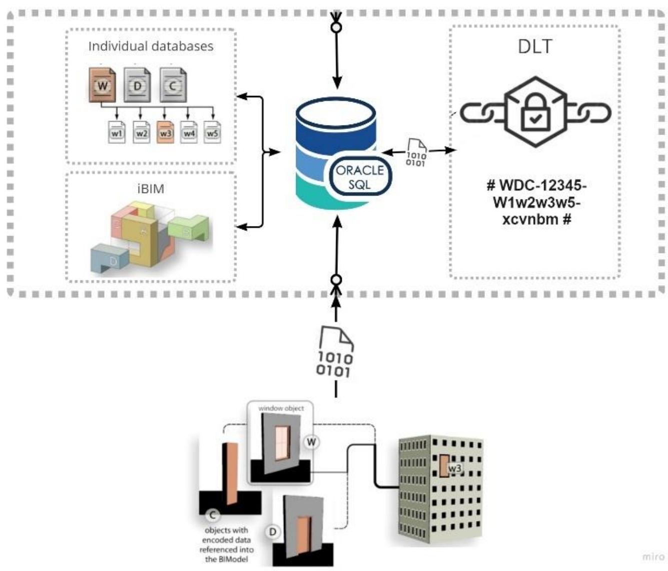


Figure 78 – Tracking of construction -> operation process (some images sourced from (Succar, B., 2009))

Process #2 Operation -> Maintenance

In this case (see Figure 79) the facility owner or project commissionaire would record the initiation of renovation activity. This can be done with a smart contract indicating the ID of the building, the ID of the construction elements that will be replaced (W3), the price range (if bidding is enabled), the time range and the location. Additionally the smart contract initiator must indicate in the smart contract (similarly to process #1) the new construction elements that will be used for replacing the old ones. These exchanges must be tracked and all construction elements must have a unique identifier.

Once the smart contract is processed by the oracle and the information is verified against the information in the databases associated with the unique hash (**# WDC-12345-W1w2w3w5-xcvnbm #) generated in process #1,** a new hash is recorded in the DLT **(# W-12345-W1w2w3w5-xcvnbm #).** At this point, two things occur simultaneously:

1) The new construction elements are linked to the building ID and the collective databases are updated + the iBIM stores this new information.
2) The old construction elements become available in the iBIM model. Their status is now "available". With specific dashboards, designers can retrieve the 3D model of the construction element and verify

all the information added by the project commissionaire (price, availability and location + technical specs which are already part of the BIM design), assess if it would meet their requirements and decide whether they want to purchase it. In case the element is purchased (either directly or with bidding), a new smart contract is initiated by the architect/construction firm following the steps illustrated in Process #1. The construction element will be delivered or collected and installed in the new building. The DLT would record the transactions and the databases would record that the construction element is now part of this new building.

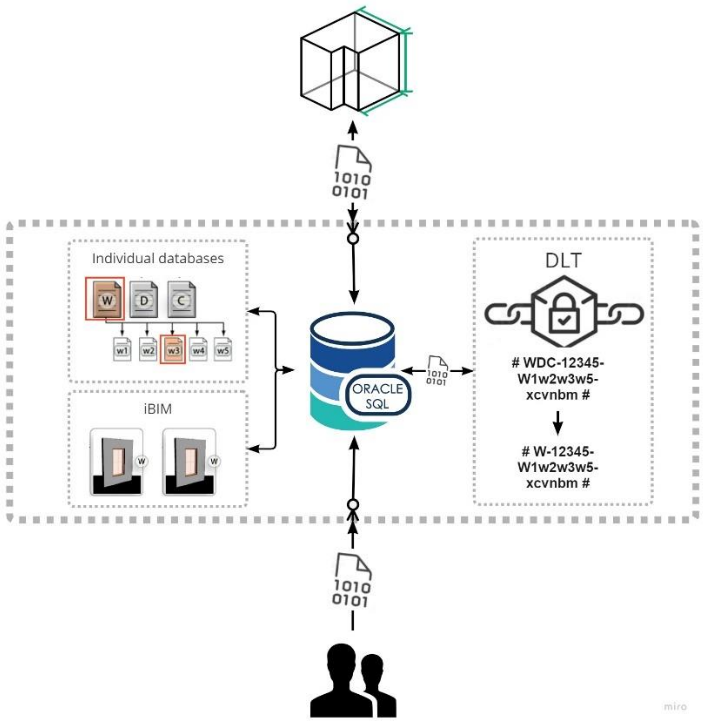


Figure 79 – Tracking of Operation -> Maintenance process

Process #3 End-of-life -> Design / Manufacturer

This process resembles closely process#2 and it includes elements of process#1. The main difference, in this case, is that the owner of the building initiates a smart contract when he/she is certain that the construction will be demolished. The smart contract will still be indicating the ID of the building, the ID and the pricing of all the construction elements (Oracle could even be attached to external databases for automatically determining the best price for the construction elements), the location and the time range for collecting them. This process can be initiated simultaneously by multiple house owners.

If the information in the smart contract is verified against the databases associated with the unique hashes generated throughout the lifetime of the building, a new hash is recorded in the DLT. At this point, the status of all construction elements present in the building of reference changes to “available”. The 3D model of these elements can be accessed through specific dashboards in the iBIM environment.

Designers and manufacturers can simultaneously access the iBIM environment, review the construction elements and if interested decide to purchase them (see Figure 80). In this case, the buyer must indicate in the smart contract whether the construction element will be reused in an existing building or not. In the former case, the steps are similar to process#1 while in the latter case the steps of process#1 will be initiated as part of a new construction project.

When the building owner selects the demolition firm, he/she can provide this firm with a concise report on which construction elements must be recovered and stored, thus facilitating their disassembly work and reducing costs associated with the demolition

Overall this system can guarantee that the metabolism of construction elements entering and exiting the built environment is tracked and verifiable by all the participants.

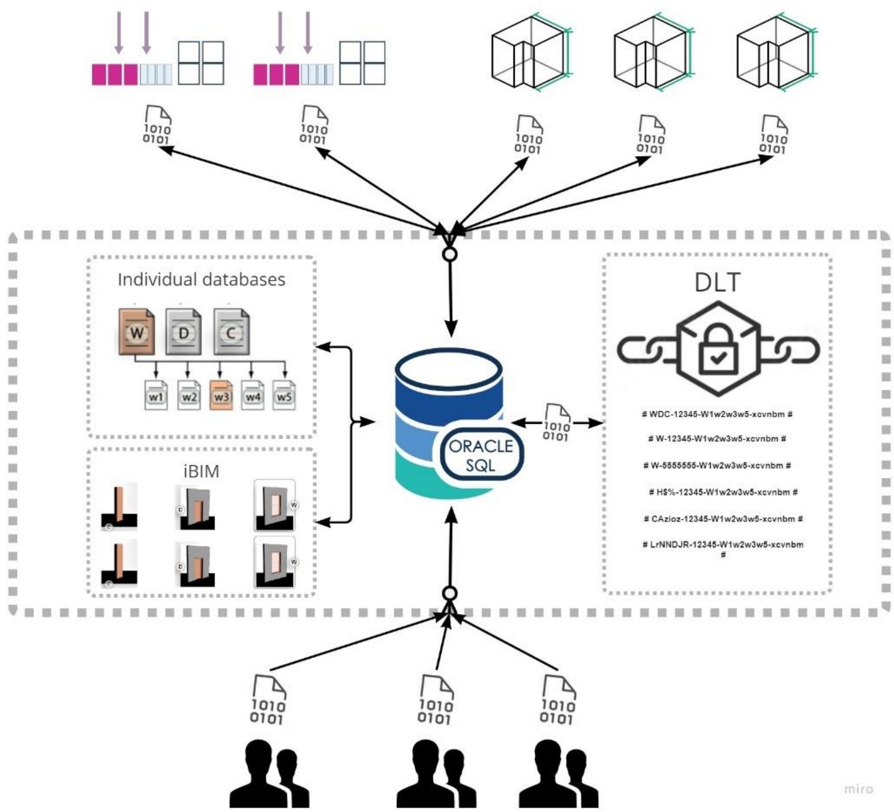


Figure 80 – Tracking End-of-life to design/manufacturer process

Summary

The current material metabolism in the Netherlands, as illustrated in Figure 16 is mainly linear with a large number of resources being downcycled to infrastructure projects. The Blockchain concept outlined above will address the challenges identified in the interviews with the construction, architect and demolition firms. Specifically, the problem and solution matrix is outlined below.

Table 19 - Problem and solution matrix

Problem/Challenge/Issue	Solution
Compliance/accountability/tracking	DLT requires tracking each activity that is mapped and designed in the Blockchain system
Quality of products	NOT SOLVABLE -> at the moment it requires manual intervention or application of sensor technology. Sensor technologies could be applied to the construction elements

	and input specific information to the smart contracts. This option is not included in this proposal
Misaligned project/process management	The framework BIM + Smart Contracts + DLT intrinsically requires collaboration without the need to centralize data. Everyone can keep their process but data management must be coordinated (more in the discussion chapter)
Discordant and inconsistent data management practices	As above
Unavailable and/or inaccurate information/data	Information will be stored in the individual databases and the DLT + Smart Contract will track the movement of construction elements throughout the supply chain.
The mismatch between offer and demand	This will no longer be an issue because the information will be readily available thanks to automated processes labelling materials as "available" even before being demolished
Ownership of information about the building	Information will be traced back to the owner through the personal IDs
Designing for circularity	A long-term effect of having fully circular material management is to encourage designing for circularity because reverse logistics practices will be strengthened and the additional costs for this material will be amortised
Lack of experience and standardized collective training	Once this approach will become a standardized one, training and experience sharing will be the norm.

The approach presented in the previous paragraphs will facilitate the decision-making process concerning material recovery and reuse. This will not be limited to the end-of-life of buildings but also to their use phase because construction elements will be tracked throughout the whole life cycle of buildings.

The benefit is moving from a push effect where demolition companies need to pro-actively map construction elements and reach out to construction and architect firms for placing orders, to a pull effect where the construction and architect firms have sufficient up-front information for evaluating and purchasing the construction element and thus force the demolition company to carry out selective demolition. This will inevitably unlock more collaboration opportunities. As illustrated in Figure 81, the current approach links different firms to the same project but there is no intra-firm/project connection because there is no industry-wide data management approach that facilitates the information sharing that would enable such a form of collaboration

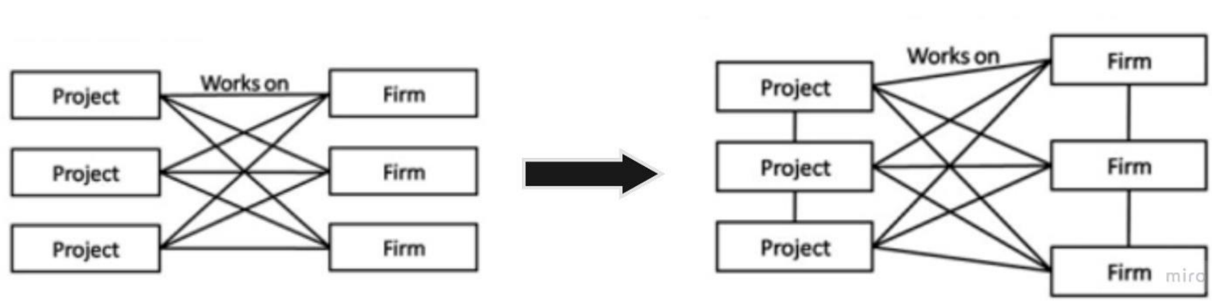


Figure 81 – Moving from a firm-project linkage to an intra-firm and intra-project linkage (adapted from (Behera, P., Mohanty, R. P., & Prakash, A., 2015))

The integration of BIM, DLT, and Smart Contracts (and ideally sensor technologies) will enable a digital twin between the physical and digital environment. The objective is to correlate the physical activities with digital ones, thus assuring that all processes are correctly tracked and that data/information is stored.

In this way construction elements will be intrinsically embedded with digital data and their movement will generate information in itself. The digital twin will allow information sharing to occur between firms as well as between projects. For instance, resources that become available from one project can be immediately streamed to another project. This requires firms to be able to access each other's data. As outlined in the interviews, firms are very resistant to data sharing which can lead to market insights by competitors. Therefore the data sharing must be made accessible while maintaining full privacy. This is

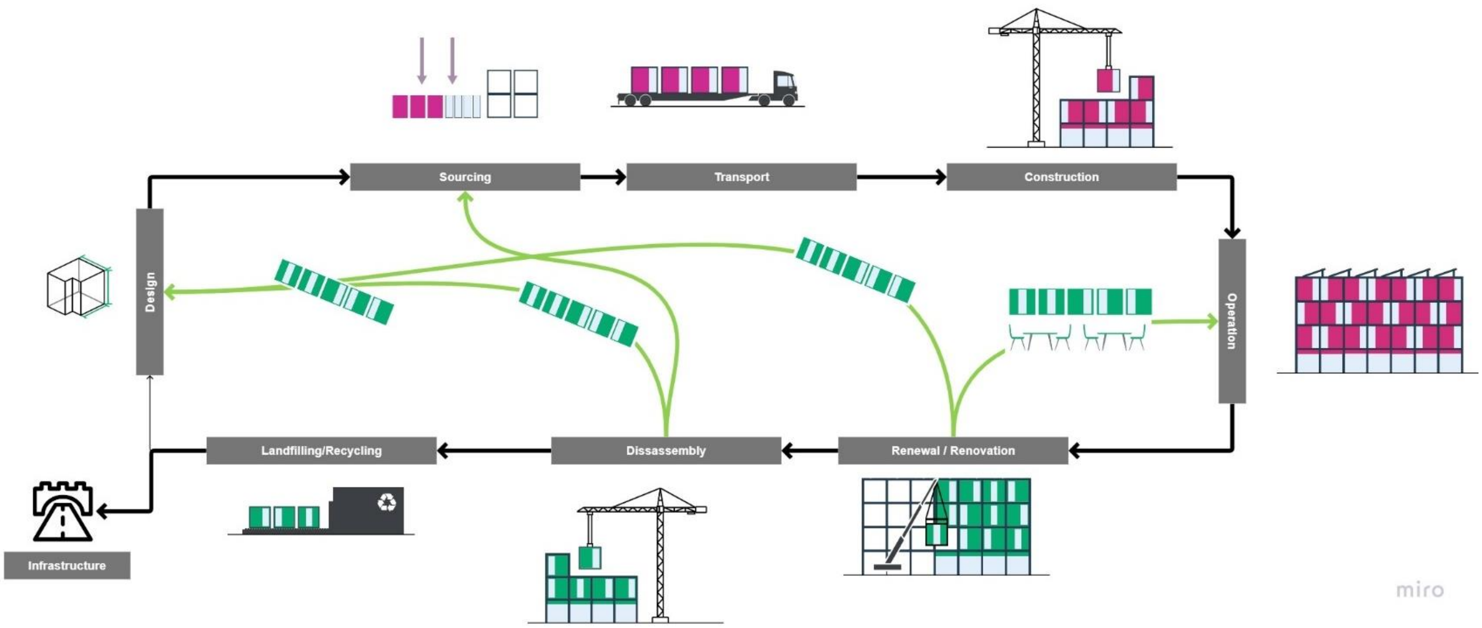


Figure 82 - Collaboration and intra-firm and intra-project material sharing

the main objective of employing DLT and Smart contracts in combination with digital asset management tools such as BIM. An additional advantage of a digital twin is that the material stock will be known and this can benefit also the government and other institutions. Material stocks will be guaranteed and certified.

Discussion

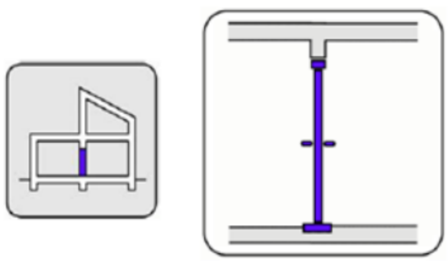
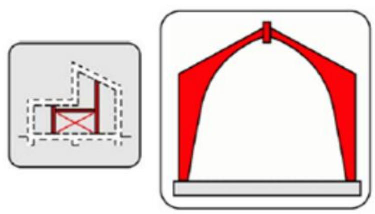
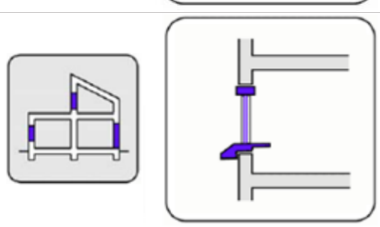
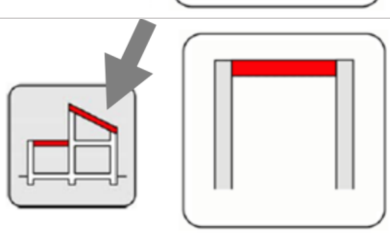
The following chapter correlates the results of this research to the theoretical background and provides additional points of reflection that can be derived from the findings.

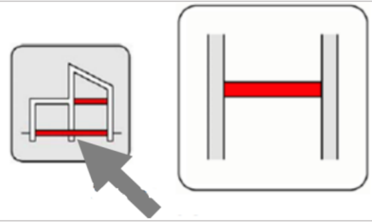
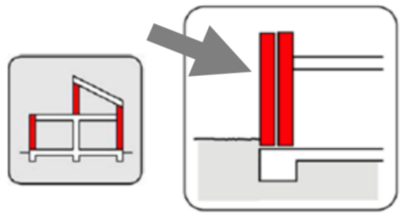
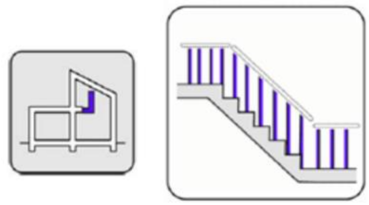
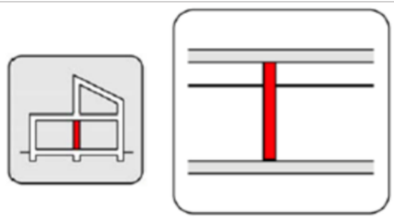
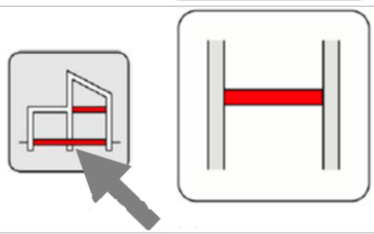
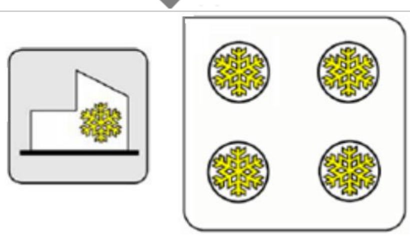
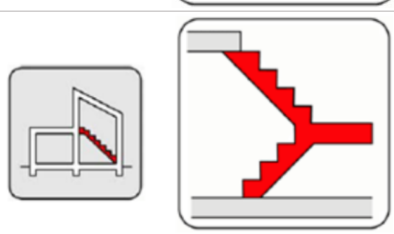
Construction elements of interest

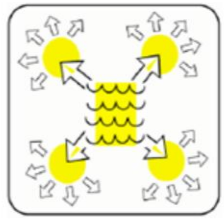
An interesting observation is the comparison of the high-value construction elements illustrated by (SGS, 2021) and outlined in Table 2 and the ones identified as high value by the interviewee (see Table 16). As illustrated in Table 20, 5 out of 10 construction elements were regarded as interesting by the interviewee. The remaining 5 were never mentioned by them during the interviews.

On the other hand, the list of the construction elements mentioned in Table 16 by the interviewee is more extensive, including 19 construction elements/materials in total.

Table 20 - Analysis of high-value construction elements mentioned by the interviewee

	Sketch	**Correlation with findings in Table 16**
Doors		Mentioned several times
Construction		Mentioned once but very complicated to recover
Frames		Mentioned several times
Insulation (roof/floor/external wall)		Mentioned several times

		
		
Railings		Never mentioned
Internal wall		Mentioned in the form of bricks
Floors		Never mentioned
Cooling systems (air conditioning)		Never mentioned
Stairs/Ramps		Never mentioned

Radiator/Heater	 	Never mentioned

Some considerations are necessary. First of all the methodology adopted by (SGS, 2021) included more participants that were more evenly distributed in the Netherlands while this research included fewer participants and all operating primarily in Zuid Holland. Also, their research included multiple research institutes, municipalities and consultancy firms. This research instead was limited to project managers and/or sustainability advisors of construction, demolition and architect firms.

As mentioned by several interviewees the perception of opportunities and limitations with regard to reuse and recovery differs significantly when moving from a theoretical to a practical plane. Consultancy firms, for instance, suggest in the material passports they compile for their customers that a large number of construction elements/materials can be easily reused (see Quote 17.0). The demolition company must then demonstrate to the customer that certain elements are technically impossible to recover or the costs are so high that it is not worth doing it.

In conclusion, the list of construction elements/materials listed in Table 16 may differ from the one compiled by (SGS, 2021) for two reasons:

1) The stakeholder's expertise is different and therefore the perception of possibilities and challenges differs accordingly
2) The interviewee taking part in this research are all, to a certain degree, currently involved with reuse and recovery practices and have therefore provided their insights based on what is practically happening rather than what is theoretically possible.

Another interesting observation is that certain construction elements/materials and applications listed by the interviewee and summarized in Table 16 do not fall under the reuse and recovery category. A clear example is concrete and asphalt. Several interviewees mentioned these as interesting materials to be recovered and reused and that this is what they are already doing. Nevertheless, from their description, it was evident they were referring to recycling (mostly downcycling for infrastructure) practices and not reuse and recover. While reading out the questions to the interviewee it was made sure that the concept of reuse and recovery was clear to them. Therefore I do not believe this has to do with a methodological flaw but rather with a misconception of waste management practices and the waste hierarchy.

Strong synergies have instead been observed between the Sankey diagram illustrated in Figure 16 and the high-value construction elements/materials listed by the interviewee. Most interviewees have for instance mentioned bricks, wood and concrete. The reason is that most lightweight residential buildings in the Netherlands apply the same construction techniques and design as well as the same construction elements/materials. Looking at random pictures of residential buildings in the Netherlands, it is very difficult to discern their location (see Figure 83, Figure 84, Figure 85, Figure 86). In other words, lightweight residential buildings have a standardized design and material composition in the Netherlands. The Sankey diagram validates this observation, most of the brick, concrete and wood mass is for instance streamed in light-weight residential buildings. This is extremely encouraging from a reuse and recovery perspective. Unfortunately, as illustrated in the Sankey diagram the large majority of recovered construction waste is currently downcycled even though the standardized material composition and design of residential buildings in the Netherlands could facilitate and even encourage recovery and reuse practices.

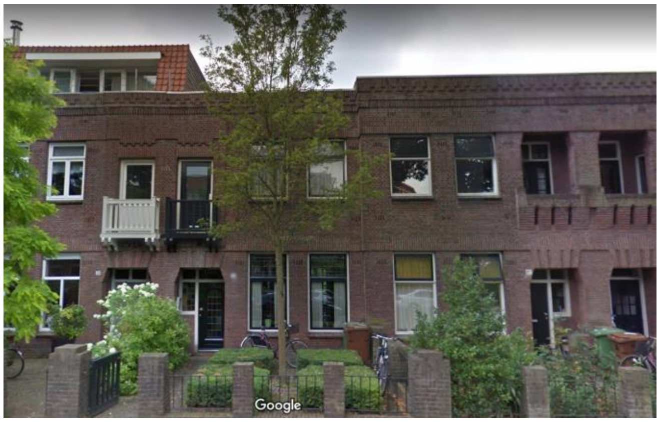


Figure 83 - Light-weight residential building in Breda (source (Google, Google Maps, n.d.))

Figure 84 - Light-weight residential building in Schiedam (source (Google, Google Maps, n.d.)

Figure 85 - Light-weight residential building in Groningen (source (Google, Google Maps, n.d.)

Figure 86 - Light-weight residential building in Enschede (source (Google, Google Maps, n.d.))

Challenges and opportunities characterizing reuse and recovery practices

The challenges faced in the C&D industry concerning reuse and recovery are consistent between the theory and the interviews.

The overarching challenge is the lack of accurate information which prevents an effective information flow to occur, thus leading to structural information gaps along the supply chain and throughout the building's lifecycle as illustrated in Figure 21. Additionally, reverse supply chains are not structurally present, leading to additional costs and investment of resources for recovering and reusing construction elements/materials. This is primarily because construction, demolition and architect firms are still bound to business models inherited from linear economic models and material management as well as data management practices which are carried out within such framework (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021) (Munaro, M. R., Tavares, S. F., Bragança, L., 2020).

A substantial difference between the insights from the literature and the findings obtained in this research is the aspect dealing with market demand. While (Hobbs, G., Adams, K., 2017) and (Park, J., Tucker, R., 2017) indicate that low market demand is hindering reuse and recovery practices, the insights gained during the interview are diametrically opposite. The Covid-19 pandemic and the recent war in Ukraine have contributed to increasing prices for commodities in a significant way which is in turn boosting the demand for reused construction elements. Therefore market demand is now becoming an enabler for this transition. This is coherent if we consider that the literature mentioned in this research was pre-pandemic and antecedent to the start of the war.

The disruption of the supply chain as a consequence of the Covid-19 pandemic coupled with the recent Ukrainian war is resulting in record prices for gas (see Figure 87) and are also affecting the prices of commodities (Simon R. ; Andrew B., 2022).

Figure 87 - Natural gas price (EUR/MWh) evolution (source (Tradign Economics, 2022)

As illustrated in Figure 88, Figure 89 and Figure 90, the costs for important materials adopted in construction, soared significantly from 2020 onwards. Lumber and steel are only now reaching back to pre-pandemic prices, but the effect of such price increments will take time to be metabolized by the industry. As indicated by (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016) some steel producers like Tata Steel, have commissioned research to assess the benefit of reusing steel in buildings rather than recycling it. Surprisingly, economic savings ranged from 6-27% for warehouses, 2-10% for whole constructions and 9-43% for offices. In this optic, enabling reuse practices, at least for steel, could have positive economic repercussions for house owners.

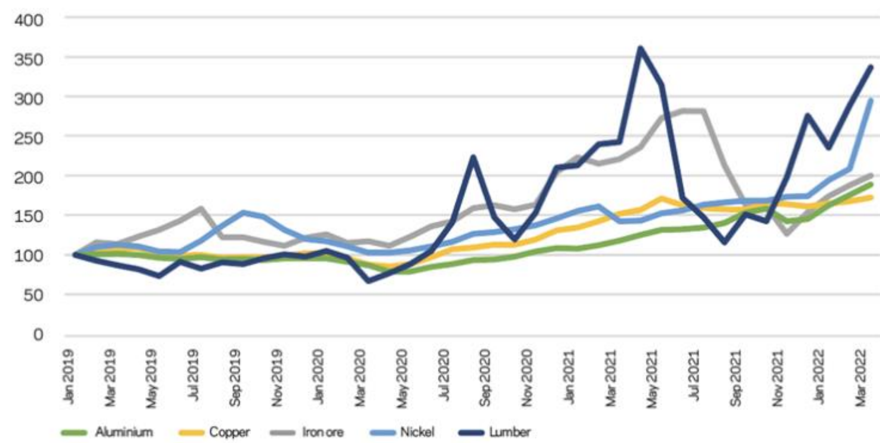


Figure 88 – Commodity prices indices 2019-2022 (source (Simon R. ; Andrew B., 2022))

Figure 89 – Lumber price (USD/1000 board feet) evolution (source (Trading Economics, 2022))

Figure 90 – Steel price evolution (source (Trading Economics, 2022))

The construction market has globally experienced constraints in resource availability, disruption and significant delays in material delivery and rising prices which have challenged firms in delivering their project at the original budget. Besides the prices increase, the construction supply chain was not prepared for sudden supply chain disruptions, leading to reduced inventories and the build-up of extreme delays in deliveries. The volatility of energy prices and the increasing prices for shipping containers di only aggravated the issue (Simon R. ; Andrew B., 2022).

Additionally, the last summer has come with unprecedented heat waves and few rainfalls which have contributed to Europe's drought. According to European Drought Observatory (EDO), this was the worst drought in the last 500 years (Philip B., 2022). Plunging water levels in European rivers will add more challenges to the recovery of industries. In Germany for example, the industry lobby groups have warned that the industries will have to reduce or stop production completely as the water levels of the Rhine will no longer guarantee the transport of cargo. On August 16th, Rhine's water levels next to the Dutch border (Emmerich) dropped by 4cm in just 24h. Shifting cargo transport to rail or road transport will take time and will come with additional costs say industry experts (The Associated Press, 2022).

In this regard, Holger Loesch (head of the business lobby group BDI) stated that: "*It's only a question of time before facilities in the chemical and steel industry have to be switched off, petroleum and construction materials won't reach their destination, and high-capacity and heavy-goods transports can't be carried out anymore*" (The Associated Press, 2022)

Drought and heat waves are only expected to become more frequent in the future. This situation will further impact commodity and energy prices. The industry will need to find solutions to this issue (The Associated Press, 2022).

The impact of the drought will put further pressure on energy prices. By moving away from Russian gas, Europe has reembraced coal as a means of generating energy. But due to the low depth of rivers, ships can only run at 50% of their capacity. Also, the France Nuclear Energy regulator (EFSA) has warned that the lower level of rivers will directly affect the performance of nuclear plants. Hydroelectric energy generation was also hit hard by the drought. The lack of stored water reservoirs and the drought forcing the preventive release of the remaining reservoirs to avoid salt to penetrate the river is only making the energy issue more significant (Ariel C., 2022).

In a study conducted by (Memon, A. H., Rahman, I. A., Abdullah, M. R., Azis, A. A. A., 2010), it has been demonstrated that incorrect planning and scheduling of work execution and material delivery (which might be correlated at times) are among the most severe factors affecting construction costs. This has also been confirmed by the interviewee.

Energy price increases and the uncertainty for large manufacturers will exert even more pressure on the construction industry. In this optic, reuse and recovery practices could play an even more important role in the future of the C&D industry. Market uncertainty and unstable supply chains due to geopolitical reconfigurations might make prices of virgin material soar significantly and at times even disrupt their supply. Urban mining could play an important role because it would allow the sourcing of resources locally or regionally. As mentioned by the OECD, supply chains should be made more resilient and efficient by focusing on strategies that allow for procuring resources locally and shortening supply chains (Organisation for Economic Co-operation and Development (OECD), 2020).

This situation of sudden supply chain disruption recalls the "Strategic and Critical Materials Stock Piling Act of 1939". This was a law enacted by the, at the time, president of the United States Franklin Roosevelt whose objective was to purchase and stockpile 42 strategic critical raw materials considered essential for producing military equipment. Similarly to the current supply chain disruption, the war affected the supply of important resources that were deemed important for the economy as well as for the continuation of the war (Wikipedia, 2022).

Construction is an extremely important industry for the socio-economic stability of a country and as outlined in the previous chapters, the Netherlands is already struggling to keep up with the housing demand (Circle Economy, Metabolic , C-creators, 2022). Sudden supply chain disruptions might only worsen the situation. Similarly to the "Strategic and Critical Materials Stock Piling Act of 1939" I think there might be a necessity in the future to have comprehensive plans for managing the supply of resources that are important for key industries. This strengthens the need for correctly mapping the resources present in the industry and having strategies in place that might allow for mining and keeping them in closed loops within society. Today, digital asset management tools can facilitate this tracking work, however, a comprehensive and long-term plan and strategy must be implemented to make a digital twin work. This is further discussed in the next sub-chapter.

The adoption of DLT, Smart Contracts and BIM for enabling a digital twin

The solution presented in sub-question 4, can potentially lead to the establishment of a digital twin in the C&D in Zuid-holland. Nevertheless, some considerations must be made because the solution presented requires some pre-conditions that, with the current state of the art in terms of data management practices and national digitalization strategies, would prevent its effectiveness.

First, the adoption of a digital twin which combines DLT, Smart contracts and BIM can be a comprehensive solution for dealing with the structural gaps characterizing the information flow within the C&D presented in Figure 21. The structural holes identified by (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021) reflect the findings of this research because similar structural holes are currently characterizing the information flow in the C&D industry in Zuid-Holland.

Digital platforms have been regarded as suitable information brokers by these researchers. The combination of DLT, Smart Contract and BIM can indeed be a viable solution because their integration allows for addressing multiple challenges concerning information flow (European Construction Sector Observatory (ECSO), 2021). It guarantees the validity and reliability of data without disclosing the identity of the stakeholder behind the information, thus guaranteeing privacy while making the information transparent. This is extremely important considering that one of the reasons for not sharing data (according to the interviewee) is the direct market insights that competitors can gain.

Additionally, DLT and Smart Contracts can help in digitalizing bureaucratic procedures while certifying the validity of the information. In other words, construction and demolition permits can be digitalized and made official by the competent authorities and consequently update the status of construction materials from "in-use" to "available". The integration of these systems can therefore guarantee the flow of information and make sure that this information can be used for driving decisions (purchasing a construction element that will become available in 1 year) and assessing contract compliance. This is extremely important because if a designer would base the construction budget on the reuse of certain construction elements, he/she needs to have the guarantee that the construction element will indeed become available at a specific point in time and therefore that the demolition activity is confirmed to occur.

This leads to the second point of this discussion. The solution presented in sub-question 4 requires as a pre-requisite the adoption of BIM for designing buildings. Two points will be discussed hereafter, the adoption of BIM for old buildings and its adoption for new ones.

BIM for old and new buildings

Old Buildings:

According to the interviewee, demolition activities in Zuid-Holland are currently focusing on buildings from the 70-80-90s that do not have a BIM model associated with them. Therefore the solution presented in sub-question 4 cannot be implemented right now as there is currently no BIM model available.

(Kovacic, I., Honic, M., 2021) is testing a method that would allow obtaining an "as-built" BIM model by employing laser scanning technologies (photo/videogrammetry), ground penetrating radar (GPR), modelling and BIM. This method is not limited to geometric representation or the mapping of surface material, but it focuses on obtaining a detailed material composition of the building together with an assessment of its status. As illustrated in Figure 91, (Kovacic, I., Honic, M., 2021) have elaborated a method named Integrated data assessment and modelling (IDAM) that combines modelling and digital scanning technologies. GPR technology can assess the material composition of the building while laser scanning technology helps in acquiring its geometric structure, this information is modelled and streamed into a BIM model in which each construction element is assigned a unique ID. The result is an "as-built" BIM model and a comprehensive database with all construction elements/materials contained in the building.

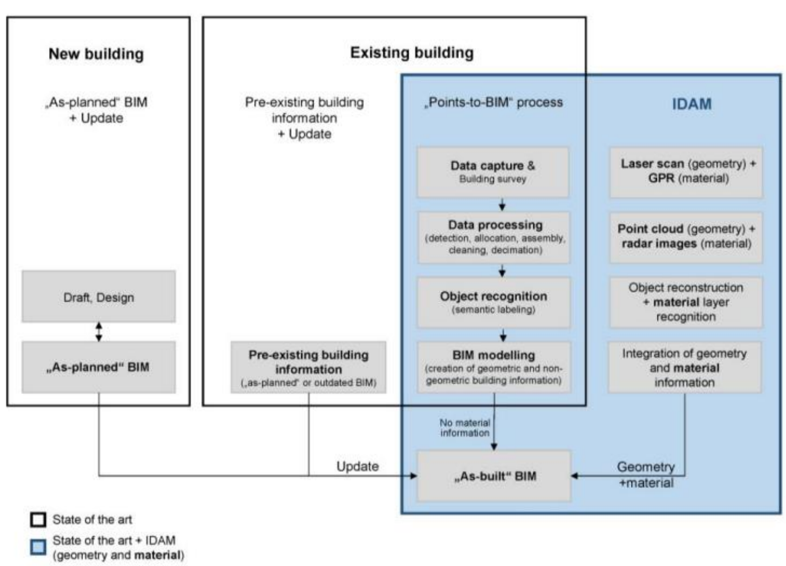


Figure 91 - BIM + Integrated data assessment and modelling method (source (Kovacic, I., Honic, M., 2021))

The results of their approach are quite interesting. Laser scan allowed to obtain of a point cloud map of the building (see Figure 92) while the GPR allowed an overview of the material composition of the building (see Figure 93).

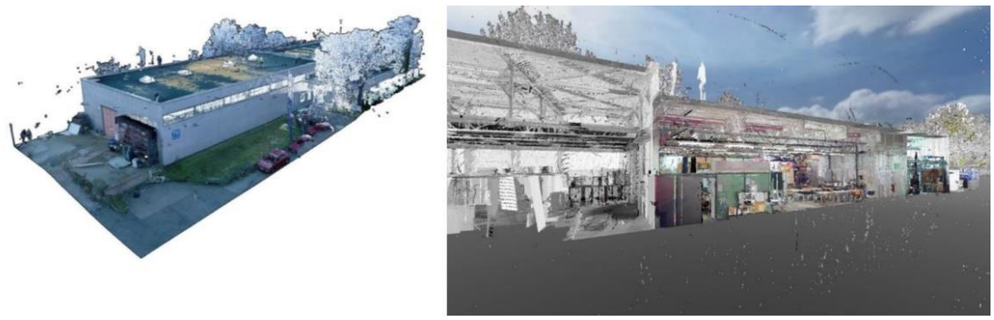


Figure 92 – point cloud map resulting from laser scan technology (source (Kovacic, I., Honic, M., 2021))

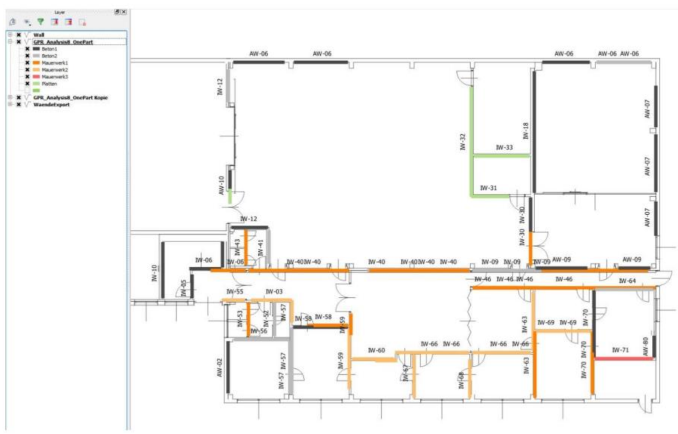


Figure 93 – Results of the GPR scan (source (Kovacic, I., Honic, M., 2021))

GPR can recognize the materials based on their absorption properties with the difference between transmitted and received electromagnetic waves. Based on this physical property the research team can have a preliminary assessment of the material composition, this requires to be triangulated and processed with other data (such as insights from demolition experts) to obtain an exact assessment of the material composition. Based on the thickness and material composition it was possible to create a multi-layer and ID-based material database within BIM. The overall framework of this approach is illustrated in Figure 94.

Although the technology does not allow for full automatization yet, it provides a feasible approach for composing BIM of old buildings in the Netherlands. Considering the standardized design and material composition of Dutch residential buildings (see Figure 83 to Figure 86), the approach could be quite efficient and accurate.

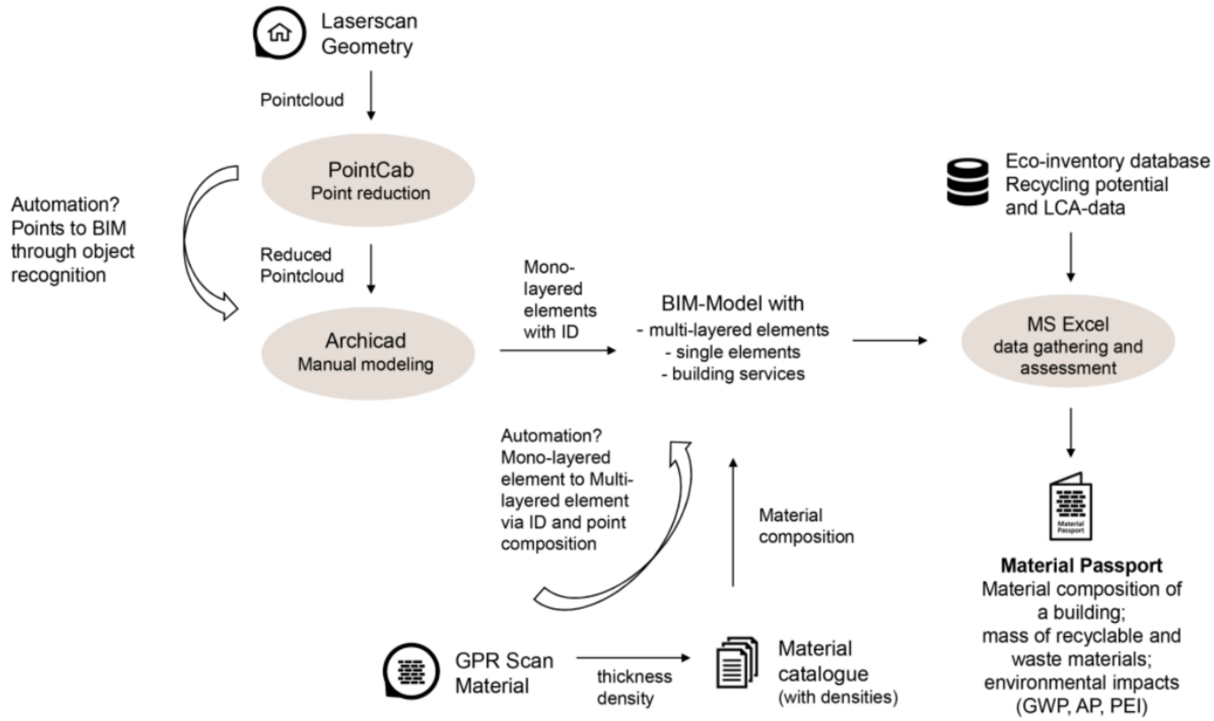


Figure 94 – The proposed framework for using BIM and IDAM methodology for generating "as-built" BIM and ID-based material passport (source (Kovacic, I., Honic, M., 2021))

Having a detailed BIM model is a fundamental pre-requisite for enabling a digital twin and for merging DLT, Smart Contracts and BIM technologies.

New buildings :

A clear outcome of the interviews is that construction firms in Zuid-Holland are not consistently utilizing BIM for developing their projects. This is a big issue for future developments of a digital twin because it will pose the same situation and challenges faced now, with the difference that 3 decades ago BIM was not available to architects and project developers.

Besides an inconsistent adoption, the Netherlands has no industry-wide standard methodology on how to use BIM, neither is BIM a mandatory requirement for projects nor public projects (European Construction Sector Observatory (ECSO), 2021). For instance, BIM and material passports are compiled at the firm's discretion.

A survey conducted by the (European Construction Sector Observatory (ECSO), 2021) has illustrated how BIM is utilized only by 29% of construction companies while 61% have never used it before. BIM is so far being primarily adopted by large companies and very little by small-medium enterprises. This has also been observed in this research's findings. Also, the adoption is limited to the design and execution phase, and rarely during the operation phase. This is corroborated by the research conducted by (Wijewickrama, M. K. C. S., Rameezdeen, R., Chileshe, N., 2021) and illustrated in Figure 21. BIM can instead contribute to the C&D industry throughout the entire building's life cycle as illustrated in Figure 95, meaning that its full potential has not been harnessed yet.

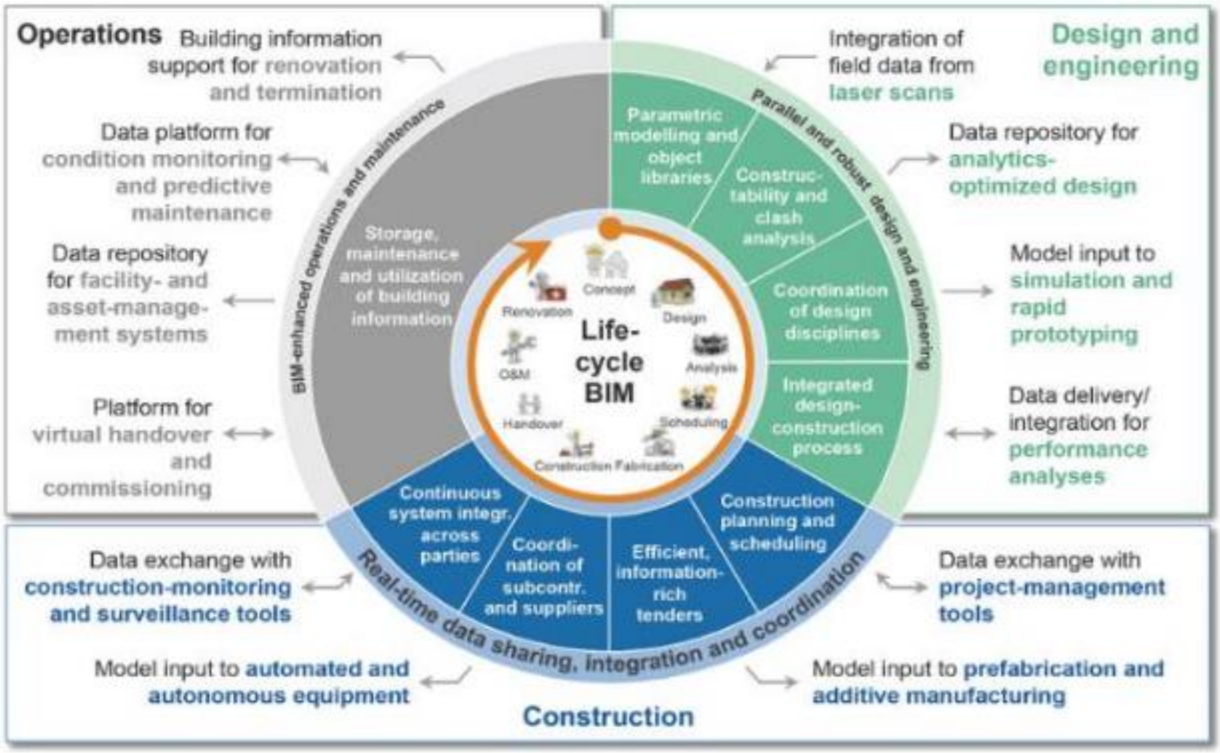


Figure 95 -Application of BIM through the building's life-cycle (source (European Construction Sector Observatory (ECSO), 2021))

According to (European Construction Sector Observatory (ECSO), 2021) the little adoption of BIM by small-medium enterprises is reasonable because large companies have more financial and human resources to be employed. The adoption of BIM requires high initial costs and very specific skills. Additionally, large companies deal with more complex projects in which complex coordination is required, thus the benefit of BIM justifies its initial investment costs (European Construction Sector Observatory (ECSO), 2021).

Lastly, small-medium enterprises have fewer resources for adopting new processes and the benefits are currently not so evident to them (European Construction Sector Observatory (ECSO), 2021).

It must also be added to this that, as highlighted in the theoretical background, low margin and high competition, coupled with the economic challenges outlined previously, are reducing the willingness of companies to take risks and adopt innovative practices such as could be BIM (Circle Economy, Metabolic , C-creators, 2022)

BIM can instead deliver multiple benefits such as more efficient process management, reduced mistakes, improved information flow, reduced inaccuracies and delays and reduced waste. Studies suggest that it can reduce overall construction costs by 7%, save 15% of costs associated with planning and risk management, and reduce waste management costs by over 57% (Zoghi, M., Kim, S., 2020) 75% of companies who adopted BIM reported positive financial returns associated with reduced material procurement costs, reduce design time and paperwork (European Construction Sector Observatory (ECSO), 2021).

Digitalization plays a pivotal role in the EC's long-term strategy. For instance, the EU Directive on Public Procurement (Directive 2014/24/EU) is aimed at incentivizing member states to use digital technologies such as BIM as a prerequisite for public procurement processes, thus encouraging companies to digitalize.

The Netherlands has no such binding requirement for tenders. (European Construction Sector Observatory (ECSO), 2021)

For facilitating the adoption of digital technologies, the EC has started some initiatives that aim at standardizing the use of such technologies. The European Committee for Standardization (CEN) will focus on developing and maintaining standards in the BIM domain. BuildingSMART is an international organization supporting the adoption of BIM standards for buildings and infrastructure (European Construction Sector Observatory (ECSO), 2021)

The digitalization initiatives taken at a national level differ across member states. Two main approaches are either **horizontal** (national digitalization policies that cover multiple industries) or **vertical** (specifically focused on the construction sector). As illustrated in Figure 111 (see Appendix IX) the Netherlands does have a horizontal digitalization strategy which **does not** include the construction industry. Therefore there is currently **no** horizontal strategy (with the construction industry) nor a vertical strategy in place. Additionally, it has no comprehensive action plan, strategy or financial instruments for boosting the digitalization process in the country. The country has opted for a market-oriented approach rather than a government-steered one (European Construction Sector Observatory (ECSO), 2021).

From a legislative point of view, (Circle Economy, Metabolic , C-creators, 2022) suggest that the Dutch government should be proactively steering the industry towards increasing reuse practices. An example, next to digitalization could be the implementation of Extended Producer Responsibility (EPR) mechanisms in the C&D industry. According to ((PBL) Netherlands Environmental Assessment Agency, 2021) this strategy will force the implementation of more sustainable design options and boost material recovery and reuse practices.

This is an important issue to be addressed for implementing the solution outlined in sub-question 4. The lack of a national digitalization strategy poses several challenges. As outlined above, the adoption of BIM is not encouraged or facilitated and it is up to the individual firms to decide whether or not to implement BIM in their digital asset management strategy. This has also an implication for the standards for collecting and sharing data which must be coordinated and aligned to reach higher BIM levels and make the solution presented in this research work. This point is further discussed in the next paragraph.

Higher BIM maturity levels

As presented in Figure 32 and Table 3, BIM can be characterized by different maturity levels which define the mole and type of information/data contained in the model and consequently the extension of collaboration that can be enabled as consequence.

(Li, J., Greenwood, D., & Kassem, M., 2019) have investigated successful implementation cases of BIM, DLT and Smart contracts. It is generally accepted that such integration can be beneficial for boosting circularity in the construction industry. However, the BIM level for allowing such a system to work efficiently needs to be at least at a level 3 BIM. This level is also referred to as iBIM (integrated BIM) and it focuses on a fully open data and process integration which allows for full interoperability between systems and databases. (Li, J., Greenwood, D., & Kassem, M., 2019).

As outlined previously, the Netherlands is currently at a level 1 BIM (object-based modelling) adoption as companies are still starting to adopt this technology. At this stage, the data management practice across the building's life cycle is still strongly linear (see Figure 96).

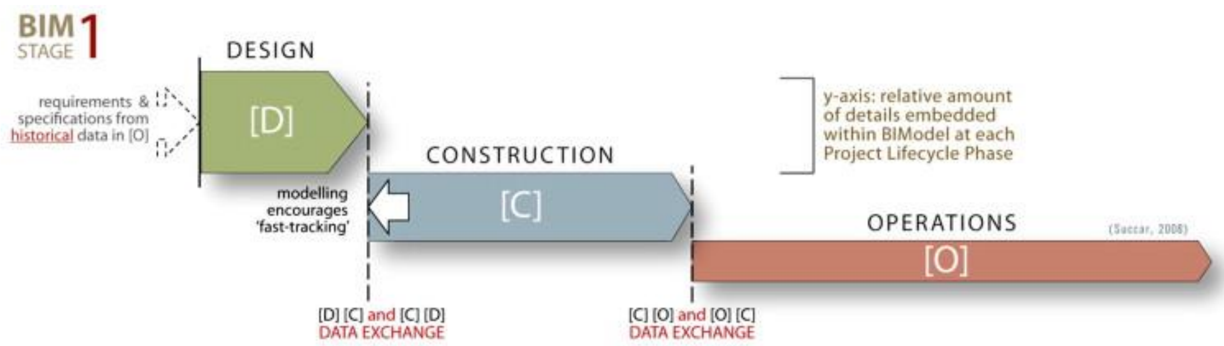


Figure 96 - Project Lifecycle Phases at BIM Stage 1 — linear model (source (Succar, B., 2009))

Instead, it is necessary to move to a level 3 BIM in which data are shared and interoperable throughout the entire life cycle of the building (see Figure 97).

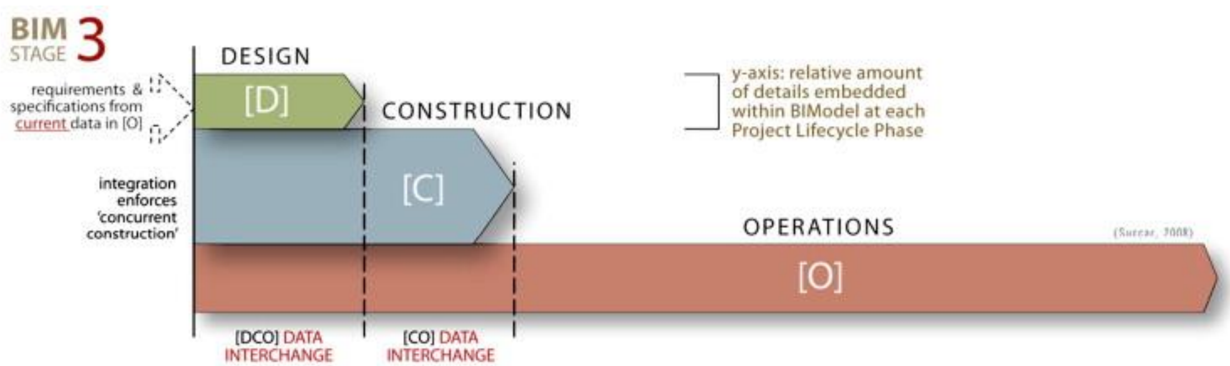


Figure 97 - Project Lifecycle Phases at BIM Stage 3 — network based (source (Succar, B., 2009))

In other words, it is necessary to move from an object-based model (level 1) to a network-based integration (level 3). (Succar, B., 2009) has identified different technological, process and policy-related requirements for enabling such transition (see Figure 98)

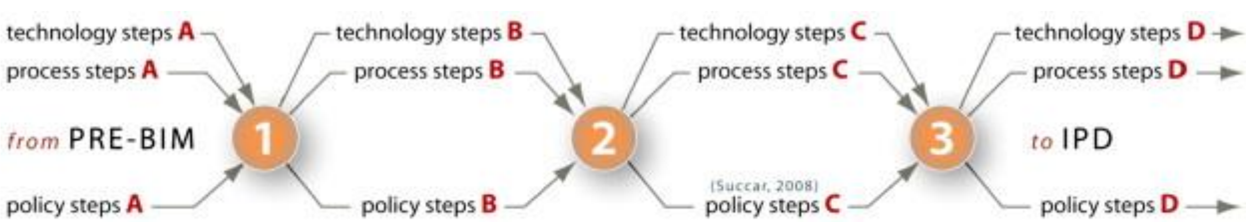


Figure 98 - Transitioning between BIM stages (source (Succar, B., 2009))

The overarching takeaway is that to move to high BIM levels, it is paramount to have a clear and concise industry-wide vision about the direction to take as well as harmonized, standardized and coordinated processes for data management. Without this pre-requisite, it will be very difficult, if not impossible, to move from object-based models to network-based BIM integrations. (Succar, B., 2009).

As illustrated before, the Netherlands has neither a digitalization plan in place nor an industry-wide standard and plan for BIM adoptions as the one adopted by the UK some years ago (bimireland, 2020) .

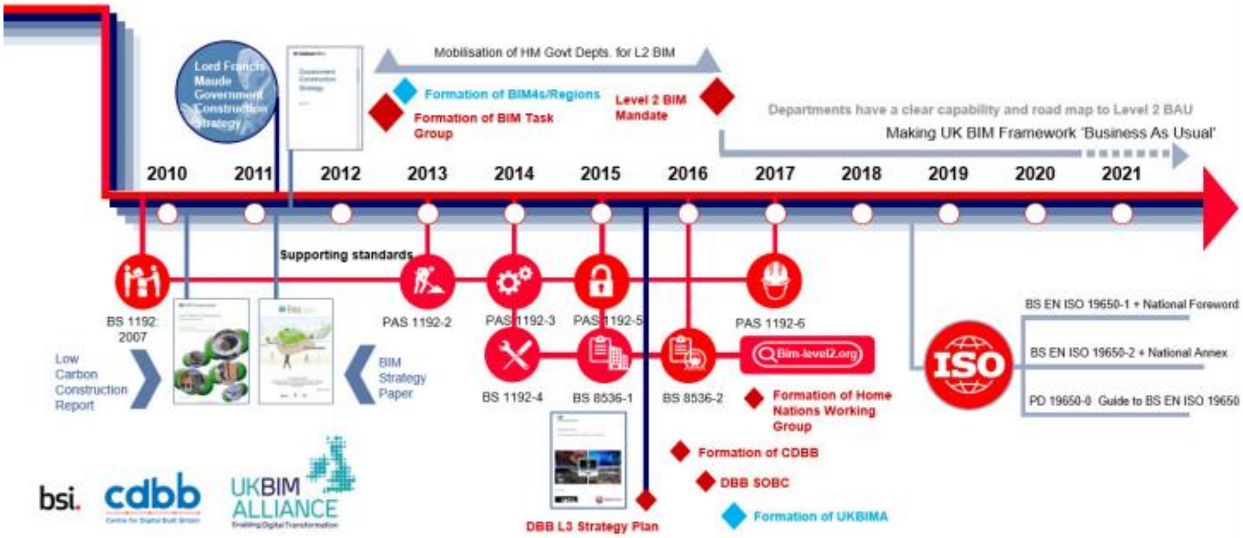


Figure 99 - BIM implementation timeline in the UK (source (Dowd, T., Marsh, D., 2020))

The UK government started defining, back in 2011, a long-term plan that would allow the industry to digitalize and become a frontrunner in Europe. The objective was to become global leaders in the construction sector through a comprehensive digitalization process that puts BIM at its core.

As illustrated in Figure 99, the first act was the "The Government Construction Strategy 2011" (GCS 2011) whose objective was to identify BIM as a technological means for the procurement processes for the public sector, making work practices more efficient and overall improve the productivity of the construction industry. To support this initiative, the UK government has created ad-hoc groups, the "BIM task group" and the "BIM4s/Regions" whose goal was to define standards and frameworks that would enable a nationwide adoption of level 2 BIM. For instance, between 2013 and 2017, standards were elaborated and shared with the industry. In 2016 the UK government decide to make level 2 BIM a mandate for the whole construction industry. This was possible because the industry had sufficient training and standard protocol that would sustain it. The BIM framework developed by the UK was also adopted by the USA, Australia, Japan and Brazil (Dowd, T., Marsh, D., 2020) .

The success of this initiative and the even clearer role that BIM could have in the industry led the UK's government to define an even more ambitious objective in the "Digital Built Britain L3 Strategy Plan" which went further with harmonizing process and data management standards to create the ground for moving the industry to level 3 BIM. For instance, it further developed the PAS-1192 series of standards (developed in 2013) with a new international BIM ISO standard, named BS EN ISO 19650. As illustrated in Figure 100, sub-protocols are also present. The overarching objective of BS EN ISO 19650 is to elaborate a collaborative framework for BIM data management throughout the building's life cycle, regardless of type and size. To give an example BS EN ISO 19650-1 identifies clear methodologies for data management and technologies used for data exchange aimed at providing all the stakeholders with timely availability of data. It further defines a "common data environment" (CDE) set-up and workflows that will guarantee correct data exchange. BS EN ISO 19650-2 goes further into detail about CDE workflows and data standards (Dowd, T., Marsh, D., 2020).

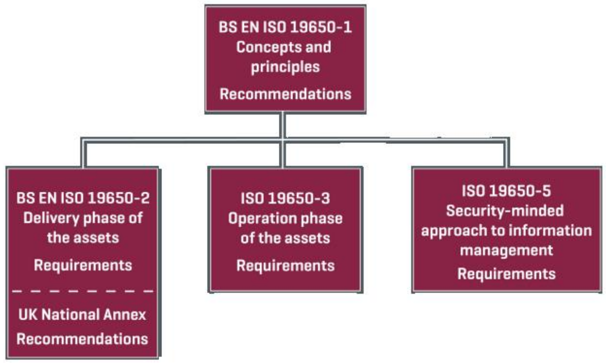


Figure 100 - BS EN ISO 19650 standards (adapted from (Dowd, T., Marsh, D., 2020))

IN 2016 the "Centre for Digital Built Britain" (CDBB) was formed and it replaced the "BIM task group" developed back in 2012. The objective of this new team is to create the conditions for bringing together industry experts, academia and policymakers to assess the benefit and challenges associated with digitalizing the economy. The ambitions of this group went further than expect and decide to replace the name level 3 BIM with "Digital Built Britain" (DBB). Data and the integration of key technologies play a pivotal role in this long-term transition. The focus is to define a bottom-up approach that guarantees the flow of data from small projects to regional levels (Dowd, T., Marsh, D., 2020).

CBDD has also defined a transition pathway for reaching level 3 BIM. The transition was broken down into 4 sequential steps 3A, 3B, 3C and 3D (see Figure 101). Steps 3A and 3B focus on defining the processes to move from federated BIM models (which are collaborative but static) to single shared and cloud-based models. 3C moves a step further and aims at utilizing data analytics, and Blockchain technology to secure cross-sector collaborations. As highlighted before, a level 3 BIM is necessary to integrate Blockchain technology. 3D will prepare the conditions for reaching level 4 BIM in the future. CBDD is aware that the process is not revolutionary but rather an evolutionary one because new technologies and innovations will potentially accelerate certain transitions or present new ones altogether.

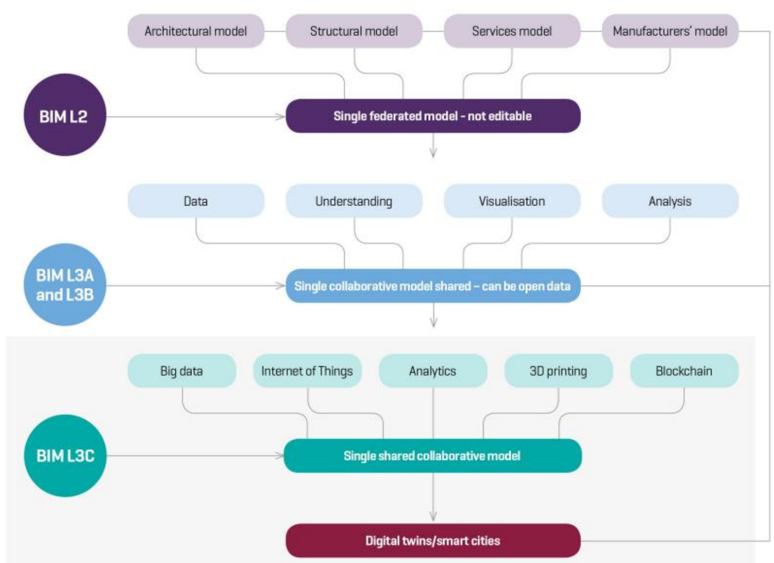


Figure 101 – UK transition from level 2 BIM to level 3 BIM (source (Dowd, T., Marsh, D., 2020))

To summarize, within 2 decades the UK was able to move the whole C&D industry to adopt BIM as a standard tool for asset management. With clear plans, it worked on defining first national and then international BIM standards that would allow the creation of coherent data and process management practices throughout the construction industry. Similarly to the levels identified by (Succar, B., 2009), namely technology, process and policy, UK's strategy has focused on multiple levels: business, information, technology and standards (see Figure 102) which together have created the conditions to move to higher levels of BIM, and thus to new business opportunities for the whole industry. The important takeaway is that these levels must work in complete synergy to create fertile ground for increasing the level of BIM within an industry. The pre-requisite, as mentioned by (Dowd, T., Marsh, D., 2020), is to have a clear vision of what role will BIM play in the digitalization of the C&D industry and then define a concise action plan with a clear value proposition and innovative business cases.

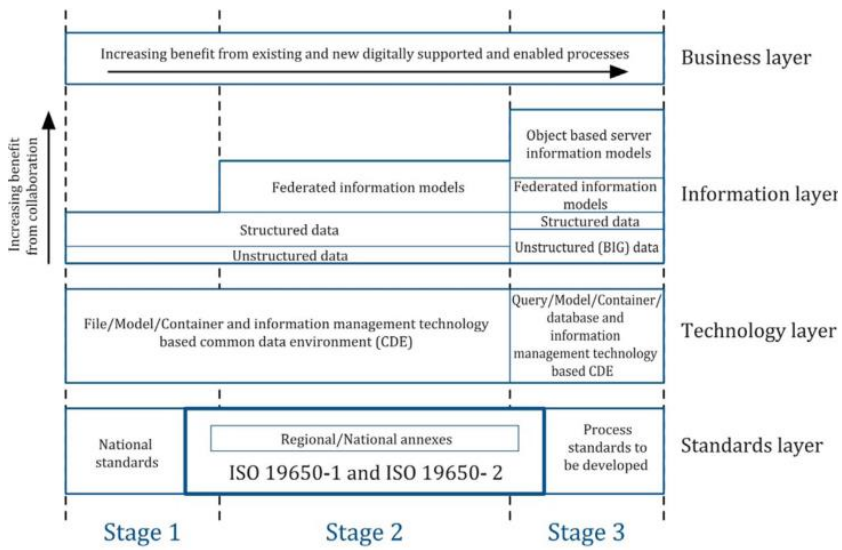


Figure 102 – UK's BIM transition divided into layers (source (Dowd, T., Marsh, D., 2020))

As outlined previously and as indicated in figure Figure 111 the Netherlands did not yet develop a digitalization long-term objective for the C&D industry which is steered by the government. Instead, the transition is market driven.

Several organizations are focusing on defining industry-wide standard procedures for the adoption of BIM, Material Passports and data management. The platform CB'23 (which stands for "Circular building in 2023") is an initiative started in 2018 whose objective is to develop and define precise national and industry-wide agreements on circularity in the C&D industry by 2023. The main activities undertaken by CB'23 entail creating and sharing a knowledge hub, mapping and addressing challenges hindering circularity and creating a nation and industry-wide agreements. The final objective is to have a circular pathway for the C&D industry (CB'23, 2022).

On a similar track are the activities carried out by the BIM-loket. BIM-loket is an organization born in 2015 whose objective is to drive and boost the digitalization process in the C&D industry in the Netherlands. The overarching objective for the BIM-loket is to make the adoption and use of BIM a standard approach in the industry and to develop national guidelines and standards that are coherent with international ones. In practical terms, BIM-loket offers and provides training to companies as well as freelancers on the use of BIM and it organizes activities and events throughout the year to involve more partners in this project as well as present the advantages offered by BIM (BIM-loket, 2022).

The most interesting and ambitious initiative is the one carried out by the DigiGO team. DigiGO is a bottom-up project, managed by the Bouw Digitaliserings Raad (BDR), which involves construction and demolition firms, technology providers and public institutions and whose objective is to define a blueprint and a roadmap for the digitalization of the C&D industry in the Netherlands. The need for initiating the DigiGO project is generated by the current lack of coherent and industry-wide data management and digitalization strategy. As outlined previously, C&D firms in Zuid-Holland are just starting to adopt digital asset management solutions but the way this is done is not aligned throughout the industry, thus hindering the possibility of reaching a high level of data interoperability and collaborations (DigiGO, 2022).

One of DigiGO's initiatives is extremely relevant and aligned with the outcomes of this research. This initiative is called **Digitaal Stelsel Gebouwde Omgeving (DSGO)** (en: Digital System for the Built Environment) whose objective is to define a framework and industry-wide agreements to make the data generated in the C&D industry reliable, safe, shareable, accessible and controlled (see Figure 103). The end goal is that all stakeholders operating at different phases of the building's lifecycle provide and can have access to data that is key for driving decision-making and thus enabling circularity practices. According to the DigiGO team, industry-wide agreements and standards on data management are a pre-condition for reaching the goal mentioned above (DigiGO, 2022). Literature and the findings of this research corroborate this assumption.

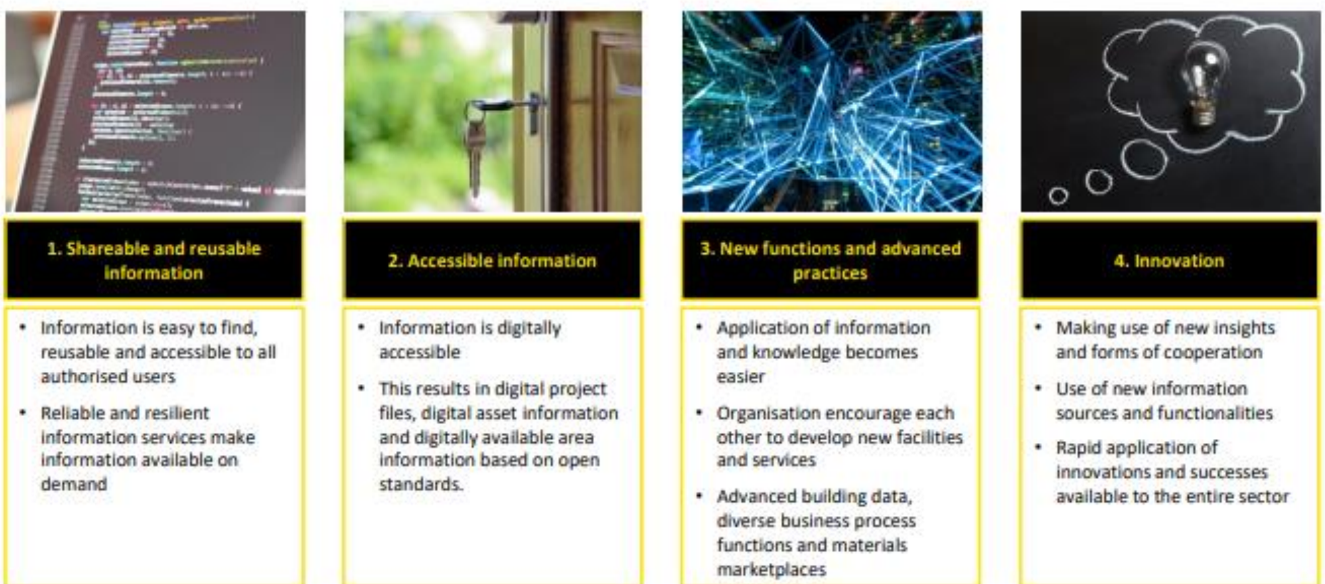


Figure 103 -DSGO ambitions (Source (Kuling J., Tan R., Bode R., 2021))

The approach adopted by DigiGO for reaching these objectives is the so-called triple-A model (see Figure 104)

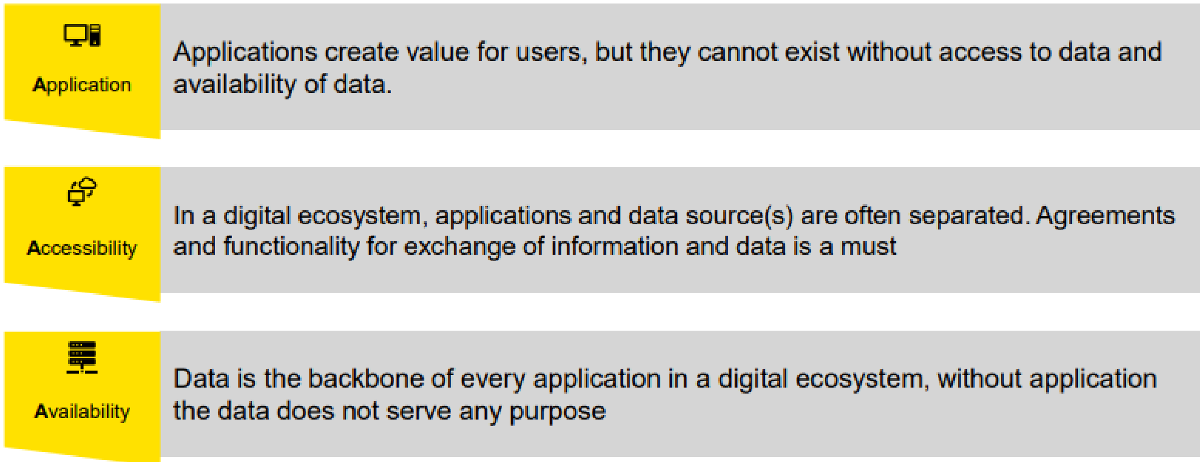


Figure 104 - Triple-A model pursued by DigiGO (source (Kuling J., Tan R., Bode R., 2021))

The model includes the **application** the **accessibility** and the **availability** theme. These three themes are interconnected and their alignment is paramount for reaching a full digitalization of the industry.

Application deals with all the tools adopted by C&D demolition industries during the design and the execution phase, which currently differ per company. The same goes for data **accessibility** and **availability.** Some companies have developed internal standards of data management, but due to competition and trust issues, competitors do not want to employ them. DigiGo is therefore working on models that can make data available with common standards and define clear industry-wide agreements for their accessibility. Solving the accessibility of data will inevitably enable their application in BIM models for example and also in their availability through the building's life cycle. As illustrated in Figure 105, the accessibility of data is key for the other themes (Kuling J., Tan R., Bode R., 2021).

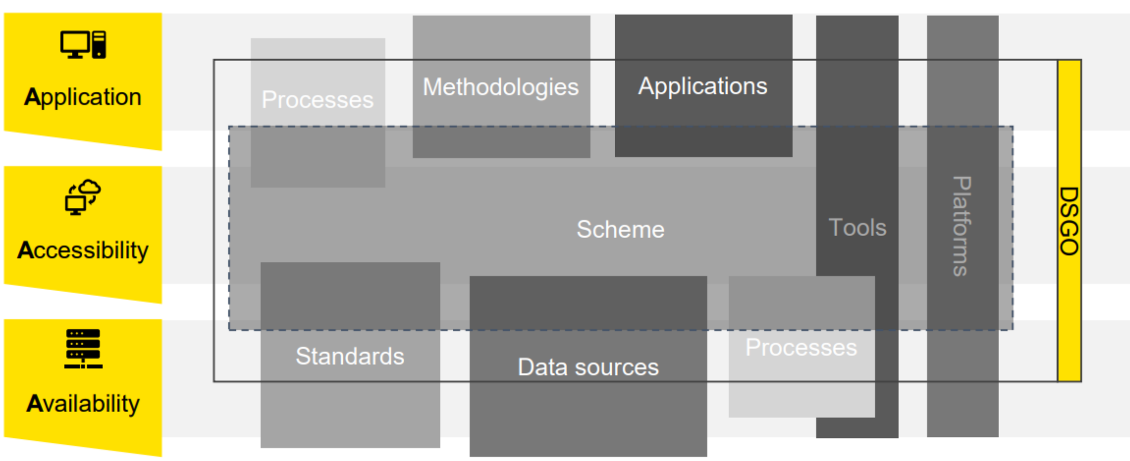


Figure 105 - Correlation of application, accessibility and availability (source (Kuling J., Tan R., Bode R., 2021))

Because of the centrality of data accessibility, this is one of the core aspects DigiGO is working on. The topic however needs to address 9 important themes (see Figure 106).

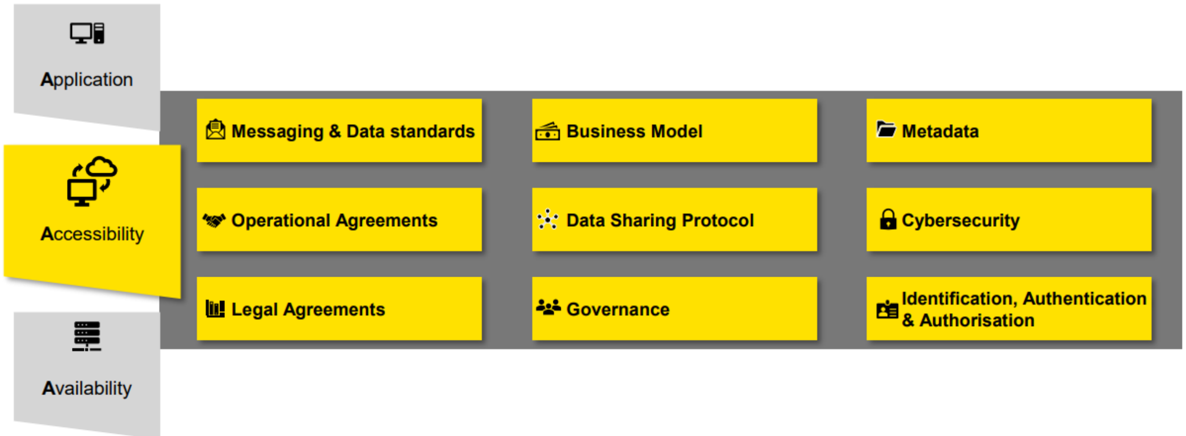


Figure 106 – 9 important themes for enabling data accessibility (source (Kuling J., Tan R., Bode R., 2021))

This is where the similarities between the integration of DLT, Smart Contracts and BIM illustrated in sub-question 4 chapter and the 9 themes of data accessibility become more evident. For instance, the framework presented in Figure 77 addresses most of the themes outlined in Figure 106. DLT and Smart contracts to operate correctly require aligning **data standards**, **operational agreements**, **legal agreements, data sharing protocols**, **governance**, **metadata** and **identification**, **authentication** and **authorisation**. Which in turn leads to **cybersecurity** and **new business models**.

In other words, besides the reliability and transparency of data, comprehensive integration of BIM, DLT and Smart contract forces the industry to define data accessibility and management practices. Otherwise, such a system cannot operate in the first place. In this perspective, the findings of this research reinforce the importance of the activities carried out by DigiGO and highlight the fundamental centrality that industry-wide data management agreements have for digitalizing the C&D industry and enabling circularity practices. Figure 107 presents the current challenges and the benefits identified by DigiGO resulting from the digitalization of the C&D industry in the Netherlands. These reconcile with the findings in the literature.

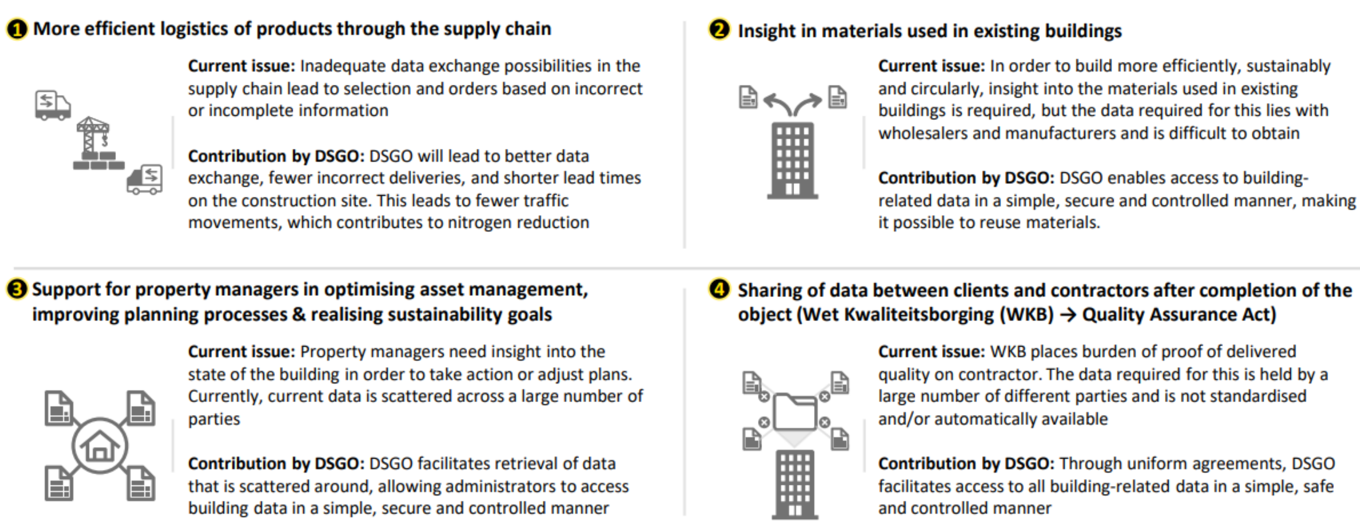


Figure 107 – Challenges and benefits enabled by the digitalization of the C&D industry (source (Kuling J., Tan R., Bode R., 2021))

The element of trust and new business models

What has been widely mentioned by the interviewee, insights gained from the literature as well as the findings of the DigiGO team is that trust is playing a very important role in the C&D industry. The industry and this was widely confirmed by the interviewee, is that competition is key to driving innovation. But at the same time competition is limiting the willingness of firms to share data/information, which is an important pre-requisite for enabling circularity in this sector (European Construction Sector Observatory (ECSO), 2021).

(Canare, T., Francisco, J. P., 2021) have researched the correlation existing between competition and innovation and have identified that the magnitude of the relation is also dependent on the type of innovation. For example, the correlation between the two is stronger when it relates to the production process of goods, but is significantly weaker when it comes to the introduction of a new tool or product in the market.

This is an interesting observation because the conservative attitude of the industry is indirectly hindering the wide adoption of new technologies, which, as illustrated in this research, could address the challenges associated with circularity practices such as material recovery and reuse.

It might be helpful to identify historical trends that allowed the emergence of new socio-technical paradigms which resulted in advances in business models and means of managing resources. According to (Heiskanen, A., 2017) this was only possible with the synergic merging of three important elements: **stimulating trust between the involved parties**, **standardisation of essential information** and **costs sharing models**. This was the case with the emergence of joint stock companies in the 16th century or with the emergence of insurance companies in the 17th century. The first two elements are currently the weak points of the C&D industry and something that the integration of DLT, Smart Contracts and BIM can address.

As widely illustrated in this research the C&D industry is intrinsically a fragmented supply chain relying on non-standardized manual input of data, which leads to disrupted, weak or missing information flows which consequently leads to disputes among parties as well as the generation of waste. And this is the key. According to (Pawlyn, M., 2016), simply put, waste is material without an information strategy.

The combination of the technologies mentioned above is revolutionary and carries with it the potential for a disruptive transformation of the industry because every material/construction element would be coupled to standardised information throughout the entirety of its lifetime and the Blockchain technology would address the issue of trust. Trusts would not be based on firms' authority but rather on their compliance and adherence to industry-wide standardized data and physical/digital asset management practices.

This is a key aspect because, in a study conducted by the UK government, a building project in the range of £25 million would require a contractor to deal with and manage around 70 sub-contractors, each one with its data management system and processes. This leads to a large number of activities which add no value to the construction process. The same study indicates that the actual operation work accounts for 40-60% of the worker's time, the rest is spent searching for materials or waiting for instructions. Similarly, contractors need to take the information provided by architects and add them to procurement platforms and cost calculation systems (Heiskanen, A., 2017).

The harmonization of processes and the standardization of data that would be required for operating the Blockchain system as illustrated in Figure 77 is intrinsically revolutionary because would make data trustful and interoperable between systems and databases. The automatized and certified record of data generated by a Blockchain can lead to process automation, and reduce redundant paperwork and manual data inputs. Even auditing activities by authorities could be facilitated (Heiskanen, A., 2017).

This, I think, is the fundamental aspect of the solution presented in this research and one of the most relevant aspects hindering the digitalization process. As reported in the findings of this research and literature, the C&D is extremely conservative and competitive, information is an important asset that can provide a competitive advantage in the market. Therefore, sharing data and information, although necessary for enabling circularity practices, is extremely limited (European Construction Sector Observatory (ECSO), 2021).

Trust is the key pillar of society. The work of (Davidson, S., De Filippi, P., Potts, J., 2016) is extremely enlightening on this point. They discuss how Blockchain technology is a revolutionary technology of governance because it revolutionizes the way we can give trust to records, how trust can be operated between stakeholders and how consensus can be reached among a set of people. This can fundamentally transform the coordination of activities and actions among and between governments, firms, citizens and other types of institutions. The key element around which this coordination operates is trust.

DLT and Smart contracts are, in fact, trust technologies, a role that was so far owned by governments or large institutions only. Ledgers and the consensus around the information contained in them Are what make the modern economy work. Two straightforward examples can be used here, banks and cadastre. Both of them rely on ledgers and the processes that lead to adding/removing information from them outline the institutional and organizational framework of society. You need a central bank to validate transactions, and thus your balance, and you need recognised governments to certify the validity of housing contracts and attribute ownership. In other words, ledgers are technologies or systems for accounting and for keeping track of who owns what, what has agreed to what, what are the value of something and the transaction of resources and things. A revolution in the technology underlying a ledger can therefore revolutionize how society and economies operate.

Trust is, in this sense a pre-requisite for ledgers. Without trust, a ledger cannot exist, let alone operate efficiently. Historically, technologies required to have centralized ledgers because trust was difficult to decentralize and therefore strong and stable governments became a central element for making economies prosper and work. Even today, corrupted governments (in which trust cannot be guaranteed) have e negative repercussions on the economic development of countries as they cannot attract external investments. External investors demand trust and the certainty that the involved parties comply with agreements. On the other hand, to secure trust, a nation must have a monopoly over violence and provide the promise of not abusing that power beyond its needs (Davidson, S., De Filippi, P., Potts, J., 2016).

DLT is a technology that can intrinsically revolutionize the element of trust and as an extension the governance of societies and economies. Once the Blockchain protocol is agreed upon and the participation framework is defined, the system can operate almost autonomously and participants can trust that information reported in the DLT and through Smart Contract is authentic, correct and fully reliable. Therefore, DLT can deliver the same trust that is currently delivered by a central entity, but with complete transparency and with no risk of manipulation (Davidson, S., De Filippi, P., Potts, J., 2016) (Tasca, P., Hayes, A., & Liu, S., 2018) .

The value delivered by Blockchain is partly related to its capability of making information flow more transparent and secure, but a large part relates to its capability of improving the organizational efficiency of a network or supply chain. Third parties can be partly or completely removed from the flow of information and redundant activities can be minimized, centralized hierarchical systems can be substituted by faster, more democratic and leaner consensus systems. According to (Davidson, S., De Filippi, P., Potts, J., 2016) centralization can be beneficial on a small scale but on a large scale, complex and evolving systems require decentralization and more flexibility to increase their robustness.

The possibility of creating ad-hoc currencies within a Blockchain system can even enable the creation of completely new economic models, something that is almost impossible in the current economic order. Hierarchical structures are currently needed for controlling opportunistic behaviours (a way of exploiting trust) in a market because relationships between firms are managed through a nexus of sometimes incomplete contracts. Blockchain can overcome opportunism and contractual incompleteness, not with hierarchies but rather through built-in transparency, democratic and manipulation-free consensus mechanisms together with automated smart contracts. Contractual incompleteness leads to uncertainty which in turn leads to information issues. Smart contracts overcome such information asymmetries because they require up-front coordination for establishing their parameters and mechanism and would then operate with almost complete autonomy (Swanson, T., 2014).

In other words, a model characterized by a lack of imperfect information and contract incompleteness requires trust among the involved stakeholders to operate. But if the information is present at all times and the contract nexus is clear with no possibility of tampering, then trust among stakeholders is no longer needed because it is guaranteed and enforced through cryptographic contracts and transparent consensus mechanisms (Swanson, T., 2014) (Davidson, S., De Filippi, P., Potts, J., 2016) .

The parallel with biological systems

The preceding paragraph illustrated how Blockchain technology can enable information flow through decentralization, horizontal hierarchies and built-in certification mechanisms. Assets are in this way embedded with information throughout their lifetime and at each step of the supply chain.

This aspect of Blockchain is extremely similar to biological systems in many ways. Biological systems have evolved to operate and thrive in closed-loop cycles in which the concept of waste does not exist.

The first similarity between the Blockchain and natural system is the flow of information and the possibility of enabling built-in feedback loops. As mentioned by (Pawlyn, M., 2016), waste is material without an information strategy. So what is the information strategy adopted by biological systems to prevent waste?

Biological systems adopt self-regulating feedback loops through multi-directional chemical reactions (He, X., Aizenberg, M., Kuksenok, O., Zarzar, L. D., Shastri, A., Balazs, A. C., Aizenberg, J., 2012). In other words, information is intrinsically embedded in chemical reactions. For example, if a key nutrient is missing in the soil, the species relying on it will detect that lower chemical reactions are occurring and consequently adjust their intake of this nutrient to survive. Food webs operate in the same way, a reduction in the mass of primary produce will create a cascade effect and reduce the mass of all the consumers downstream.

The strategy of biological systems is, therefore, to bind information to all transactions (chemical reactions) and use automatic and built-in feedback loops for adjusting supply/demands both, up and downstream.

The information of each transaction cannot be altered. Blockchain and the solution illustrated in Figure 77 aim at enabling the same mechanism. Information can be embedded in assets (construction elements) and the supply chain can use this information for adjusting demand and supply. For example, knowing with absolute certainty that a given amount of bricks will become available at a specific location and time can allow construction firms to reuse it in a new building. Similarly, the increasing costs of construction materials can indicate to the supply chain that material recovery and reuse might be the cheapest solution to undertake.

In this perspective, Blockchain can shift the trust of information from firms onto assets through built-in mechanisms and the information that becomes available can enable feedback loops that would allow for to rebalance of the supply chain. The current lack of information, lack of trust among firms and companies and the lack of a built-in feedback loop in the current asset management practices in the C&D industry in Zuid-Holland are making the industry, even more, subject to sudden disruptions as occurred during the COVID-19 pandemic, and now potentially with the sudden increase of energy prices.

This leads to the second similarity. As discussed previously, centralized governance and linear hierarchies can be beneficial for small structures. Linear supply chains, as the one characterizing the C&D in Zuid-Holland, are stiff and are not reactive to sudden disruptions. Biological and ecological systems, on the other hand, are intrinsically regenerative and resilient because they do not rely on linear flows of resources (and information). Ecological systems, for example, have according to (Pawlyn, M., 2016), multiple species able to perform the same function which increases the redundancy of the whole network. There is a direct correlation between the degree of redundancy in a system and its stability and vulnerability to external shocks. In other words, ecological systems adopt higher degrees of redundancy to increase their long-term resilience (in the sense of the capacity to prepare for disruptions, recover from them and adapt to changes). Therefore, for a system to be resilient requires to be **aware of the assets contained in it**, and be **diverse**, **integrated, interoperable**, **self-regulating** and **adaptive** (Rodin, J., Maxwell, C., 2014). The Blockchain configuration presented in this research can, directly and indirectly, deliver all the aspects making a system resilient as described by (Rodin, J., Maxwell, C., 2014). The availability of information throughout the entire supply chain can track assets and make them known by the system. Extending this possibility to all C&D firms because the information is not precluded to a limited set of firms. Processes can, therefore, be integrated, and the system can regulate itself and can adapt to sudden changes. Currently, the C&D in Zuid-Holland is, according to the indicators outlined here above, not resilient because it is not able to fulfil these indicators.

All these characteristics of ecological systems allow them to function in a state of dynamic equilibrium and to quickly adapt or metabolise sudden shocks (Pawlyn, M., 2016). Simultaneously, it allows the system to dynamically adjust the amount and type of output with a given amount of input. This is fundamentally why natural systems do not generate waste as conceived by humans. And here lies a fundamental difference between human-made and ecological systems. The latter becomes more resilient and stable over time while human-made systems are becoming more unpredictable and unstable over time. Table 21 provides a summarized comparison of human-made systems and ecological/biological systems.

Table 21 - Key differences between human-made and ecological/biological systems (source (Pawlyn, M., 2016))

Conventional human-made systems	**Ecological/Biological systems**
Linear flows of resources	Closed-loop/feedback-rich flows of resources
Disconnected and monofunctional	Densely interconnected and symbiotic

Resistant to change	Adapted to constant change
Wasteful	Everything is nutrient
Often centralised and mono-cultural	Distributed and diverse
Hierarchically controlled	Panarchically self-regulating
Engineered to maximise one goal	Optimised as a whole system
Extractive	Regenerative
Use global resources	Use local resources

Looking at this table, the similarities between the solution presented in this research (see Figure 77) and the characteristics of the ecological/biological system are significant.

The synergic use of DLT, Smart contracts and BIM could maximize the retention of construction elements/materials within closed loops, where recovery and reuse should be favoured over other practices as indicated in the waste hierarchy in Figure 11.

Likewise, the system would interconnect information throughout different processes in the supply chain. This would lead to dense connections between firms and activities.

Consequently, the flow of information would become multidirectional and present at every stage of the supply chain, allowing thus the system to adapt and change to external influences.

Waste would be reduced because information and data about material supply and demand and their characteristics would allow retaining construction elements/materials in closed loops as long as their quality is sufficiently high for the construction requirements and standards.

Unlike the hierarchical structure required for certifying information, the solution presented in this research could be characterized as panarchic and self-regulating. This is because each link in the supply chain is both a resource as well as an information flow. Smart contracts and DLT would certify the validity of each transaction and this could be retrieved in specific software such as BIM. Therefore the demolition of a building could be seen as the beginning of a new project. Similarly to what occurs in nature where the death of an organism is just a transition point for resources. A building, like an organism, temporarily stores resources for fulfilling a specific objective. Once the objective is fulfilled the resources must be released and flow to new purposes.

Such dynamic and multi-directional information and resource flow can ultimately lead to optimizing the whole system. Predicting the availability of resources and their location can optimize procurement processes, designs and transport for new projects.

The last two elements are key for closing the circle. Knowing the material composition of buildings and when these can be released can in the long-term transform the way construction and demolition activities are conducted within the industry. Resources are no longer static but rather dynamic and can be interchanged from project to project. Buildings could be updated more frequently and resources could be used where needed the most.

Conclusion and recommendations

The research presents the challenges that the C&D industry in Zuid-Holland is currently facing concerning recovering and reusing construction elements.

Although a large part of the demolition waste in the Netherlands is currently downcycled to infrastructure projects, the literature indicates that higher value-retaining activities identified in the waste hierarchies should be pursued. In other words, reuse practices should be favoured over recycling ones.

The C&D industry is intrinsically complex, capital and labour intensive and is characterized as a high-risk industry. Its supply chain is fragmented and involves a large number of stakeholders distributed in time and space. Each one has its asset management as well as data management process. Also, the collaboration between stakeholders is oftentimes temporary and developed around the design and execution of a construction or demolition project. Because of this, the C&D industry is characterized by mistrust and information sharing is limited.

This situation is hindering circularity practices in the C&D industry in Zuid-Holland. The main challenges faced by construction and demolition firms relate primarily to the lack of trustful and harmonized data and information, misaligned and non-coordinated processes and asset management practices, which directly affect the possibility of assessing the cost-effectiveness of recovering and reusing construction elements, even when these are potentially in good quality.

The combination of Blockchain technology, DLT, Smart contract and BIM can on one side enable digital and physical asset management practices and on the other make data and information secure, transparent and tamper-proof, while securing its confidentiality.

The challenges outlined by the participants in this research about the reuse and recovery of construction elements are consistent with the challenges identified by the literature. Blockchain technology (in the form of DLT and Smart contracts) can address and tackle these challenges. Nevertheless, Blockchain technology must be combined with an asset management tool like BIM for making the solution consistent and scalable at an industry level. Additionally, the level of BIM must be at least at level 3 for enabling industry-wide intra-project and intra-firm collaboration and interoperable with blockchain technology.

In this perspective, the precondition for the solution presented in this research is the implementation of national and industry-wide data management protocols and standards that would harmonize the collection, management and distribution of data across the C&D industry. Additionally, the adoption of BIM should be employed throughout the entire life cycle of a building. Without this, the solution outlined in this research cannot be implemented.

For future research it is recommended to:

1) extend the analysis of challenges characterizing reuse and recovery practices to the whole C&D industry and assess the consistency
2) Define small pilot projects where the implementation of Blockchain, DLT, Smart Contracts and BIM can be tested and where limitations and opportunities can be defined
3) Run extensive Life Cycle and Life costing analysis on the implementation of such a solution and compare to similar digitalization strategies and with the current state of the art

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Appendixes

Appendix I – Blockchain Taxonomy

The Blockchain taxonomy hereafter presented is structured in the following way: it outlines the main and sub-components and establishes the relationship existing between them, subsequently for each sub (and/or sub-sub) component some empirical model layouts are presented and compared.

Drafting and understating the relationship existing between the main, sub and sub-sub components allows for conceptualizing ad-hoc Blockchain design and models which can be operated depending on the desired outcome. Because Blockchain building blocks can be blended and arranged together in different ways, Blockchain technology can be operated in an extremely versatile way.

Table 22 below outlines the Blockchain taxonomy structured into main, sub, sub-sub components as done by (Tasca, P., & Tessone, C. J., 2019).

Table 22 – Blockchain taxonomy as structured by (Tasca, P., & Tessone, C. J., 2019)

Main	Sub	Sub-sub	
Consensus	*Consensus network typology*	Decentralized	
		Hierarchical	
		Centralized	
	Consensus immutability and failure tolerance	PoW	
		PoS	
		PoA	
		PoC&PoStor	
		PoB	
		Hybrid	
	Gossiping	Local	
		Global	
	Consensus agreement	Latency	Syncronous communication
			Asyncronous communication
		Finality	Deterministic
			Non-deterministic
Transaction capabilities	*Data structure in the Blockheader*	Binary Merkel tree	
		Patricia Merkel tree	
	Transactional model	UTXO	
		Traditional Ledger	
	Server Storage	Full node only	
		Thin node capable	

	Block storage	Transaction	
		User balance	
	Limits to scalability	Number of transactions	
		Number of nodes	
		Number of users	
		Possible values	
		Block confirmation time	
Native currency/Tokenization	*Native Asset*	None	
		Own cryptocurrency	
		Convertible multiple asset	
	Asset supply management	Limited-Deterministic	
		Unlimited-Deterministic	
		Pre-Mined	
	Tokenization	No Tokenization present	
		Tokenization + Third part Add-ons	
		Tokenization	
Extensibility	*Interoperability*	Implicit interoperability	
		Explicit interoperability	
		No interoperability	
	Interoperability	Implicit Intraoperability	
		Explicit Intraoperability	
		No Intraoperability	
	Governance	Open-source community	
		Technical	
		Alliance	
	Scripting Language	Turing Complete	
		Generic non-turing complete	

		Application specific non-turing complete	
		Non-turing complete + External data	
Security and Privacy	*Data encryption*	SHA-2	
		ZK-SNARKS	
	Data privacy	Built-in Data privacy	
		Add-on data privacy	
Codebase	*Coding language*	Single language	
		Multiple languages	
	Code License	Open-source	
		Closed-source	
	Software architecture	Monolithic design	
		Polylithic design	
Identity management	*Access & Control layer*	Public Blockchain	
		Permissioned public Blockchain	
		Permissioned Private Blockchain	
	Identity Layer	KYC/AML	
		Anonymous	
Charging and rewarding system	*Reward system*	Lump-sum reward	
		Block + Security reward	
	Fee system	Fee reward	Mandatory fees
			No fees
			Optional fees
		Fee structure	Variable fees
			Fixed fees

Consensus

This main component relates to the rules and mechanisms that allow for updating and maintaining the creocrd in the digital ledger. In other words it is the underlying mechanism guaranteeing the trustworthiness, autenticty, reliability and accuracy of the records in the digital ledger (Tasca, P., & Tessone, C. J., 2019) (Bonneau, J., Miller, A., Clark, J., Narayanan, A., Kroll, J. A., Felten, E. W., 2015).

Consensus mechanism can vary in Blockchain technologies, and their advantages and disadvantages relate primarily to energy efficiency, transaction speed, scalability and manipulation/censorship resistance (Tasca, P., & Tessone, C. J., 2019) (Mattila, J., 2016). These mechanisms make up the backbone for the validation process responsible for dealing and overcoming security aspects during the validation process itself. Table x above outlines the sub-components entailed in the consensus component. These sub-components must be considered in their totality when blended together because their individual configuration and their combination directly determines the how and when the bockchain agreement is achieved and the digital ledger must be updated (Tasca, P., & Tessone, C. J., 2019).

Consensus network typology

Thi sub component describes the type of interconnection and information flow between the nodes for the purpose of transaction recording and validation.

Having a centralized type of network can have a positive effect on the costs associated with configuration, adjustment and maintenance but it is characterized by a central point of failure thus reducing the redundancy of the entire system. This aspect also limits the scalability of such configuration. (Tasca, P., & Tessone, C. J., 2019). To avoid having point of failure concentrated into a single point, centralized systems can be structured into hierarchical layers which allow for improved scalability and redundancy (Tasca, P., & Tessone, C. J., 2019).

In a decentralised network arrangement instead, all nodes are equivalent to each other. Blockchains are most of the times are configured in this manner.

To summarize, consensus network typologies are primarily determined by the level of centralisation involved in the validation process, and the possible layouts identified by (Tasca, P., & Tessone, C. J., 2019) are illustrated hierafter.

Decentralised

This configuration allows and enables direct transactions between every node present in the network. The advantage of this system is to have a higher degree of redundancy, increased validation speed and transparency (Tasca, P., & Tessone, C. J., 2019). Bitcoin adopts this type of peer-to-peer (P2P) network.

Hierarchical

Thy type of network can be implemented for centralized and decentralized configurations. IN this case the nodes can adopt different roles. For example, you can have tracking/stock and validating nodes (Tasca, P., & Tessone, C. J., 2019). Tracking/stock nodes are the access point for submitting transactions and, making queries in the digital ledger. Validating nodes have the same functionality as tracking/stock ones but can additionally trigger validation, votes and amendment processes (Tasca, P., & Tessone, C. J., 2019). Hierarchical networks are often times called “Consortium Blockchains” (Tasca, P., & Tessone, C. J., 2019).

Centralized

This type of network is structured around a central authority able to control and filter what is added/removed to the digital ledger. This type of network drifts off to the main purpose of a Blockchain network which is to provide a decentralised validation system. For instance, centralized networks are most of the times implemented in private Blockchain networks (Tasca, P., & Tessone, C. J., 2019). In the

Blockchain environment, centralized networks are regarded as a non-proper design for a Blockchian because it undermines its core principles of transparency (Tasca, P., & Tessone, C. J., 2019).

Consensus Immutability and Failure Tolerance

This sub-element concerns primarily with faults, errors and failures that can occur in the Blockchain network. Failures can be of different nature and type, and system for preventing them are very costly, also because it is almost impossible to design a infallible system (Tasca, P., & Tessone, C. J., 2019).

A Blockchain system is considered to be fault-tolerant when it continues to guarantee the reliability, validity and security of the information stored within the digital ledger (Tasca, P., & Tessone, C. J., 2019). Generally, Blockchain does not require a central database, but rather it creates duplicates in a such a way that all servers connected to the Blockchain network are a perfect replica of the digital ledger and the information stored in it (Tasca, P., & Tessone, C. J., 2019). This is why adding a new information/record to the digital ledger has a significant cost in terms of computational power, but is quite cheap in terms of peer verification. In this perspective a Blockchain network requires an extremely efficient consensus mechanism that ensures that each node in the network has an original version of the transaction history, and that this information is consistent throughout all nodes (Tasca, P., & Tessone, C. J., 2019).

To summarise, the mechanism and layout guaranteeing consensus immutability directly determines the the failure tolerance of a Blockchain network. The main layouts and mechanisms are hereafter presented.

Proof-of-Work (PoW)

Bitcoin adopts a Proof-of-Work type of setup in order to ensure immatubaility of records. The main principle of PoW is that computing devices (also named "miners") are connected to a peer-to-peer network and have the task of validating new transactions and add these to the complete record of all existing and validated transactions (Tasca, P., & Tessone, C. J., 2019). The miner first generates a new block by solving a complicated cryptographic function and then includes it to the Blockchain network, thus validating all transactions included in the mined block (Tasca, P., & Tessone, C. J., 2019). As illustrated in Figure 49, the miner generates a new hash function which combines the hash values contained in the preceding block and the information contained in the new transaction (Tasca, P., & Tessone, C. J., 2019).

Such computational processes must be run with specialized hardware (ASICs) which are extremely expensive and energy intensive, leading to a significant electricity footprint (O'Dwyer, K. J., Malone, D., 2014).For this reason, miners have gathered in so called mining pools. The mian drawback of the PoW mechanism is its high demand for resources and the upfront large investments costs associated with the hardwear required for mining (Tasca, P., & Tessone, C. J., 2019).

Proof-of-Stake (PoS)

IN this setup the block generation is connected to the amount of proved digital assets owned by a user (Tasca, P., & Tessone, C. J., 2019). IN other words, the probability for a user to be selected for verifying a new block of information is directly proportional to the share of assets the user has within the system. The premise of this setup is that users with al arger share of the entire system will provide more trustworthy information and should therefore be considered reliable validators (Tasca, P., & Tessone, C. J., 2019) (Mattila, J., 2016).

PoS can be applied in two different ways.

1) Randomized block selection: an algorithm looks for the lowest hash and the largest stack size (Tasca, P., & Tessone, C. J., 2019).
2) Coin-age based selection: this method combines randomization with coin-age coefficient (obtained by multiplying the amount and the time of assets hold by a user) (Tasca, P., & Tessone, C. J., 2019)

The main advantage of PoS over PoW is that the former can prevent monopoly mining and resource intensive activities involved in the mining process (Tasca, P., & Tessone, C. J., 2019).

Proof-of-Authority (PoA)

In this set up, users are not required to solve mathematical calculations for obtaining new hashes but rather to adopt pre-configured authorities that allow the nodes to communicate between each other. In other terms, certain nodes have the exclusive authority of creating new block and add these to the Blockchain (Tasca, P., & Tessone, C. J., 2019).

PoA is a perfect match for private and consortium networks where some actors (for example authorities) have the monopoly to control the content added to the digital ledger. These users/nodes will have a set of private keys able to sign and certify new blocks, thus acting as trusted signers in the Blockchain network (Tasca, P., & Tessone, C. J., 2019).

Nevertheless, this set-up poses some important challenges such as monopoly and top-down control over mining frequency, distribution of mining load among the the trusted signers and the protection and update of the signer’s list (Tasca, P., & Tessone, C. J., 2019).

Proof-of-Capacity/Proof-of-Space and Proof-of-Storage

In this case the the validation of blocks does not occur via computing cycles, but rather via a non-volatile space that a user employs for computing the activity. IN other words, miners are incentivised to allocate hard-drive capacity to the network and this increases their chance of mining new blocks and getting rewarded (Tasca, P., & Tessone, C. J., 2019).

In this set-up the verification of information occurs through hash trees without the need for storing them. This mechanism is less energy intensive than the PoW because less computions are required in the process (Tasca, P., & Tessone, C. J., 2019).

The validation flow of PoC entails an initiation phase and subsequent execution phases run between the prover (P) and the verifier (V) (Dziembowski, S., Faust, S., Kolmogorov, V., Pietrzak, K., 2015). Instead of proving that work has been conducted, P needs to prove to V that some bytes of storage have been allocated for securing the infromation (Dziembowski, S., Faust, S., Kolmogorov, V., Pietrzak, K., 2015). P and V store only small pieces of invormation, and at a later point in time, V is allowed to initiate a proof and determine whether the pieces of information reconcile or not (Dziembowski, S., Faust, S., Kolmogorov, V., Pietrzak, K., 2015)

Proof-of-Burn (PoB)

IN this set up, the verification occurs through the burning of digital assets by the miners. Alike PoS, PoB aims at reducing the waste of resources generated through the PoW process, nevertheless PoB still requires PoW-mined assets for functioning (Tasca, P., & Tessone, C. J., 2019).

Hybrid

More advanced consensus immutability and failure tolerance methods combine PoB and PoS (Tasca, P., & Tessone, C. J., 2019). Due to the complexity and the set up of such configuration, developers become the central authority controlling the Blockchain (Tasca, P., & Tessone, C. J., 2019)

Gossiping

Blockchain system are usually decentralised and redundant storage systems whose information is extremely difficult to hijack (Tasca, P., & Tessone, C. J., 2019). The way the information is carried through the network of computer/devices can be customized and adapted from a Blockchain system to another. Due to lack of a central authority, the nodes are responsible for transmitting the information they possess to all the actors in the network (Tasca, P., & Tessone, C. J., 2019). Gossiping is the routing whereby a node transfers information, either of a new block to existing nodes or the info of the entire Blockchain, to selected list of nodes.

IN decentralised systems, gossiping requires significantly more time to propagate and to enter into a consensus state. Sometimes the lag time is so large that consensus in the Blockchain cannot be reachedm (Tasca, P., & Tessone, C. J., 2019).

Gossiping can be structured in two possible layouts.

Local

The validation and information occurs locally between a pre-set of nodes (Tasca, P., & Tessone, C. J., 2019). IN this case nodes can share transaction records and also reach a consensus without having to know all the nodes present in the network, thus allowing the information to be managed locally . Subsequently the information is sent throughout the whole network.

Global

The process of gossiping occurs between a list of specific nodes selected by so called fallback nodes who maintain a list of all nodes present in the network (Tasca, P., & Tessone, C. J., 2019). Whena new node connects to the system, fallback nodes allocate for the purpose of gossiping a randomly chosen list of nodes to the new node (Tasca, P., & Tessone, C. J., 2019).

Consensus Agreement

This element is defines the rules governing how records/information are autonomously and independently updated by the nodes of a system (Tasca, P., & Tessone, C. J., 2019). In other words, how a system composed of many nodes can achieve consensus for storing verified information even in the presence of malicious nodes or participants. This has primarily to do with how nodes communicate between each other (Tasca, P., & Tessone, C. J., 2019).

Latency

This sub element describes the ruled underlying message propagation in the network.

Synchronous Communication

Synchrnous messages are those arriving within a pre-defined and known time interval. In this case messages are bound to specific process speed and communication delay parameters which will lead to discarding the message if not respected (Tasca, P., & Tessone, C. J., 2019). Delays due to exogenous factors can always occur, but as said, the message will be discarded. Specially, the timestamp contained in the block is compared to the timestamp of the preceding blocks and if it does not meet specific process speed and communication delay aprameters ads mentioned before, the block is rejected. In some systems, transactions are either validated or rejected in matter of seconds (Tasca, P., & Tessone, C. J., 2019).

Asynchronous Communication

On the other hand, asynchronous messages are not bound to process speed and communication delay parameters. In this case messages can take indefinite time to arrive. This set up can be advantageous because nodes do not have to be active when information are transferred to them. But at the same time this has an impact on the unpredictable response time which makes it extremely difficult to design specific Blockchains application requiring swift response times (Tasca, P., & Tessone, C. J., 2019).

Finality

This sub-component describes whether information to be stored in a Blockchain should be considered to be stored permanently in the records. Although possible, this si not the core functionality of a Blockchain-based system in which new nodes/users entering the system can for example ovvrride the current consensus history with a longer and more updated one (Tasca, P., & Tessone, C. J., 2019).

IN other words, finality is used to assess and measure the time needed for guaranteeing tha the transaction/agreement occurred on the Blocchain network will ot be reversed or changed (Obasi Ifegwu, n.d.)

Non-Deterministic

In this layout, the system employs a randomized and inherently probabilistic consensus in which the probability of consensus increases over time. The new block can propagate through the newtowkr and create information bifurcations which will be eventually solved, but which cannot be ruled out, thus making the protocol non-deterministic (Tasca, P., & Tessone, C. J., 2019).

Deterministic

In this specific protocol, consensus agreements are certain and transactions get confirmed/rejected almost immediately. This type of protocol is extremely important smart contracts.

Transaction Capabilities

This makes up the second main component of Blockchain technology and it relates to the scalability of transactions and how potential interoperability with other applications and platforms.

An important challenge currently characterzing Blockchain technology is the transaction throughput, which is far from competing with centralized payment system such as the one supporting credit cards. This can only be tackled by redesigning nand improving parameters such as data storage in blockheader and transaction per seconds (TPS) (Tasca, P., & Tessone, C. J., 2019)

Data Structure in the Block header

A block header as illustrated in FIGURE X, has the capacity to store the information of the block as a whole. The information contained in the block header can vary, but generically it contains info about the block version, previous block hash, timestamp, nBits and nonce (randomized number generated by the miner and added to hashed block in a Blockchain) (Tasca, P., & Tessone, C. J., 2019).

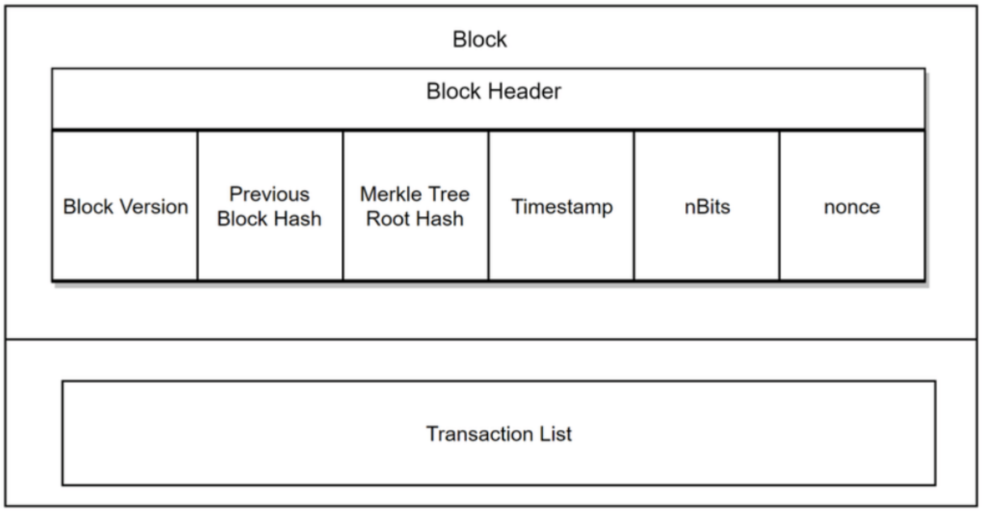


Figure 108 - (Puranam, K. S. R., Gaddam, M. C. T., Panda, S. K., Reddy, G., 2019)

The block header has in this sense different functions, on one hand it has the transaction hashes aimed for validation , on th other hand it contains information for different application on external applications (Tasca, P., & Tessone, C. J., 2019).

The data structure directly influences the capability of the Blockchain system to store information and records. Two possible data structure layouts are herafter presented.

Binary Merkle Tree

In this data structure (Figure 109), the block header contains of the previous block the hash, timestamp, mining difficulty value, proof of work nonce and finally the root hash containin the transaction/records for that specific block that will be used for the verification process (Tasca, P., & Tessone, C. J., 2019). In this case, the longest chain contains the current information status of the Blockchain.

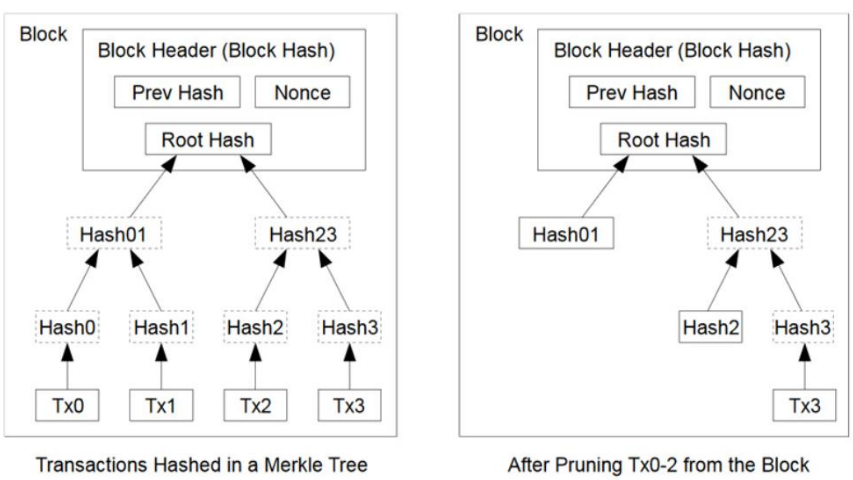


Figure 109 -Block head structure in Merkle Tree (Nakamoto, S., 2008)

The advantage is that old transaction records can be removed from the system and end up in freeing space. Their information will be carried on in the hash included in the new block (see Figure 109).

Patricia Merkle Tree

This configuration allows for more data storage such as adding and removing information about balances and nonces of accounts. This allows for validation of transactions to occur faster and in a more flexible way (Tasca, P., & Tessone, C. J., 2019).

In practical terms, this method allows to verify specific branches in the information tree such as transactions, receipts (effect of each transaction) and the state of the whole Blockchain (Tasca, P., & Tessone, C. J., 2019). What happens is that, even blocks outside the longest information chain, can contribute to the validation process, thus allowing for a more decentralized verification system (Tasca, P., & Tessone, C. J., 2019). Figure x below provides an example of a Patri

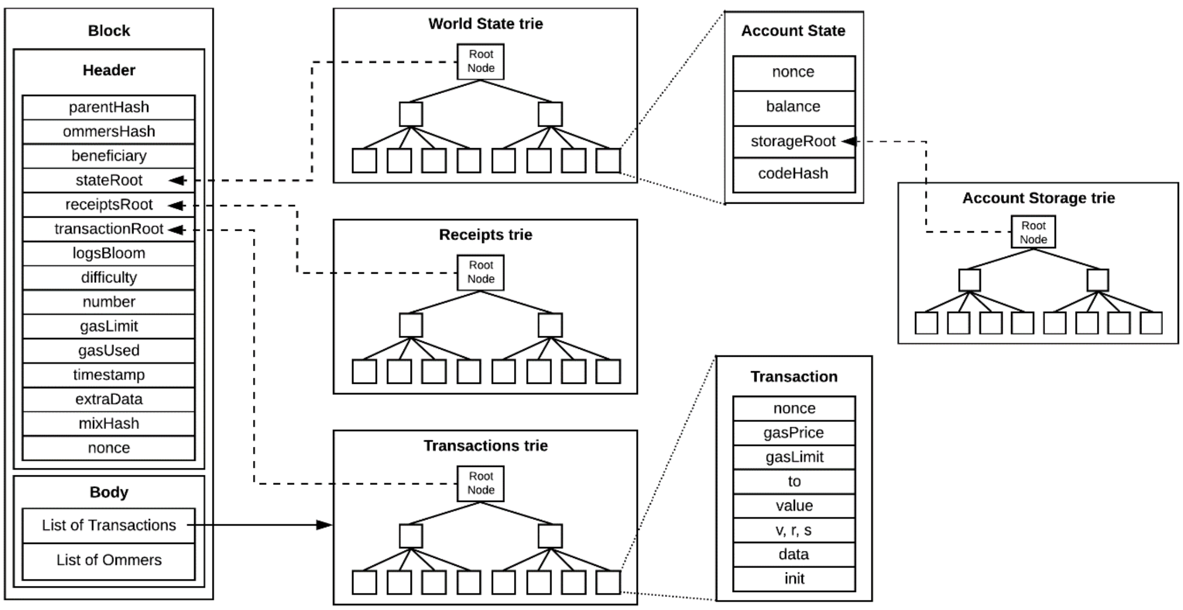


Figure 110 - Patricia Merkle Tree strcuture applied in the Ethereum environment (Lucas Saldanha, 2018)

Transaction Model

The transaction model is a sort of accounting ledger responsible for recording what comes in and out from a transaction. IN other words, the transaction model is responsible for defining how nodes, connected to the P2P network, update and store information in the digital ledger. The challenging aspect here is that the model must guarantee safe data and prevent non-trustful data (data originating from wrong behaviours such as a double spending) to enter end be recorded in the digital ledger (Tasca, P., & Tessone, C. J., 2019). Two modules are hereafter presented.

The Unspent Transaction Output (UTXO)

This model utilizes a pre-defined number of refractory blocks that prevent users from utilizing transaction outputs for new transactions. This prevents users from utilizing fees and it blocks rewards of any sort before the Blockchain is fully validated (Tasca, P., & Tessone, C. J., 2019).

Traditional Ledger

IN this system every single transaction is recorded in the digital ledger. This method allows also to record all increments/decrease of balances and records. In Ethereum for example, this system is also employed for associating each transaction to a specific order execution (Tasca, P., & Tessone, C. J., 2019).

Server Storage

In order to make the decentralized nature of Blockchian technology work, nodes connected to the P2P network must be indistinguishable from each other (Tasca, P., & Tessone, C. J., 2019). This is made possible by nodes being able to access different layers of information and/or by other nodes only storing partial information (called "thin clients") and connecting instead to the P2P network. Two possible nodes layout are possible.

Full Node Only

All nodes are of the same kind and these are all connected to the network and taking part in the validation process. IN other words, all nodes contain the same information and are all part of the P2P network. This leads to a high degree of information redundancy which makes the system more resilient to malfunctioning and external attacks (Tasca, P., & Tessone, C. J., 2019).

Thin Node Capable

IN this specific set up, some nodes contain only a selected fraction of the whole body of information contained in the Blockchain. This set-up has a significant advantage when it comes to scalability (in terms of amount of nodes and volume of information managabel in the ledger) but a disadvantage in terms of resiliency as only small fraction of nodes contain the Blockchain information as a whole (Tasca, P., & Tessone, C. J., 2019).

Block Storage

As mentioned previously, the information stored in a Blockchain system directly influences its scalability and complexity. Block storage defines what type of information is stored and is therefore retrievable from the digital ledger (Tasca, P., & Tessone, C. J., 2019). Two layouts ofr block storage are currently possible.

Transactions

In this case, transactions are the only information stored in the digital ledger.These transactions contain the inputs and outputs aimed at mapping who is emitting and who is receiving a specific transaction. This approach is applied to cryptocurrencies such as Bitcoin and IOTA, as well as for property transfer applications (Tasca, P., & Tessone, C. J., 2019).

User Balance.

This layout records primarily users's balance which is a grat advantage in terms of storage requirement by the system. Nevertheless, this can limit the possibility of reversing back transactions and certifying accountabilities (Tasca, P., & Tessone, C. J., 2019).

Limits to Scalability

All the elements affecting the scalability of a Blockchain system must be seen in their entirety and also in relation to each. Having a crude and categorical analysis of them, such as the one prestnede hereafter, has the oly objective of outlining how different sub-elements contribute to limiting the Blockchain system as a whole.

In Blockchain scaling is a property that defines how the growth of the system influences its performance. For example, a larger number of nodes can sustain a larger number of unverified transactions which in turn increases the overall network traffic. If each node has only 1 connection, then the network traffic would grow linearly with the number of nodes. But in a system where every node is connected to each other, then the network traffic would grow quadratically in relation to the number of nodes. In this case, if the network traffic would be considered the limiting factor of the system, different nodes configurations could have different implications on scalability. Because of this different kind of limits arise as a result of how the system is scaled and to its size. System size can refer to many elements composing a Blockchain technology, such as number of nodes, transactions, users, the amount of network traffic and so on (Tasca, P., & Tessone, C. J., 2019).

5 sub elements,hereafter presented, are categorized in relation to their contribution to limits to scalability:

Number of Transactions

This layout refers to the number of implementations, or number of operations, that can be processed within the block, regardless of the information stored in the Blockchain. A good example here is Bitcoin whichi limits the number of transactions that can be processed in the block. In the Bitcoin environment, new blocks appear every 10 minutes and the number of transactions are therefore limited for a given time window (Tasca, P., & Tessone, C. J., 2019).

Number of Users

This layout refers to the number of objects/elements within the Blockchain network with stored information. As mentioned previously, limiting elements or layers can appear irrespective of other elements as well as interdependent and complementary (Tasca, P., & Tessone, C. J., 2019). IN this specific case for example, the number of users will have a direct influence on the number of transactions outlined above. In systems storing both transactions and balances the number of users is a direct limitation in the system (Tasca, P., & Tessone, C. J., 2019).

Number of Nodes

The role of nodes connected to the Blockchain networks is to transmit and verify the information stored on the Blockchain and consequently on the digital ledger as a whole. Number of nodes are strongly linked to the topic of gossiping which deals with how information is diffused in the system (Tasca, P., & Tessone, C. J., 2019) Decentralized systems might lead to larger propagation time and thus, a larger number of nodes might limit the possibility oh having a fully decentralized system simply because consensus mechanisms might be hindered and never reach a consensus state (Tasca, P., & Tessone, C. J., 2019).

Possible Values

This sub-elements refers to how damaging the layout is to the overall system performance and these layout can be categorized according to the following values:

(i) indifferent
(ii) at most linear
(iii) at most quadratic
(iv) worse than quadratic.

The first value represtns a system in which the characteristics of the system itself are independent from the number/amount of certain elements., while the remaining three values represent a situation where the system is actually is dependent on the number of elements present in the .

For example, on yhe Bitcoin system the performance of the network is indifferent from the number uof users as number of users has never been translated into property network. On the other hand, number of transactions instead is linearly proportional to the network traffic (Tasca, P., & Tessone, C. J., 2019).

Block Confirmation Time

Confirmation time describes the time it takes fro a certain action (fro example a transaction) to be added to whole Blockchain and to be validated by the next block that will be added onto the Blockchain.

The confirmation time, as also illustrated previously, can take different approaches, it can be deterministic (addition of new blocks occurs at regular time intervals) or stochastic (new minng activites increases the inter-block discovery time exponentially and so does the conrimation time).

Native Currency/Tokenisation

Tokens are a mechanism employed in Blockchain systems for incentiveizing the participation of users in the verification process.

Currently Blockchain systems are employed for the transfer of property records (like money) in the form of crypotcurrencies. In the crypotcurrecny world, users participating in the system (by adding/issuing new blocks to the Blockchain) have the possibility of being rewarded with a token. This has two beefnits, it allows the introduction of new assets in the blockcahi system, it incentives users to actively participate in the verficiation process, thus increasing the trustworthiness of he system as a whole (Tasca, P., & Tessone, C. J., 2019).

The value of a token assigned to a users can vary and is usually associated with its production costs (Sompolinsky, Y., Zohar, A., 2018). For example, Bitcoin invented its own asset calss in the from of “the bitcoin” for allowing transactions within the system, while Ethereum allows to exchange different tokens on its system thanks to the employment of smart contracts (Tasca, P., & Tessone, C. J., 2019).

The advantage of the tokenisation and smart contracts is that Blockchains systems can allow for very diverse use cases involving asse transfer, exchange and allocation (Tsukerman, M., 2015) . This opens the door for the interoperability of Blockchain with differente databases and system newtowrks.

Native Asset

Systems adopting a Blockchain technology can decide to employ a native asset (usually cryptocurrencies) also named tokens whose owner can assign a value and whoe function is to allow the information to be transferred within the network.

There is still large debate on whether these tokens can be regarded to be commodity currencies and whether these digital assets will replace traditional ones in the future (Grinberg, R., 2012) (Luther, W. J., 2016).

The layout describing native assets are hereafter presented

None

In this case, the Blockchain system does not require a native asset for incentivising the users to participate in the validation process. This is common in private Blockchain networks (Tasca, P., & Tessone, C. J., 2019).

Own Cryptocurrency

This is mostly applied in the cryptocurrency environment where the Blockchain system is build on a single asset compatibility token, meaning that the system deals with the transfer of property of its own token only (Tasca, P., & Tessone, C. J., 2019).

Convertible Multiple Assets

Other more innovative solutions allow different Blockchain system to interoperate with each other and thus allowing for the transfer and exchange of different types of tokens and make us of smart contracts (Tasca, P., & Tessone, C. J., 2019). This is very interesting for incorporating exchange markets directly into the Blockchain system (Tasca, P., & Tessone, C. J., 2019).

Tokenisation

Token can act as digital bond for his owner. The ownerhip of such token depends on the data in the Blockchain and it can be transferred between holders through transactions. The transfer of the token does not require the approval by any external authority, thus enabling a wide range of application and use cases (Tasca, P., & Tessone, C. J., 2019). The important aspect of tokens is that these can have customizable properties, in some cases they can represent currencies and in other cases assets and pieces of information (Conley, J. P., 2017) .

Three possible layouts are currently possible in terms of tokenisation in Blockchain systems.

No Tokenisation Present.

Some Blockchain systems do not employ and entail the use of tokens.

Tokenisation Through Third-Party Add-Ons

IN this case the tokenisation process is allowed by the adoption of external systems. For example, the integration of Bitcoin and Colour-coin enables tokenised transactions within the Blockchain system (Tasca, P., & Tessone, C. J., 2019).

Tokenisation

System like Etherum allow to create new tokens through the use of smart contracts between different systems. This flexibility allows fr extrme possibilities and elastic applications (Tasca, P., & Tessone, C. J., 2019).

Asset Supply Management

As mentioned previously, the mechanism for the creation of digital assets varies across different Blockchain technologies, and so does the way these assets are managed in the system. This has an implication on the incentive scheme and the economic framework that governs the system (Tasca, P., & Tessone, C. J., 2019).

Three possible layouts for asset supply manamgent are identified and presented:

Limited-Deterministic

In this case the supply of new assets is limited in time or in absolute numbers. For example Bitcoin has a well defined growth trajectory and growth limit. This approach incentives the users to both adopt the technology and to actively participate in the verification process, as well ass incentivizing the accumulation of assets (Tasca, P., & Tessone, C. J., 2019)

Unlimited-Deterministic

IN tis case, the system has not limit in the generation of assets. IN the cryptocurrency world, some systems (such as Dogecoin and Freicoin) have opted for an unlimited supply of assets, but did not gain wide acceptance from the public as of yet (Tasca, P., & Tessone, C. J., 2019).

Pre-Mined

IN other cases, all assets have been mined and distributed to the users up-front. In this case the reward system focuses on incentivizing the redistribution of the assets rather than its creation and validation (Tasca, P., & Tessone, C. J., 2019).

Extensibility

The extensibility of the system defines how easily and efficiently can the system be integrated and expanded with/to other system architectures. This aspect is dependent on the alignment and combination of the sub-elements herafter presented.

Interoperability

This sub-element describes the capacity of the Blockchain system to exchange and transfer information with external systems. The interoperability deals with how data can enter, exit or being retrieved from data provieders that are not based on blockhain technologies such as financial data providers (Dilley, J., Poelstra, A., Wilkins, J., Piekarska, M., Gorlick, B., Friedenbach, M., 2016).

Interoperability can be configured as follows.

Implicit Interoperability

This layout requires the mediation by a smart contract who is capable of allowing transactions to take place under specifi and pre-configured conditions. Conditions can be customized and adapted to system-specific statuses. This implies that the Blockchain can deal with any type of condition that can be specified, coded and transmitted through a smart contract (Tasca, P., & Tessone, C. J., 2019).

Explicit Interoperability

IN this case the interoperability is explicit because it is not preconfigured and therefore dealt through a smart contract with pre-set conditions. In this case the design principles of the Blockchain system as a whole will mediate and allow for the interoperability (Tasca, P., & Tessone, C. J., 2019).

No Interoperability

IN this layout the Blockchain system has no possibility for interacting with external softwares, neither through design principles nor through the mediation of aa smart contract. For example, Bitcoi has no interoperability implemented in its system, and an only communicate with external softwares thank to external information layers (Tasca, P., & Tessone, C. J., 2019).

Intraoperability

It refers to the capacity of the Blockchain system to exchange information and interact with other Blockchain systems (Kan, L., Wei, Y., Muhammad, A. H., Siyuan, W., Gao, L. C.,Kai, H., 2018). As with the interoperability aspect, this elements deals with how data can enter, exit or being retrieved from different Blockchain systems (Tasca, P., & Tessone, C. J., 2019).

Implicit Intraoperability

Similarly to the interoperability, implicit intraoperability is made possible by the use of smart contracts with pre-defined and customizable conditions.

Explicit Intraoperability

In this case the script allowing for intraoperability is not mediated through a smart contract but rather through the design of the system. It is called explicit because it is the design of the Blockchain system which allows the two systems to communicate (Tasca, P., & Tessone, C. J., 2019).

No Intraoperability

IN this case the Blockchain system has no possibility for interacting with other systems. There are some work arounds which require complicated integration and softwares (Tasca, P., & Tessone, C. J., 2019).

Governance

This elements regards what governane rules are implemented within the Blockchain. This element is extremely important In determining the successful implementation fo a Blockchain system and its capability to adapt, change and intereact (Tasca, P., & Tessone, C. J., 2019).

It is possible to distinguish between technical rules of self-governance which are defined b participants through softwares, protocols, algorithms and procedures and regulatory rules which are instead defined by regulatory bodies through regulatory frameworks, policies and rules (Atzori, M., 2017).

Three governance layout are hereafter presented.

Open-Source Community

Under this layout, protocol developers and validators are part of an open community and they are all eligible for coordinating upgrades and adjustment to the Blockchain.

Bitcoin for example is maintained by a group of core developers who work in close contact with miners and together with them they agree on changing parameters and editing certain settings of the Bictoin network. Lterature criticezes this type of governance as it is accused of becoming too centralized and obstructive over time (Tasca P., 2018).

Technical

In this case it is the technical rules are somewhat governed by the system employed for supporting the Blockchain network. For example IBM and Microsoft, have offered technical solutions for Blockchain architectures and in such cases the rules governing the Blockchain environment were dictated by the companies owning the hardware, sfotwares and eervices (Tasca, P., & Tessone, C. J., 2019).

Alliance

This set up is usually promoted by industry consortia. The objective is to create shared paltforms that can allow for common business models and standards. Specifically, only companies who meet certain criteria (part of the consortia, payd the membership fee and so on) has the license to collaborate and set the rules of the Blockchain system as a whole. The objective is that the Blockchain system mutually benefits the alliance of users who have created it (Tasca, P., & Tessone, C. J., 2019).

Scripting Language

Blockchain systems are extremely versatile in their application and be customized to specific situations. This means that every Blockchain can have different rules/conditions under which certain data/transaction are included and stored in the digital ledger.

The conditions are defined and specified through algorithms which are created through scripting languages (coding). This implies that the scripting language which support the execution fo the algorhitm has a direct influence on the freedom to create conditions leading to certain actions as well as the computational power required for fulfilling a specific condition (Kim, H., Laskowski, M., 2017).

Four scripting language layouts are hereafterpresented:

Turing Complete

Turing complete is a scripting language that allows developers to create their own algorithm and thus their own application. This combined to the possibility of utilizing smart contract, results in an extremely versatile and tailored use of the Blockchain system (Tasca, P., & Tessone, C. J., 2019). As of today, litearutre points out some scalability and security concerns rearding the employment of Turing complete scripting language in Blockchain systems (Atzei, N., Bartoletti, M., Cimoli, T., 2017)

Generic Non-Turing Complete

In this case the scripting language is limited and cannot be extendend, thus limiting possibility of integrations and applicability. This also limits the integration with databases external to the Blockchain system (Tasca, P., & Tessone, C. J., 2019).

Application-Specific Non-Turing Complete

In this case the language is limited but designed fro specific cases or pruposes. This allows a certain degree of freedom when it comes to coding programs and functionalities but within predictable boundaries (Tasca, P., & Tessone, C. J., 2019).

Non-Turing Complete + External Data

This language mantians the main limitations of the non-turing complete language, but it extends the possibility of including external databases through so called "oracles". If the oracles are considered to be reliable, the languale allows to integrate them to the Blockchain network in a simple and validation-proof manner (Tasca, P., & Tessone, C. J., 2019).

Security and Privacy

The different an various application of Blockchain are highlighting the risks, from an operational and technical level, associated with security and privacy aspects o users and transactions. Security and privacy are two of the key pillars upon which Blockchain is structured (Tasca, P., & Tessone, C. J., 2019).

For example, cryptocurrencies were the target of cyberattacks which were possible due ot design flaws of the system and also the poor management of sensitive data (Lin, I. C., Liao, T. C., 2017).

Security in Blockchain system does usually comprise:

1) Mismanagement of information (the information is either altered, deleted, destructed and disclosed etc.)
2) Vulnerabilities set forth by implementation (Information takes too long to be validated and is therefore vulnerable)
3) Mismanagement of Cryptographic mechanism (using algorithms that are too weak)
4) Mismanaging of user special privilege

Security and privacy in Blockchain system is governed through 2 sub-systems, namely data encryption and privacy.

Data Encryption

To encrypt data Blockchain systems adopts cryptographic primitives (Algorithms) that ensure the authenticity, integrity and temporal order of data (Tasca, P., & Tessone, C. J., 2019).

Data encryption can be carried out through two main layouts hereafter presented.

SHA-2

It stands for "Secure Hash Algorithm" and it was originally developed by the National Security Agency fo the United states. This layout is the most adopted one for hashing [" process of translating a given key into a code" (Claudio Buttice, 2021)] .This layout requires some information from the transaction issuer (for example its public key) for validation to take place (Meiklejohn, S., Orlandi, C., 2015)

ZK-SNARKS.

IT stands for "Zero-Knowledge—Succinct Non-interactive Argument of Knowledge" and unlike the SHA-2 layout, this one needs to additional data for valitading hashes, because the hashed and the encrypted are proof of the existence of the transaction. The advantage of this novel method is that users are anonymized to a greater degree (Tromer, Ben-Sasson E. Chiesa A., E. Virza M. Garay JA Gennaro., 2014).

Data Privacy

The combination of public and private key with hashing should ensure that only the recipient can read and have access to the transaction information. However, research has demonstrated that in the case of Bitcoin for example, Blockchain transactions can be linked together in order toe xtract additional information and even retrieve the identify of users (Tasca, P., Hayes, A., & Liu, S., 2018)

Different solutions able to encrypt data in such a way that although the transaction it visible and retrievable, the underlying information are not accessible. IN other words input and output of data is not affected while data and processes are inaccessible.

Data privacy and encryption are strongly interrelated and two possible layouts on how to enhance data privacy are herafter presented.

Built-In Data Privacy

Built-in layouts are those systems that guarantee data/information obfuscation as a built-in feature of the system.

For example, a Blockchain system called ZeroCash has a buil-in encryption mechanism that allows to hide and to make anonymus information (sender/receiver/amount) despite having all payments published on a public Blockchain network (Sasson, E. B., Chiesa, A., Garman, C., Green, M., Miers, I., Tromer, E., Virza, M., 2014)

A Blockchain called Enigma instead has implemented a system where data are split among n users and this implies that multiple users are needed for completing the computation or for revealing any data in the ledger (Tasca, P., & Tessone, C. J., 2019)

CORDA on the other hand has implemented a node-to-node (N-to_N) system in which only he parties involved in the transaction have access the transactions information. This is extremely useful for transactions requiring high degree of confidentiality. Third parties can audit the data only based on invitation (Tasca, P., & Tessone, C. J., 2019).

Add-On Data Privacy

This is widely adopted fro public Blockchain networks, and in this case the system relies on external softwares fr hiding the information.

One method is the mixing service which groups together different transactions in order to become a unique transaction. For example person 1 and 2 want to send a coin/asset to person 3 and 4 respectively, then the system would record the information of person 1 and 2 as input and of person 3 and 4 as output in one unique transaction. This makes it impossible to track back and sicern who is the sender and the receiver of such transaction (Tasca, P., Hayes, A., & Liu, S., 2018).

Another system called secret sharing allows data to be stored across n users. You would need exactly n users for reconstructing the data because n-1 users cannot recover any information from the system (Tasca, P., Hayes, A., & Liu, S., 2018).

Other two methods fro hiding the sender and recipient of transaction which can be employed by any Blockchain system are the ring signature and stealth addresses.

Alternative add-on data privacy tools include ring signatures and stealth addesses which hide the recipient of a transaction and can be used by any Blockchain.86, 87

In the ring signature (conceived by Rivest, Shamir and Tauman), the system ties the transaction to the private key of multiple senders although only one is the real initiator. In this way the verifier can identify that one of the keys belongs to the correct sender but not who the sender is (Rivest, R. L., Shamir, A., Tauman, Y., 2001).

For the stealth address instead, the receiver must generate a dedicated address together with a secret key and share this with the person he wants the receive a coin/asset form. The sender uses this address and combines it to a random number to generate a new address where the coin/asset will be transferred to and shares this with the receiver who will need the first secret key plus the random number generated y the sender for unlocking this address (Tasca, P., & Tessone, C. J., 2019).

Codebase

IN Blockchain the codebase characterizes the challenges and opportunities faced by developers and what can the Blockchain system deliver and how it can transform in the future.

The sub elements composing the codebase of a Blockchain system are hereafter presented.

Coding Language

The coding language refers to how program used in the Blockchain system are interconnected and communicate to each other. Two possible layouts are presented.

Single Language

In this case the network adopts on one unique language which can be Java, C++, Python and others (Tasca, P., & Tessone, C. J., 2019).

Multiple Languages
In this case the network adopts multiple coding language. For example Ethereum utilizes C++, virtual machine language and Go (Tasca, P., & Tessone, C. J., 2019)

Code License
Code license refers to the possibility of changing code source used for the Blockchain network. Two possible layouts are hereafter presented.

Open-Source
IN this case other developers can access and work on the source code thus allowing for continued development, faster code growth and adoption (Tasca, P., & Tessone, C. J., 2019).

Closed-Source
Usually this approach is pursued in private Blockchain networks. Users and developers cannot freely access and edit the source code of the Blockchain network. The objective is to prevent the generation of unexpected and unchecked bugs and characteristics which might the expected functioning of the network, thus hijacking the objective of the network itself (Tasca, P., & Tessone, C. J., 2019).

Software Architecture

This element refers to the structure adopted by the blockcahin system, and it cmomprises the software elements, their relationshisp and the properties as a results form these elements and their relation (Tasca, P., & Tessone, C. J., 2019).

In other words, the architecture has a direct effect on how the Blockchain system operates and how it can change in the future.

Two possible software architectures are hereafter presented.

Monolithic Design

All functionalities and features are offered by a Blockchain system built as a single-tier software, without modules. For example aP2P connectivity, criterion for consensus, smart contracts, user permission, account balances and others are all managed by the same Blockchain system. Bitcoin and Ethereum are built like this. This type of architecture is not very extensible in the long-run (Tasca, P., & Tessone, C. J., 2019).

Polylithic Design
In this case, certain features/functionalities are decoupled from the Blockchain system. For example it is possible to decouple the P2P layers and the consensus engine from the transaction validation process in the Blockchain. The advantage is that the Blockchain system can be linked to other software with different programming language, and not necessarily the one the consensus engine is written on (Tasca, P., & Tessone, C. J., 2019).

Identity management

The identity management element deals with how to ensure access to sensitive data needed for allowing an effective governance model to the Blockchain system. The complexity arises from the fact that multiple roles with different level of authority exist within the system. These roles can be taken by different type of participants such as developers, users, administrators etc.

In general terms, the identity amangment is built into the system itself, thus allowing for a computer driven enforcement.

The sub-components forming the identify manager are hereafter presented.

Access and Control Layer

The governance structure is strongly dependent on the construction and architecture of the digital ledger and its purpose. Fro example, the digital eldger can be managed and governed by a central authority or it can be run in a decentralized manner where the users itself adheres and enforces the governance rules. The type of governance defines the control policies, manamgent functions as well as the authorization process. These rules determine the permission of users in accessing and using the blockcahin system (Tasca, P., & Tessone, C. J., 2019).

IN a blockcahin system it is aramount to have and grant different permissions in relation to the level of access to data and the control on them. In general, the system design and the access and control layer's feature must make sure to answer the fllowing questions

Users with "read" / "write' access?
Who can "manage consensus" (updating and maintaining integrity of digital ledger) ?

Private blockcahins have usually a closed number of users with read/write permissions combined to a consensus algorithm whichi limits the contribution to the digital ledger and maintenance of the Blockchain integrity as whole to only a pre-selected group of users (Tasca, P., & Tessone, C. J., 2019). On the other hand, publc Blockchain do neither control the number of users with read/write permissions nor limits the consensus algorithm to a pre-selected set of users (Tasca, P., & Tessone, C. J., 2019).

In any case, the authority to perform transactions within a blockcahin network can fall under one of the following structures (Guegan, D., 2017)

Public Blockchain

IN this setup, all users (nodes) are granted with a read and write permissions and can, without the need for third-party control, update and manage the digital ledger. Bitcoin is a good example. Here every participant can utilize a Blockchain system to exchange Bitcoins, run full nodes and/or become miners and take part in the transaction validation process (Tasca, P., & Tessone, C. J., 2019).

Permissioned Public Blockchain

In this specific setup, all users are granted with a read permission, but only a preselected set of nodes can have a write permission and the possibility to participate in the consensus management.

For example, in some Blockchain systems (such as Ripple, Ethereum, Hyperledger Fabric) falling under this set up participants who are part of a so called "Unique Node List" can take part in the transaction validation process (Tasca, P., & Tessone, C. J., 2019).

Permissioned Private Blockchain

This specific set up is the most limiting one as it read/write and consensus mechanisms permissions can only be granted by a centralized authority (Tasca, P., & Tessone, C. J., 2019).

Identity Layer

This layer focuses on attributing and identifying a digital identity in a specific context. IN other words, all those attributes that if merged together help the unique identification of a user (UID). The important aspect in a blockcahin network is that the UID of users is protected from fraud and its uniqueness is preserved throughout its life cycle (Tasca, P., & Tessone, C. J., 2019).

Once the UID can be guaranteed, it can be bind to digital credentials which will act as a trsuted proxy used for any trust-related action and functionality performed on the blockcahin network such as digital signature, authentication, encryption logins and access control (Tasca, P., & Tessone, C. J., 2019).

Two identity layer layouts are hereafter presented.

KYC/AML

Some Blockchain systems adopt a Anti-Money-Laundering (AML) and Know-Your-Customer (KYC) system which is able validate data and user's attribute on certified databases . This ensures quality of the data on the Blockchain and the infromation linked to the UIDs. (Tasca, P., & Tessone, C. J., 2019)

Some system focusing on financial services, force the partnering software to implement an KYC/AML identity layer in order to verify and certify user's information (Tasca, P., & Tessone, C. J., 2019).

Anonymous

In this case, the system has no identity layer aimed at identifying users. Bitcoin for example employs no identity layer and literature has highlighted the risk of money laundry through the Bitcoin system (Maurer, F. K., 2016)

Charging and Rewarding System

The costs associated with operating and maintaining a Blockchain system are usually internalized by the system's users. The cost model is strongly dependent upon the architecture configuration of the system, the type of governance enforced in the system and the data-structure and computation power required form the system (Tasca, P., & Tessone, C. J., 2019).

One of the mostly costly processes is the associated with the verification because it needs to sustain and allow for the verification of multiple transactions that cann be added to the digital ledger. To face suche costs, Blockchain systems adopt an incentive scheme that allows for such processes to be performed.

The sub-components contributing to the charging and rewarding system are hereafter presented.

Reward System

This component deals with the reward mechanism adopted for compensating all those users who are actively taking part in the transaction validation, verification and data storage. Two layouts are identified for reward systems.

Lump-Sum Reward

In this case users receive a reward in relation to their activities around storage and verification/validation of transactions. In Bitcoin for example the user who creates a new block is rewarded with the first transaction (also named coinbase). Lump-sum can be a fixed or variable value, depends on how it is implemented in the system (Tasca, P., & Tessone, C. J., 2019).

Block + Security Reward

Other layouts include additional reward systems with the objective of incentivizing the security of the Blockchain. For example, Ethereum rewards both the creation of a new block and also running the validation process on forked blocks which are still valid and can still be added to the ledger. This approach increases cross-validation of transactions (Tasca, P., & Tessone, C. J., 2019).

Fee System

Fee in this case are those rewards that users provide to other users when requesting and getting delivered computational power, validation, network for storage and data retrieval activites (Tasca, P., & Tessone, C. J., 2019).

Fee can be branched into two sub-components, fee reward and fee structure.

Fee Reward

These fees are those fees that users must pay for utilizing the Blockchain system. Literautre has also highlighted how the fee system influences how verifiers behave within the system (Möser, M., & Böhme, R., 2015).

Three possible layouts are identified and presented.

Optional Fees

In some Blockchain system the user can pay a variable and optianl fee for the validation process. However, the fee is inversely proportional to the processing time for adding a transaction to a block and consequently to the Blockchain. The higher the fee the lower the processing time as miners will be more incentivized to perform the work (Tasca, P., & Tessone, C. J., 2019).

Mandatory Fees

IN this case the Blockchain architecture and governance forces all users to add fees to all transactions added to the system (Tasca, P., & Tessone, C. J., 2019).

No Fees

Some system like the Hyperledger Fabric, combine network layers and identity layers without any transaction fee (Tasca, P., & Tessone, C. J., 2019).

Fee Structure

When it is the system itself charging fees, then these can either follow a fixed or variable structure. Both are hereafter presented.

Variable Fees

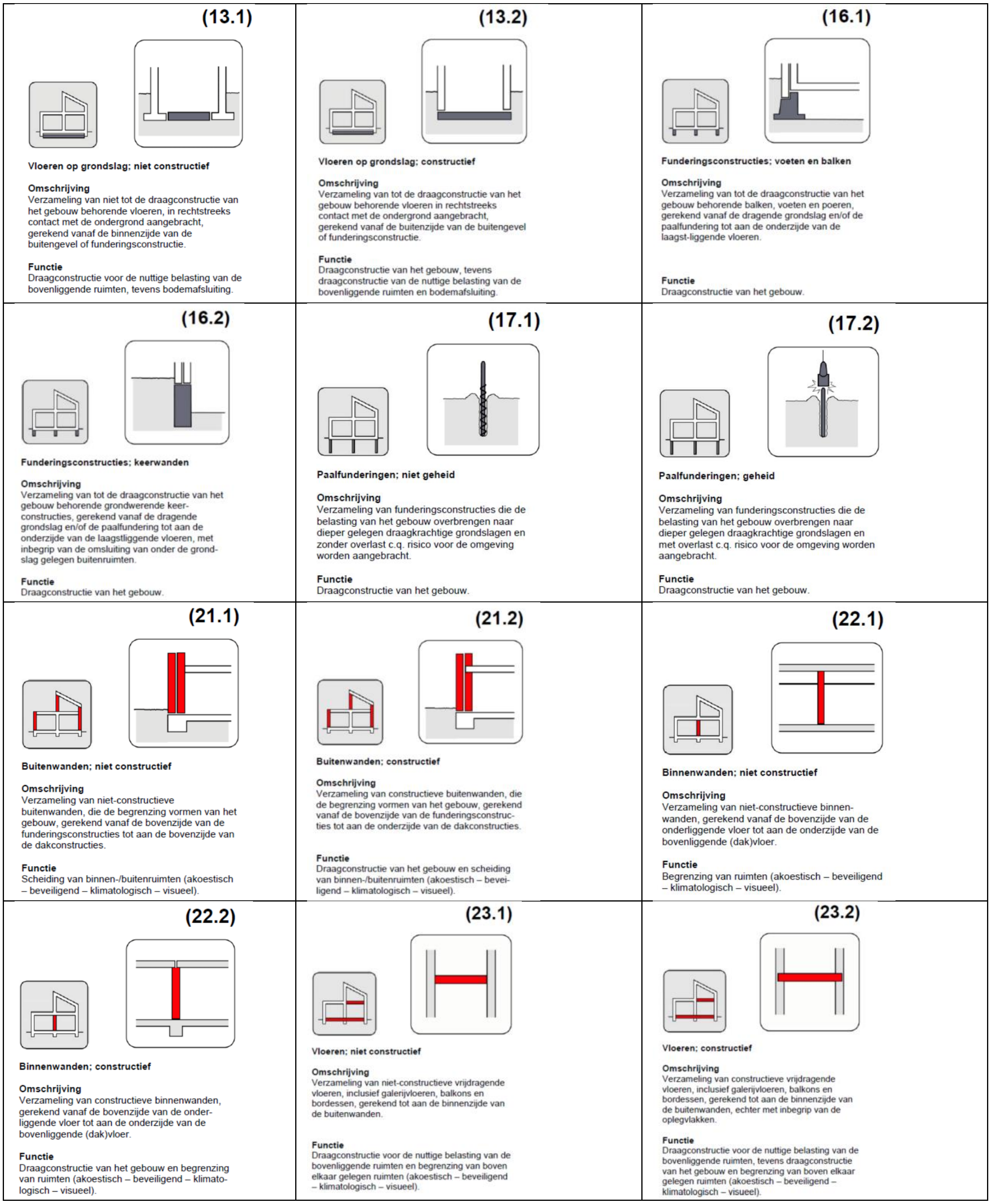
The fee is in this specific case linked to the transaction size, the larger the space taken within a block, the higher the fee a user must pay. The fee is usually defined in Satoshis/byte of transaction. A Satoshi represents 0.00000001 Bitcoins. If a user pays 300,000 Satoshis for a transaction of 1,000 bytes we obtain a value of 300 Satoshi/bytes. Miners do usually prioritize transactions with the highest value of Satoshi/bytes. This implies that to avoid queuing, the user must either increase the fee or reduce the size of the transaction (Tasca, P., & Tessone, C. J., 2019).

Fixed Fees

IN this layout the fee is not linked to the size but to the request itself. You can have systems that offer different fee rates depending on the request (data retrieval, computational power, storage etc.) (Tasca, P., & Tessone, C. J., 2019).

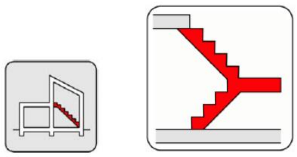
Appendix II – High-value reuse construction elements

Table 23 – High value construction elements for reuse purposes, according to NL/SfB classification for building components (adapted from (SGS, 2021))



(13.1) **Vloeren op grondslag; niet constructief** **Omschrijving** Verzameling van niet tot de draagconstructie van het gebouw behorende vloeren, in rechtstreeks contact met de ondergrond aangebracht, gerekend vanaf de binnenzijde van de buitengevel of funderingsconstructie. **Functie** Draagconstructie voor de nuttige belasting van de bovenliggende ruimten, tevens bodemafsluiting.	**(13.2)** **Vloeren op grondslag; constructief** **Omschrijving** Verzameling van tot de draagconstructie van het gebouw behorende vloeren in rechtstreeks contact met de ondergrond aangebracht, gerekend vanaf de buitenzijde van de buitengevel of funderingsconstructie. **Functie** Draagconstructie van het gebouw, tevens draagconstructie van de nuttige belasting van de bovenliggende ruimten en bodemafsluiting.	**(16.1)** **Funderingsconstructies; voeten en balken** **Omschrijving** Verzameling van tot de draagconstructie van het gebouw behorende balken, voeten en poeren, gerekend vanaf de dragende grondslag en/of de paalfundering tot aan de onderzijde van de laagst-liggende vloeren. **Functie** Draagconstructie van het gebouw.
(16.2) **Funderingsconstructies; keerwanden** **Omschrijving** Verzameling van tot de draagconstructie van het gebouw behorende grondwerende keer-constructies, gerekend vanaf de dragende grondslag en/of de paalfundering tot aan de onderzijde van de laagstliggende vloeren, met inbegrip van de omsluiting van onder de grond-slag gelegen buitenruimten. **Functie** Draagconstructie van het gebouw.	**(17.1)** **Paalfunderingen; niet geheid** **Omschrijving** Verzameling van funderingsconstructies die de belasting van het gebouw overbrengen naar dieper gelegen draagkrachtige grondslagen en zonder overlast c.q. risico voor de omgeving worden aangebracht. **Functie** Draagconstructie van het gebouw.	**(17.2)** **Paalfunderingen; geheid** **Omschrijving** Verzameling van funderingsconstructies die de belasting van het gebouw overbrengen naar dieper gelegen draagkrachtige grondslagen en met overlast c.q. risico voor de omgeving worden aangebracht. **Functie** Draagconstructie van het gebouw.
(21.1) **Buitenwanden; niet constructief** **Omschrijving** Verzameling van niet-constructieve buitenwanden, die de begrenzing vormen van het gebouw, gerekend vanaf de bovenzijde van de funderingsconstructies tot aan de bovenzijde van de dakconstructies. **Functie** Scheiding van binnen-/buitenruimten (akoestisch – beveiligend – klimatologisch – visueel).	**(21.2)** **Buitenwanden; constructief** **Omschrijving** Verzameling van constructieve buitenwanden, die de begrenzing vormen van het gebouw, gerekend vanaf de bovenzijde van de funderingsconstruc-ties tot aan de onderzijde van de dakconstructies. **Functie** Draagconstructie van het gebouw en scheiding van binnen-/buitenruimten (akoestisch – bevei-ligend – klimatologisch – visueel).	**(22.1)** **Binnenwanden; niet constructief** **Omschrijving** Verzameling van niet-constructieve binnen-wanden, gerekend vanaf de bovenzijde van de onderliggende vloer tot aan de onderzijde van de bovenliggende (dak)vloer. **Functie** Begrenzing van ruimten (akoestisch – beveiligend – klimatologisch – visueel).
(22.2) **Binnenwanden; constructief** **Omschrijving** Verzameling van constructieve binnenwanden, gerekend vanaf de bovenzijde van de onder-liggende vloer tot aan de onderzijde van de bovenliggende (dak)vloer. **Functie** Draagconstructie van het gebouw en begrenzing van ruimten (akoestisch – beveiligend – klimato-logisch – visueel).	**(23.1)** **Vloeren; niet constructief** **Omschrijving** Verzameling van niet-constructieve vrijdragende vloeren, inclusief galerijvloeren, balkons en bordessen, gerekend tot aan de binnenzijde van de buitenwanden. **Functie** Draagconstructie voor de nuttige belasting van de bovenliggende ruimten en begrenzing van boven elkaar gelegen ruimten (akoestisch – beveiligend – klimatologisch – visueel).	**(23.2)** **Vloeren; constructief** **Omschrijving** Verzameling van constructieve vrijdragende vloeren, inclusief galerijvloeren, balkons en bordessen, gerekend tot aan de binnenzijde van de buitenwanden, echter met inbegrip van de oplegvlakken. **Functie** Draagconstructie voor de nuttige belasting van de bovenliggende ruimten, tevens draagconstructie van het gebouw en begrenzing van boven elkaar gelegen ruimten (akoestisch – beveiligend – klimatologisch – visueel).

(24.1)

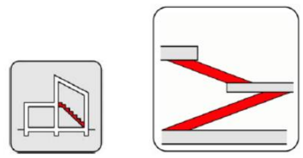


Trappen en hellingen; trappen

Omschrijving
Verzameling van trappen, zowel binnen als buiten het gebouw, inclusief de bijbehorende bordessen.

Functie
Doorverbindingen van ruimten op verschillende vloerniveaus en begrenzing van ruimten (akoes–tisch – beveiligend – visueel).

(24.2)

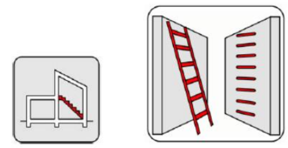


Trappen en hellingen; hellingen

Omschrijving
Verzameling van beloopbare en berijdbare hellingen, inclusief de bijbehorende bordessen.

Functie
Doorverbindingen van ruimten op verschillende vloerniveaus en begrenzing van ruimten (akoes–tisch – beveiligend – visueel).

(24.3)

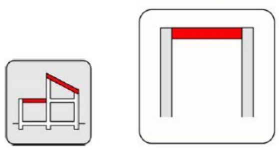


Trappen en hellingen; ladders en klimijzers

Omschrijving
Verzameling van zowel binnen als buiten het gebouw aangebrachte ladders en klimijzers.

Functie
Doorverbinding van ruimten op verschillende vloerniveaus.

(27.1)

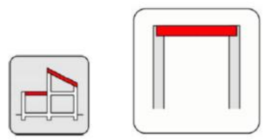


Daken; niet constructief

Omschrijving
Verzameling van niet-constructieve daken, zowel hellend als vlak, die de begrenzing van het gebouw aan de bovenzijde vormen, gerekend vanaf de binnenzijde en vanaf de bovenzijde van de buitenwanden.

Functie
Scheiding van binnen- en buitenruimten (akoes–tisch – beveiligend – klimatologisch – visueel).

(27.2)

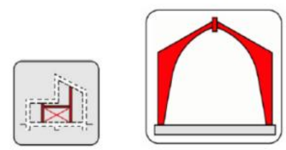


Daken; constructief

Omschrijving
Verzameling van constructieve daken, zowel hellend als vlak, die de begrenzing van het gebouw aan de bovenzijde vormen, gerekend vanaf de binnenzijde, echter met inbegrip van de oplegvlakken en vanaf de bovenzijde van de buitenwanden.

Functie
Scheiding van binnen- en buitenruimten (akoes-tisch – beveiligend – klimatologisch – visueel) en draagconstructie van het gebouw.

(28.1)

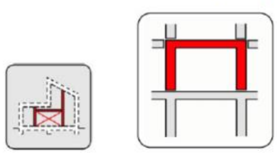


Hoofddraagconstructies; kolommen en liggers

Omschrijving
Verzameling van hoofddraagconstructies van het gebouw indien deze voornamelijk uit kolommen, liggers en/of spanten bestaan en door constructieontwerp en/of uitvoeringsmethode niet te splitsen zijn in de groepen (21.0) t/m (27.0).

Functie
Draagconstructie van het gebouw.

(28.2)

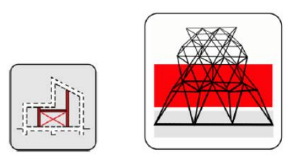


Hoofddraagconstructies; wanden en vloeren

Omschrijving
Verzameling van hoofddraagconstructies van het gebouw indien deze voornamelijk uit wanden en vloeren bestaan en door constructieontwerp en/of uitvoeringsmethode niet te splitsen zijn in de groepen (21.0) t/m (27.0).

Functie
Draagconstructie van het gebouw.

(28.3)

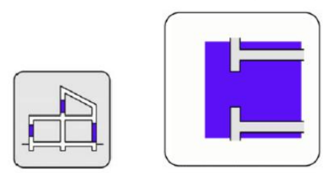


Hoofddraagconstructies; ruimte-eenheden

Omschrijving
Verzameling van hoofddraagconstructies van het gebouw indien deze voornamelijk bestaan uit wanden, vloeren en daken, die als één zelfdragende doosconstructie worden ontworpen en/ of gefabriceerd en om deze reden niet te splitsen zijn in de groepen (21.0) t/m (27.0).

Functie
Draagconstructie van het gebouw.

(31.1)

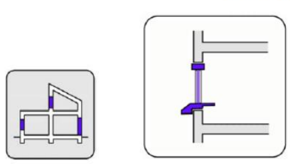


Buitenwandopeningen; niet gevuld

Omschrijving
Verzameling van niet-gevulde openingen in buitenwanden.

Functie
Toetreding van daglicht en buitenlucht.

(31.2)

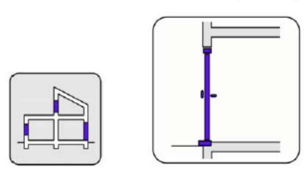


Buitenwandopeningen; gevuld met ramen

Omschrijving
Verzameling van met ramen en raamkozijnen gevulde openingen in buitenwanden.

Functie
Scheiding van binnen- en buitenruimten (akoes-tisch – beveiligend – klimatologisch – visueel), toetreding van daglicht en natuurlijke-ventilatie-voorziening.

(31.3)

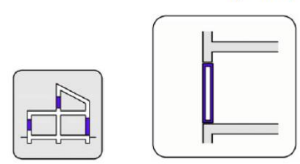


Buitenwandopeningen; gevuld met deuren

Omschrijving
Verzameling van met deuren en deurkozijnen gevulde openingen in buitenwanden.

Functie
Scheiding van binnen- en buitenruimten (akoes-tisch – beveiligend – klimatologisch – visueel) en gebouwtoegang.

(31.4)

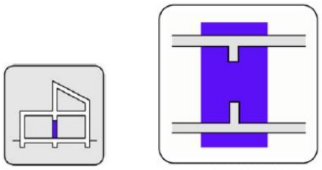


Buitenwandopeningen; gevuld met puien

Omschrijving
Verzameling van met puien (inclusief ramen en deuren) gevulde openingen in buitenwanden.

Functie
Scheiding van binnen- en buitenruimten (akoes-tisch – beveiligend – klimatologisch – visueel), toetreding van daglicht, natuurlijke-ventilatievoor-ziening en gebouwtoegang.

(32.1)

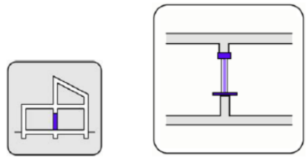


Binnenwandopeningen; niet gevuld

Omschrijving
Verzameling van niet-gevulde openingen in binnenwanden.

Functie
Doorgang en doorzicht tussen binnenruimten.

(32.2)

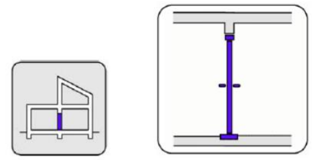


Binnenwandopeningen; gevuld met ramen

Omschrijving
Verzameling van met ramen en raamkozijnen gevulde openingen in binnenwanden.

Functie
Doorzicht tussen binnenruimten en scheiding van binnenruimten (akoestisch – beveiligend – visueel).

(32.3)

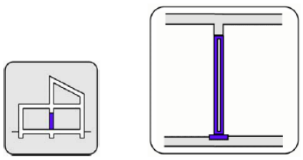


Binnenwandopeningen; gevuld met deuren

Omschrijving
Verzameling van met deuren en deurkozijnen gevulde openingen in binnenwanden.

Functie
Doorgang en doorzicht tussen binnenruimten en scheiding van binnenruimten (akoestisch – beveiligend – visueel).

(32.4)

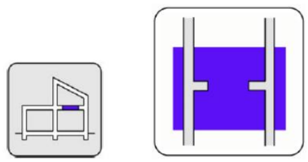


Binnenwandopeningen; gevuld met puien

Omschrijving
Verzameling van met puien (inclusief ramen en deuren) gevulde openingen in binnenwanden.

Functie
Doorgang en doorzicht tussen binnenruimten en scheiding van binnenruimten (akoestisch – beveiligend – visueel).

(33.1)

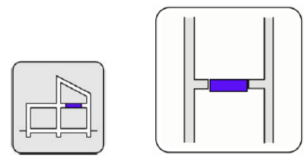


Vloeropeningen; niet gevuld

Omschrijving
Verzameling van niet-gevulde openingen in vloeren.

Functie
Doorzicht en doorgang tussen verschillende niveaus.

(33.2)

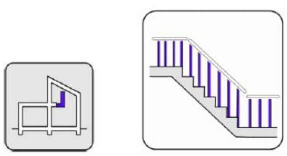


Vloeropeningen; gevuld

Omschrijving
Verzameling van met een vulling voorziene openingen in vloeren.

Functie
Doorzicht en doorgang tussen verschillende niveaus en scheiding van binnenruimten (akoestisch – beveiligend – visueel).

(34.1)

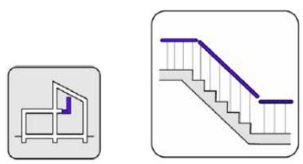


Balustrades en leuningen; balustrades

Omschrijving
Verzameling van voltooiingen van balkons, galerijen, loggia's, vides, trappen, hellingen, vloer- en dakopeningen en dakranden door middel van balustrades.

Functie
Beveiliging van en steunpunt voor personenverkeer.

(34.2)

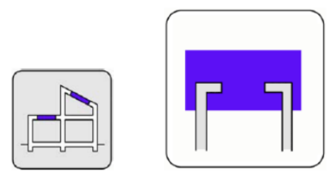


Balustrades en leuningen; leuningen

Omschrijving
Verzameling van voltooiingen van trappen en hellingen door middel van leuningen.

Functie
Steunpunt voor personenverkeer.

(37.1)

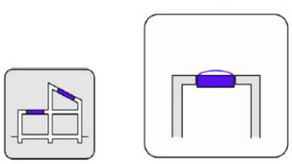


Dakopeningen; niet gevuld

Omschrijving
Verzameling van niet van een vulling voorziene openingen in daken.

Functie
Toetreding van daglicht en buitenlucht.

(37.2)

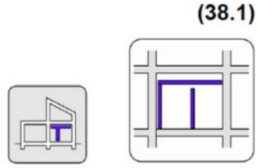


Dakopeningen; gevuld

Omschrijving
Verzameling vanmet een vulling voorziene openingen in daken.

Functie
Scheiding van binnen- en buitenruimten (akoestisch – beveiligend – klimatologisch – visueel), toetreding van daglicht, natuurlijke-ventilatievoorziening en daktoegang.

(38.1)

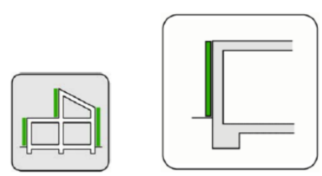


Inbouwpakketten

Omschrijving
Verzameling van complete bouwsystemen voor de scheiding van binnenruimten en vulling van binnenwandopeningen, indien deze geen onderdeel vormen van de draagconstructie van het gebouw en door ontwerp en/of uitvoeringsmethode niet te splitsen zijn in de groepen (31.0) t/m (37.0).

Functie
Scheiding van binnenruimten (akoestisch – beveiligend – visueel) en doorzicht en doorgang tussen binnenruimten.

(41.1)

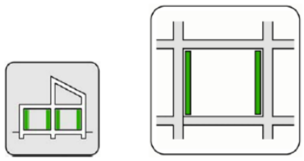


Buitenwandafwerkingen

Omschrijving
Verzameling van afwerkingen van de buitenzijde van buitenwanden, gerekend vanaf de wandconstructie.

Functie
Bescherming en verfraaiing.

(42.1)

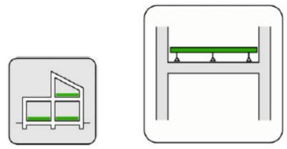


Binnenwandafwerkingen

Omschrijving
Verzameling van afwerkingen van de binnenwanden en van de binnenzijde van de buitenwanden, gerekend vanaf de wandconstructie.

Functie
Bescherming en verfraaiing, aanpassen van binnenwanden op gebruiks- en onderhoudseisen.

(43.1)

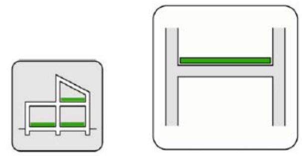


Vloerafwerkingen; verhoogd

Omschrijving
Verzameling van afwerkingen van de bovenzijde van vloeren door middel van een verhoogde constructie, gerekend vanaf de ondervloerconstructie.

Functie
Creëren van bijzondere ruimten en van installatieruimten.

(43.2)

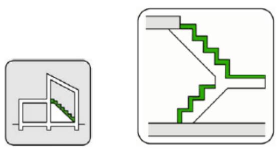


Vloerafwerkingen; niet verhoogd

Omschrijving
Verzameling van afwerkingen van de bovenzijde van vloeren rechtstreeks op de al dan niet verhoogde vloerconstructie aangebracht, gerekend vanaf de ondervloerconstructie.

Functie
Bescherming en verfraaiing en aanpassen van vloeren op gebruiks- en onderhoudseisen.

(44.1)

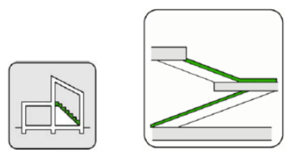


Trap- en hellingafwerkingen; trapafwerkingen

Omschrijving
Verzameling van afwerkingen van trappen en tussenbordessen, gerekend vanaf de trapconstructie.

Functie
Bescherming en verfraaiing en aanpassen van trappen en bordessen op gebruiks- en onderhoudseisen.

(44.2)

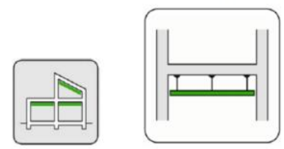


Trap- en hellingafwerkingen; hellingafwerkingen

Omschrijving
Verzameling van afwerkingen van hellingen en tussenbordessen, gerekend vanaf de hellingconstructie.

Functie
Bescherming en verfraaiing en aanpassen van hellingen en bordessen op gebruiks- en onderhoudseisen.

(45.1)

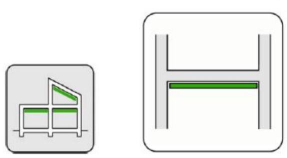


Plafondafwerkingen; verlaagd

Omschrijving
Verzameling van afwerkingen van de onderzijde van vloeren of daken met een verlaagde constructie, gerekend vanaf de bovenliggende vloer- of dakconstructie.

Functie
Bescherming en verfraaiing, aanpassen van plafonds op gebruiks- en onderhoudseisen en creëren van installatieruimten.

(45.2)

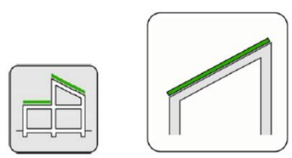


Plafondafwerkingen; niet verlaagd

Omschrijving
Verzameling van afwerkingen van de onderzijde van vloeren of daken, rechtstreeks op de vloer- of dakconstructie aangebracht, gerekend vanaf de bovenliggende vloerconstructie.

Functie
Bescherming en verfraaiing, aanpassen van plafonds op gebruik - en onderhoud eisen.

(47.1)

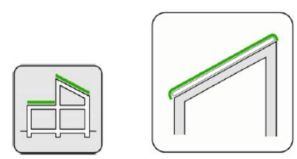


Dakafwerkingen; afwerkingen

Omschrijving
Verzameling van afwerkingen op de bovenzijde van horizontale en hellende daken en dakterrasafwerkingen, gerekend vanaf de (constructieve) dakvloeren.

Functie
Bescherming tegen buitenklimaat en aanpassen van daken op gebruiks- en onderhoudseisen.

(47.2)

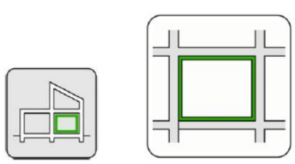


Dakafwerkingen; bekledingen

Omschrijving
Verzameling van bekledingen op de bovenzijde van horizontale en hellende daken en dakterrassen, gerekend vanaf de dakafwerking

Functie
Bescherming tegen buitenklimaat en aanpassen van daken op gebruiks- en onderhoudseisen.

(48.1)

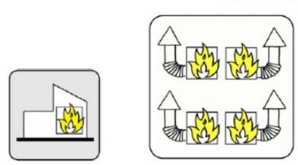


Afwerkingspakketten

Omschrijving
Verzameling van complete systemen voor de afwerking van binnenruimten, door ontwerp en/of uitvoeringsmethode niet te splitsen in de groepen (41.0) t/m (47.0).

Functie
Bescherming en verfraaiing en aanpassen van binnenruimten op gebruiks- en onderhoudseisen.

(51.1)

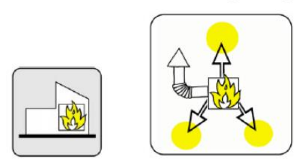


Warmte-opwekking; lokaal

Omschrijving
Verzameling van lokale voorzieningen voor opwekken en ter beschikking stellen van warmte ten behoeve van klimaat en sanitair van een enkele ruimte.

Functie
Lokaal opwekken van warmte.

(51.2)

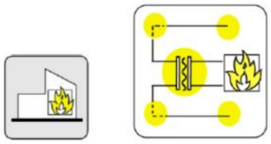


Warmte-opwekking; centraal

Omschrijving
Verzameling van centrale voorzieningen voor opwekken en ter beschikking stellen van warmte ten behoeve van klimaat en sanitair, vanaf het afleverpunt van de brandstof tot en met de hoofdverdeelinrichting van de warmtedistributie.

Functie
Centraal opwekken van warmte.

(51.3)

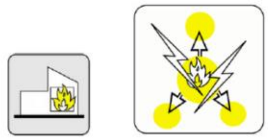


Warmte-opwekking; toegeleverde warmte

Omschrijving
Verzameling van centrale voorzieningen voor ontvangen van elders opgewekte en toegeleverde warmte voor omzetten en ter beschikking stellen van warmte ten behoeve van klimaat en sanitair, vanaf de warmte-omzetting tot en met de hoofdverdeling van de warmtedistributie.

Functie
Omzetten van toegeleverde warmte.

(51.4)

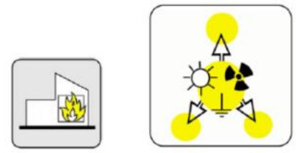


Warmte-opwekking; warmte-krachtkoppeling

Omschrijving
Verzameling van centrale voorzieningen voor gecombineerd opwekken en ter beschikking stellen van warmte voor klimaat en sanitair en kracht voor elektrische voorzieningen, vanaf het afleverpunt van de brandstof tot en met de hoofdverdeling van de warmtedistributie en van de elektrische energie.

Functie
Centraal gecombineerd opwekken van warmte en kracht.

(51.5)

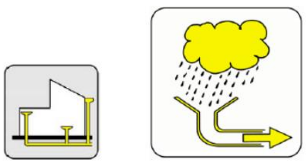


Warmte-opwekking; bijzonder

Omschrijving
Verzameling van centrale of decentrale voorzieningen voor opwekken of omzetten van warmte met bijzondere of alternatieve systemen voor klimaat en sanitair.

Functie
Bijzonder of alternatief opwekken en omzetten van warmte.

(52.1)

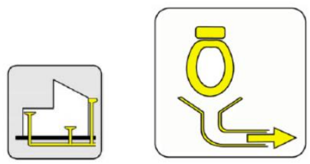


Afvoeren; regenwater

Omschrijving
Verzameling van voorzieningen voor opvangen en afvoeren van regenwater, zowel in als aan het gebouw, met de vaste ontvangstpunten, tot ca. 500 mm buiten de gevels.

Functie
Afvoeren van regenwater.

(52.2)

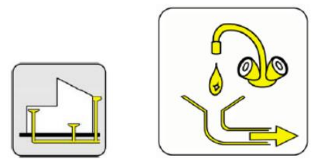


Afvoeren; fecaliën

Omschrijving
Verzameling van voorzieningen voor afvoeren van fecaliën, met de vaste aansluitpunten, tot ca. 500 mm buiten de gevels.

Functie
Afvoeren van fecaliën.

(52.3)

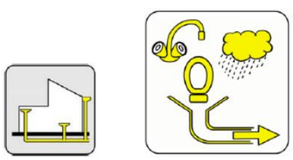


Afvoeren; afvalwater

Omschrijving
Verzameling van voorzieningen voor afvoeren van afvalwater, met de vaste ontvangstpunten, tot ca. 500 mm buiten de gevels.

Functie
Afvoeren van afvalwater.

(52.4)

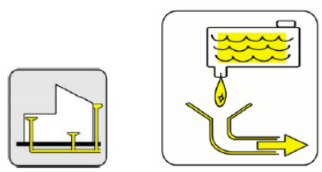


Afvoeren; gecombineerd

Omschrijving
Verzameling van voorzieningen voor het gecombineerd afvoeren van regenwater, fecaliën of afvalwater, met de vaste ontvangstpunten, tot ca. 500 mm buiten de gevels.

Functie
Gecombineerd afvoeren van regenwater, fecaliën of afvalwater.

(52.5)

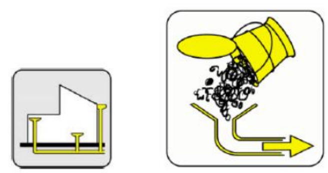


Afvoeren; speciaal

Omschrijving
Verzameling van voorzieningen voor afvoeren van speciaal afvalwater, met de vaste ontvangstpunten, tot ca. 500 mm buiten de gevels.

Functie
Afvoeren van speciaal afvalwater.

(52.6)

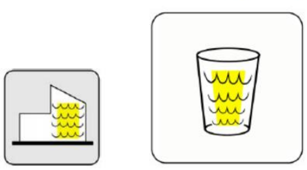


Afvoeren; vast vuil

Omschrijving
Verzameling van voorzieningen voor afvoeren van vast vuil, met de vaste ontvangstpunten, tot en met het verzamelpunt.

Functie
Afvoeren van vast vuil.

(53.1)

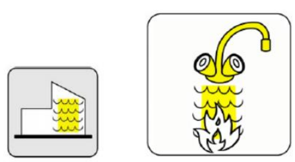


Water; drinkwater

Omschrijving
Verzameling van voorzieningen voor transporteren van drinkwater, vanaf de hoofd- of dienstvoeding tot aan de verbruikspunten.

Functie
Transporteren van drinkwater.

(53.2)

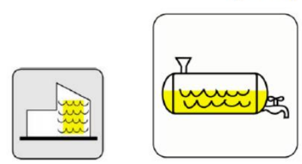


Water; verwarmd tapwater

Omschrijving
Verzameling van voorzieningen voor bereiden en transporteren van verwarmd tapwater, vanaf de koudwater-aansluiting op de waterverwarmer tot aan de verbruikspunten.

Functie
Opwekken en transporteren van verwarmd tapwater.

(53.3)

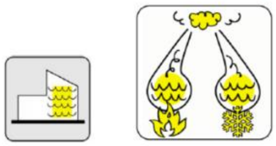


Water; bedrijfswater

Omschrijving
Verzameling van voorzieningen voor transporteren van bedrijfswater, vanaf de behandelingseenheid of het ontvangstpunt tot aan het afname- of verbruikspunt.

Functie
Transporteren van bedrijfswater.

(53.4)

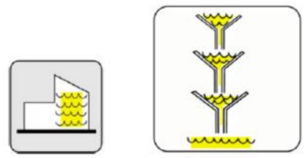


Water; gebruiksstoom en condens

Omschrijving
Verzameling van voorzieningen voor opwekken en transporteren van gebruiksstoom en condens, vanaf de koudwater aansluiting op de stoomopwekker tot en met de verbruikspunten en de condensterugvoer of -afvoer.

Functie
Opwekking en transport van gebruiksstoom en condens.

(53.5)

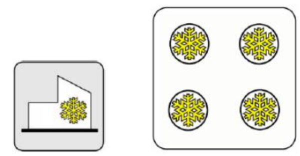


Water; waterbehandeling

Omschrijving
Verzameling van voorzieningen voor behandelen van de kwaliteit van water, vanaf het ontvangstpunt van het onbehandelde water tot aan het distributienet van het behandelde water.

Functie
Behandelen van de kwaliteit van water.

(55.1)

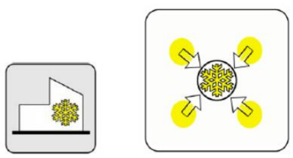


Koude-opwekking; lokaal

Omschrijving
Verzameling van voorzieningen voor lokaal opwekken en afgeven van koude voor het onderhouden van een behaaglijkheids- en conserveringsklimaat.

Functie
Lokale koude-opwekking.

(55.2)

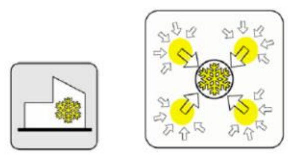


Koude-opwekking; centraal

Omschrijving
Verzameling van voorzieningen voor centraal opwekken van koude voor het onderhouden van een behaaglijkheids- en conserveringsklimaat tot en met de hoofdverdeelinrichting van de koude-distributie.

Functie
Centrale koude-opwekking.

(55.3)

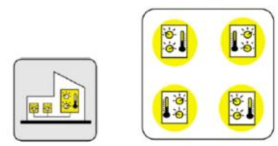


Koude-opwekking; distributie

Omschrijving
Verzameling van voorzieningen voor centraal distribueren van koude voor het onderhouden van een behaaglijkheids- en conserveringsklimaat vanaf de hoofdverdeelinrichting van de koude-opwekking tot en met de aansluiting van de koelers.

Functie
Centraal distribueren van koude.

(58.1)

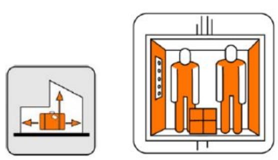


Regeling klimaat en sanitair; specifieke regelingen

Omschrijving
Verzameling van voorzieningen voor zelfstandig meten, regelen en besturen van installaties voor klimaat en sanitair, vanaf de aan te sluiten hoofdvoeding tot aan de regelorganen in het te regelen medium.

Functie
Specifieke regelingen van installaties voor klimaat en sanitair.

(66.1)

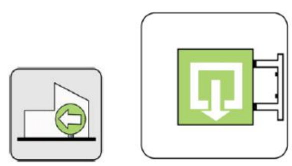


Transport; liften

Omschrijving
Verzameling van voorzieningen voor het verticaal transport van personen en goederen door middel van betreedbare liften.

Functie
Gemechaniseerd verticaal transport van personen en goederen.

(71.1)



Vaste verkeersvoorzieningen; standaard

Omschrijving
Verzameling van als standaardinrichting te beschouwen vast ingebouwde of aangesloten voorzieningen voor geleiding van verkeersstromen en inrichting van verkeersruimten.

Functie
Geleiding van verkeer.

(74.1)

Vaste sanitaire voorzieningen; standaard

Omschrijving
Verzameling van als standaardinrichting te beschouwen vast ingebouwde of aangesloten sanitaire voorzieningen, gerekend vanaf de aansluitpunten.

Functie
Hygiënische voorzieningen voor personen en gebouwen.

Appendix III – Questions for semi-structured interview

MSc Industrial Ecology [Master Thesis -Chiodo Alex-]

Interviews (Questions)

1. What does your company's activities focus on ?
    a. Construction
    b. Demolition
    c. Renovation

2. What is the size of your company (rough nr of employees/departments)?

3. What materials/construction elements (Top 3) are currently of most interest in your sector? (From a re-use/recovery perspective)
    *a. *Re-use: no need for re-manufacturing/refurbishing/recycling. Can be utilized as it is.*
    *b. *Recovery: selective demolition (carefully removing material/construction elements)*

4. Why these specific ones ?

5. What is the step-by-step decision-making process undertaken in your construction/demolition/renovation activity/ies for re-using and/or recovering material/construction elements (buildings only)?
    *a. (*If you are not yet re-using/recovering materials/construction elements, please outline the current default process)*

6. What are the data you need (now and in the future) for cost-effective re-use and recover of materials/construction elements?

7. What are, based on your experience, the ((mainly data-related)) challenges with regard to:
    a. (Construction) Reusing materials/construction elements
    b. (Renovation) Reusing & Recovering materials/construction elements
    c. (Demolition) Recovering materials/construction elements

8. Anything more you want to add?

Appendix IV – Informed consent form submitted and signed by interviewee

MSc Industrial Ecology [Master Thesis -Chiodo Alex-]

Interview (Terms & Conditions)

Dear Participant,

You are being invited to participate in a research study titled "*Can Blockchain technology tackle the data-related challenges associated with re-using/recovering materials/construction elements in/from buildings. Opportunities/Challenges for Blockchain implementation from a private sector perspective.*"

This study is carried out in the context of the **Interdisciplinary Thesis Lab: Circular Building Materials and (re)Manufacturing Hub**, as part of the Industrial Ecology MSc Master Thesis for the academic year 2021-2022.

This interview focuses on mapping the decision-making processes associated with re-using/recovering materials/construction elements in/from buildings and synthesizing the perceived data-related challenges associated with them. These will be compared and related to the characteristics/features currently offered by Blockchain technology.

The interview will have a duration of approximately 60 minutes. To obtain valid information, I kindly ask you to respond as sincerely as possible. Your participation in this study is **entirely voluntary** and **you can withdraw at any time. You are free to omit any question**.

I believe there are no known risks associated with this research study. To the best of my ability, **your answers in this study will remain confidential**. I will minimize any risks by **anonymising the answers. Personal information (e.g. personal name and company's name)** will only be available to me and my research supervisors. Information shared with external parties will be **anonymous** and will neither indicate your personal information, nor those of the company you represent in this research.

Finally, I request your permission to record this interview. Do you agree with the recording of the interview? The recording will not be shared with external parties.

Yes: ___ No: ___

Taking part in the study

Please tick the appropriate boxes

I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.

Yes: ___ No: ___

I agree that my responses, views or other input can be quoted anonymously in research outputs

Yes: ___ No: ___

I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team.

Yes: ___ No: ___

I have read and understood the study information dated **xxxxxxx**, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.

Yes: ___ No: ___

Signatures

_______________________ _______________________ _________

Name of the participant [printed] Signature Date

I, as a researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

__________________________ ____________________ _________

Researcher name [printed] Signature Date

For any further clarification or if you wish to be informed about the results of this research project, please contact me:

*Corresponding researcher:

Chiodo Alex
Email address: a.chiodo@umail.leidenuniv.nl / chiodo.alex@gmail.com
Phone nr: 06 82539235 (NL)

Appendix V – Quotes used for analysis of sub- question 2

Table 24 - Relevant quotes for sub- question NR 2

[Quote 7.6]	"These steps indicate the workflow. Actually the steps depend on the scale and character of the project. • Making a preliminary design • Finding local and circular materials • Adapting the design to the found materials • consultation with client about final design • Buying the materials • organisation of transport and logistics of materials • construction"
[Quote 7.7]	"**Alex**: In point 5 you say: Finding local and circulair materials / Adapting the design to the found materials; How do you do this and what specific information/data do you need for undertaking these steps? **Answer**: We need dimensions, photos, sometimes we need to check the quality on site. **Alex**: When do you know that material/construction elements become available? Who contacts you ? **Answer**: I send an email and demolishment copmanies reply to me. **Alex**: Do you pay for these materials/construction elements? **Answer**: Yes, off course. Our client does. **Alex**: Do you retrieve these from existing buildings in the demolition phase/before demolition, or only after demolition? **Answer**: Both. interior materials you can retrieve before demolition. The facade should be complete untill demotlion. After demolition is most handy, then the demolishment company puts the materials outside or on transport for us."
[Quote 7.8]	"**Alex**: You decide on site what material you can reuse for a new project ? **Answer**: Sometimes on site, but sometimes the demolisher sends pictures to us when we ask for it. We have a network of demolishment companies. When we need certain materials, we mail our network and wait for replies. They send us pictures and specs. Some demolishment companies have their own websites where they publish pictures of available materials. Sometimes we know the building owner or building user and get a tour in the building that soon will be demolished."
[Quote 7.9]	"Alex: Do you store somewhere the information of the material you have reused in a new project? Answer: We always make a document called 'harvest map'. This is a nice graphical overview in which the reused materials are visible. it would be great to put the technical specs there, too."
[Quote 8.0]	"(…) the supply of materials is never a problem for us. There are loads of materials an buildings available. Therefore we always work on demand. I mean, we only spent time on certain materials when we have an application for them. The demand of materials is always smaller than the supply of materials."
[Quote 10.3]	" Alex: DO you check the BIM model /material passport of a building to take a preliminary decision? Answer: No, we do not. Since we do not use BIM yet. Since the building that we have retrieved materials from, didn't have a bim model or passport. Also we are not really familiair yet with BIM. Alex" Do you make material passports of the new buildings you design ? Answer: No"
[Quote 5.7]	" (…) the government the party assigning the work to us (Like building the bridge) then we do the contracting. Or in the first phase we do the governance process (for example how do things work), are there any environmental issues. Then the designing part, the contracting part but the building itself we don't carry it out. Contracting to a construction company is something the government does, not us. And to make it more complex, often the government asks our specialists and consultancy and procurement to do the procurement process for them."
[Quote 5.8]	"Money is the key. If you look at the housing consortium in the Netherlands (municipalities, institutions) and you look at what they have built you see they are using the same type of materials. Project developers have made so many efficient steps in creating a product that they can capitalize on. With the lowest construction and material cost and the biggest profit. The construction process is always a money-driven process. You have to respect certain standards. And this is interesting about materials beoming scarce and now the cost of material is entering part of the procurement process. In our world **EMVI: economisch meest voordelige inschrijving** means that costs are always the most important driving factor."
[Quote 5.9]	"In procurement it happens now that in an EMVI you say you want to use better materials. Then the construction company has an incentive to do something. And then we have the MKI (ECI) (https://ecochain.com/knowledge/environmental-cost-indicator-eci/) standards that are used in the procurement process. So there is a CO2 standard in the civil engineering process where they have to show their Milieu KOsten Indicator (ECI) rating. LINK: https://www.kiwa.com/nl/en/themes/sustainable-entrepreneurship/sustainable-certification/mki-value/"
[Quote 6.0]	"And there is a difference between the construction of buildings and the construction of civil engineering projects. Because in project development the piece of land is sold to the best bid and it really depends on the municipality. (…) someone from the municipality of Amsterdam was telling about an area they have developed and the goal was to make it sustainable and circular. So all these aspects were driving the development. Construction companies or project developers who wanted to build there had to show in their plans that they would build in a certain way. Amsterdam has the unique advantage that everybody wants to build there and there is a lot of money to be earned. But if you look at other places in holland you see that this ideological aspect (of circularity) is less important."
[Quote 6.1]	" If there aren't incentives to do it in a more sustainable/circular way, the markets are not going to do it on their own. Because competitors will do it for less money. of course, there are exemptions where the unique selling point of a company (being circular) is the core of their business. But those are very scarce right now."
[Quote 10.2]	"If we look at all XXXX we have an infrastructure department and we have a development department. Building and development Department are working together a lot. One of them buys the ground and asks the other company to build houses/apartments or schools on it"
[Quote 6.2]	"Mostly driven by money. So financial reasons. A factor is that in holland we have many offices which are not used and we need a lot of houses. So there are a lot of offices available used for building houses in them . So you take everything out, piping, windows roof and so on. You keep the old frame but you build a new building in it."
[Quote 6.3]	"Designer are also looking into old designs to see what can be reused. But this is not very common"
[Quote 6.4]	"Currently we only know on the spot when some material is available. SO if someone of our clients decides to make a new building out of the old one. Then this is no problem. But when we need materials from another project and put it from client A to client B, then it is a bit of a problem (…)"
[Quote 6.5]	"We have the bouwen woning verenigen (company with a lot of apartments) that wants to demolish an apartment complex and built an apartment complex somewhere else in the city. There it would be easier to implement a reuse scheme. But doing this large scale it would be harder."

[Quote 6.6]	"My job is to inform xxxx about incoming projects of our clients and there is no one project that we tender at the time the project starts. Usually it its month, years later the tender. Especially because of the elements outlined before (weather, labour, the condition of the plot, licences). When there is one stakeholder that says I am against this project-> you delay 1 year. If you find something in the ground, you need to do research and delay the project. This is the problem."
[Quote 6.7]	"There are group of people thinking for 5 years about a project and then in 2 month we make the project. Like a sort of funnel."
[Quote 6.8]	"The easiest is to reuse on the same project. And the planning can also be merged into one. But I think this is complicated on multiple sites."
[Quote 7.0]	"What I find important is to have a project where we make our own designs. But oftentimes we develop projects for other clients. So where we have a developer and a building company the possibility of recovering and employing reused material would be more feasible. This is one of the very important parts. Because when we work on client's designs, we are not able to adjust the design and make it fulfil certain needs."
[Quote 7.1]	"A lot of them are not my decision because when we receive a project most of those decision are already taken by the architect and the owner of the building (commissionaire). Oftentimes they have already decided what is going to happen with the old and with the new building."
[Quote 7.2]	"(…) 10% we are also developers and the remaining 90% of jobs are just execution."
[Quote 7.3]	"IN the last project we have executed the construction. A part of the construction was maintained while another part was reused and integrated in the new building. Some years ago we have kept the basement of a building. This project was at the centre of an old town and there was not enough space to demolish the basement so we talked to the developer and the construction engineer. And we decided together to reuse it and we designed the new construction with the same plot."
[Quote 7.4]	"I think we are a bit late with the adoption of BIM. But we use it very little. Most of the designs we get from the architects/engineers is in BIM, so we use it but we make a lot of small projects, not big ones."
[Quote 7.5]	"But currently for our renovation works we have no BIM models as these are too old and have no digital model."
[Quote 8.1]	"Look at the full reuse process I send you in a previous mail ;). Next to this, the deconstruction company is only reusing products that are in potential profitable (look at the timber process on the circular building hub in Utrecht). So if many refurbishments steps are necessary and safely dismantling which can be costly, costs more than recycling and profit of selling them, then they won't do it."
[Quote 8.2]	"Or you attend a tender or you get a call from a customers and that they need a demolition, we make a calculation for the total demolition and during this process our circular advisor looks at the building and identifies all the material that are worth reusing."
[Quote 8.3]	"**Alex**: does he go there physically. And can you describe the action he undertakes for doing this inventorization process. **Axel**: Walks through the building, take pictures and take notes. It is quite a very basic inventory of the building and the materials that he sees. And based on his experience he determines whether something is interesting or not. And then he checks his network. Then there are 2 options, either he makes a very basic inventorization in excel or word but now we are building an app via which he can make a database of each building he makes an inventory of. And the database can be connected to our webshop. This is the second level."
[Quote 8.4]	"the third level is to make a material passport which will make more and more often. If we make a complete material passport, 1-5 days in a building and then we take dimension and pictures of everything. That is a very high level of detail and therefore very expensive. But then you know exactly the details of the building. For very large projects we do that. We do not do that for more than 6-7 times a year."
[Quote 8.5]	"(..) it all starts with making inventorization of all materials that can be reused, the secondly if we win the tender/or get the assignment of the customer. The minute that happens Sebastian tarts looking for buyer, he start calling people in his network. We also receive shopping lists from Architects (looking for this and that) so we look for buyers and at the same time he posts the materials that he thinks are hard to sell on our webshop. And so this process is not finished because I want him to put all our materials on our webshop so that's a good reputation of what we do. After that the deconstruction team (reuse team) [we have 3 of those teams] go to the building and they take out all the materials that Sebastian has on this list and then preferably they go form the project to the buyer. Otherwise it goes to one of our circular hubs and we store it there until we sell it."
[Quote 8.6]	"**Alex**: So what is the lag time that Sebastian has between getting the tender and deciding the material gets stored in the Hub or you decide to throw it away. How do you get the decision of keeping it in the material hub or throwing it away. **Answer**: I think 95% of the materials Sebastian puts on the list we actually take out. And if we do not sell it we take it to the hub. Of course we do not sell 100% but what we do see is that some thing stay in the HUB for long time and eventually get thrown away. But that is actually a small percentage and is getting less. Over the years we got more experienced on what is the demand of certain products. That also means that if something is very nice but we think that there is no demand, we try to sell it. But if there is no demand we do not take it out and we demolish it."
[Quote 8.7]	"(…) the architect would not buy the material tomorrow for starting to build in 2 years so there is a time gap of 2-3 years between the moment we know exactly what is in the property and the time the architect starts actually build the new building."
[Quote 9.0]	" The ROI is very similar right now. Of course it changes per project but the demolition companies that do all in the traditional way are still doing fine and actually making large amounts of money with no problem. Because we like to invest in circular projects, even if sometimes we make less money doing in the circular way, we see this as a long term investment. We work for most big construction companies and most big real estates developers. They all want us to work circular, They all want us to work sustainable and safe. They call us because they know we work as circular as possible. So talking about ROI it is less interesting to do it circular then the traditional way. But still companies doing it circular are anticipating the increasing of prices and also legislations. They will be ready when this will become the norm. Again, I am really convinced that our customers are our customers because we work with this attitude. Sustainability is a huge and very important. Especially for the big companies. So they want to gather partners who work as suitable as possible. As long as it does not cost them too much."
[Quote 9.1]	**"Alex**: do you decide with your partners what materials can be harvested and reused ? Do you also discuss specifically on a product (case-by-case) level? **Answer**: Yes in a short way. But let me give a mor concise example. For example the cable trail are easy because you do not have regulation about those, you just need to dust them off, remove the coating, and painting. Sometimes they put them high next to the ceiling and in those cases you have no issues in terms of regulations. With wood for example, we have different qualities defined (A,B,C products). The A goes to one specific partner and he has many requirements and the piece needs to comply to specific specs. Otherwise it becomes a B quality and so on. So we find different ways of reusing it (C for example can be shredded) In any case we tend to find ways of reusing them."
[Quote 9.2]	"(…) we have a variety of materials, But I define them in 2 categories: bulk (needs the breakdown and refurbishment like bricks and concrete) and you have element-base (wood, sanitary, cable container and so on). Within the element base: this is a bit easier. If you dismantle a building and you have products on element we have rules with our partners that they pick up all the those elements with a reversed logistics. We have some distributors who have a lot of organizations within holland and a lot of clients. So they have a very large logistics and reversed logistics with empty cargo. So these empty cargos go to our demolitions sites, pick up the elements we have put aside and then put them on stock and sell them again. This is quite simple. Sometimes these elements need a bit of refurbishment.For the bulk materials instead, it is a bit a different scope. IN this case during the dismantling side this is easy. You just need to selectively demolish and keep it clean. So extract and separate concrete, bricks, gypsum. So you need to divide things in different compartments. Then maybe we do the logistics or the partner does it. Then they have the whole process for breaking this down and making a new product out of it. The business case is that we sell these

	products (bulk or element base) to our partners (we are like a middle man). They buy it from us as if it would be purchased as new products (the way they include them in stock) from suppliers."
[Quote 9.3]	"**Alex**: As far as I understood, you have 2 distinct flows for 2 distinct material categories. One are products that are ready to be reused in a new building structure, the second group are bulk products that need to be reduced to a raw state in order to be re-processed into new materials. Is this right ? **Answer**: yes correct. And for each material/partner we have some sort of different business case. So we have partners in 4 different categories: producers, distributors, waarmakers/traders (helps distributors and producers with selling and distributing the products on the market), knowledge partners (only services like ABN Amro, companies making the LCA of products)"
[Quote 9.4]	**Alex:** focusing on element-based materials. • how efficiently is this working for you ? • Out of x elements you collect how many are re-sold? • Do you always recover the same materials ? or do you conduct an assessment before doing it ? **Answer**: It really depends which materials we are talking about because our electro technical partner (for the cable container) this is very simple to remove and install. (…) there are different ways and challenges about quality, regulations and compliance. With other elements like the cable tray this is very simple and the business case is quite consolidated and stable. We have calculated the added value, the environmental impact and the business feasibility and have arranged the logistics to support it. SO then we made the business case with the reversed logistics. We have to scope in/out how are we using the materials and how do we build the right business case. IN the material base many products can use the same structure. For example the sanitary have the business case as the cable tray, they just need slightly more cleaning. So you have the same business case that can be applied to different partners. So I think that once you set this up once you can replicate it more times with more and different partners. We have the experience and take the partner through the process. For the reuse percentage you can look it in 2 ways. Currently it is not possible to reuse elements a 100% because we don t have enough partners for reusing everything. Also there are some products that cannot reuse at the moment. Only if you have different thought of it and rearrange their configuration. Then you have to scope in on 2 levels: 1. if we have a material that we have a contract for with our partner the contract should say that if it has the right specs you should take it (think about gypsum is very vulnerable and can break very easy and this depends on building the dismantling and how the house is constructed) Then you have the total scope of the materials we are currently recovering. Also this depends on the building. You have certain buildings with a lot of concrete or steel (which we do not recover) so the percentage (of recoverable) varies a lot per project. And we have a lot of materials right now that we can recover but at the moment we brought back to life 63 products and materials. I think at the moment that we have in a continuous flow we have 15/20 materials"
[Quote 9.5]	"Starts with we get a question from customer or from the Municipality or institutions. They ask you to make a quote for demolition **Step 1 Offer and estimation** You have 1 day for walking around and see the materials. You get the digital floor plans of the building for making our estimations (estimations are made by the team). I walk around too to see if there are materials I can reuse and resell instead of throwing them away. Some materials are also offered to other parties if they can get it out from themselves. I make an estimation about the market of wood for example. The market can change and the price tomorrow can be higher. I make a price and we put this in the total price and in the plan. We care about circularity so if we can we try to recover it or we give it to the customer. We give the plan and price to the customer and we get their reaction within 1 month with a reason. **Step 2 Allocation** If we start with the project I go in the building and put all the materials/products on my laptop and try to sell it to my network. I have my partners, customer, and big companies who resell it. Sometimes some people want a piece of wood in their garden. I try to sell the whole building like that."
[Quote 9.6]	"I have a large network and with every project it is expanding a bit more. We work in whole NL and the partners differ from area to area. Someone from a certain area will not drive the whole way to Groningen for a wooden beam."
[Quote 9.7]	"I first contact my network then I go on platform like Insert where you have only companies there and then you have marktplaats the website. When I say to people do you know insert they don't. Because of this Marktplaats is better. The last resource is going to local companies who need materials. We create an event for them and they can take the material if they need it. They have these project where they take the wood and they refurbish it for other things they might use it. Sometimes it depend on the contract with the customer who defines in the contract who to call first for reusing the material. So sometimes it is the customer telling us who to prioritize in these activities. I go first to my network because these are trusted partners. I am assured they will come and take it out by this date. If I contact people outside my network they make an offer but then they do not show up. This is the difficulty because I cannot trust them. I need to stick to a certain deadline and I cannot delay if people do not show up. The head of the project will tell me that we have to go ahead and things will eventually go to recycling."
[Quote 9.8]	"When we are on site we are already too late to make this decision. We have a deadline within which everything has to be out. The way it works today, they call an architect and get a plan, then the papers and then they think about the building still standing there. Then they call a demolition company and get a price for bringing it down."
[Quote 9.9]	"You always go do a site visit with other demolition companies and they way you look at things Is very specific to you and your network."
[Quote 10.0]	"Alex: What is the time window you have from when you get to project to when you decide to either sell or demolish everything. Answer: We have no time. We set some internal deadlines and if we do not meet them then we decide to demolish everything."
[Quote 10.1]	"(…) material passport system that is connected to the tender. Basically in the tender you have to fill in the volumes of materials you will be reusing and this will give you a score and based on this you get the job or not. This is such a unreliable system. But more companies are getting into this mechanism now. But you are not sure whether you can resell this material on the market."
[Quote 5.6]	*"If I see 10k of stuff I can sell, my demolition price goes down by 10k for the customer."*

Appendix VI – Tender conditions with reuse indicators

3.6.1 Selectiecriteria

Criterium	Beschrijving	Aandachtspunten	Doelstelling Aanbesteder
S1 Affiniteit met de circulaire economie	De inschrijver dient met haar organisatie affiniteit te hebben met de transitie naar een circulaire economie aangetoond met een korte omschrijving van haar visie hierop. De visie dient te voldoen aan de volgende kenmerken: - Maximaal één A4 aan toelichtende visie van de organisatie met betrekking tot haar bijdrage aan de transitie naar een circulaire economie.	De mate waarin met de visie de affiniteit wordt aangetoond om als organisatie bij te dragen aan de transitie naar een circulaire economie. Dit wordt concreet gemaakt, geen abstracte termen, met bijvoorbeeld: - Visie transitie naar een circulaire (bouw)economie en de (toekomstige)rol van Inschrijver hierin; - Door het aangeven van een missie en visie van de organisatie; - Concrete beschrijving van werkzaamheden die de organisatie verricht, naast de primaire taken, om de circulaire economie verder te brengen, kennis hierop te ontwikkelen en te delen; - De wijze waarmee de organisatie bijdraagt aan het verder brengen van Hoogwaardig hergebruik van producten, materialen en (grond)stoffen danwel de circulaire economie; - Het aantonen/ meetbaar maken van de impact met betrekking tot Hoogwaardig hergebruik en aanleveren van cijfers die de impact op circulariteit aantonen. - Het aantonen/ meetbaar maken van de impact met betrekking tot duurzaamheid: CO2, milieu-impact, aansluiting op de duurzaamheidsdoelstellingen (sustainable development goals).	Aanbesteder wil Gegadigden partijen selecteren voor de dialoogfase die het meest geschikt zijn een aanbieding te doen die aansluit bij de projectambities en bij zal dragen aan het behalen van de projectdoelstellingen.
S2 Hoogwaardige hergebruik beton (prefab vloerelementen, prefab wandelementen, gestort beton)	Eén referentie -welke niet ouder dan vijf jaar gerekend vanaf de sluitingsdatum van de Aanmelding welke Hoogwaardig hergebruiken van vrijkomende betonnen constructie onderdelen zoals vloeren, kolommen, wanden en liggers, door ze bij voorkeur voor dezelfde functie toe te passen, laat zien. De referentie dient te voldoen aan de volgende kenmerken: - Maximaal één A4 aan toelichting met betrekking tot de referentie en de bijdrage van de Gegadigde hieraan; - Tevredenheidsverklaring opdrachtgever referentie; - De referentieopdracht is niet ouder dan vijf jaar gerekend vanaf de sluitingsdatum van de Aanmelding; - De referentieopdracht is naar behoren uitgevoerd, zowel met betrekking tot de wijze van uitvoering als met betrekking tot het resultaat.	De mate waarin de referentie Hoogwaardig hergebruiken van vrijgekomen betonnen constructie onderdelen zoals vloeren, kolommen, wanden en liggers, door ze bij voorkeur voor dezelfde functie toe te passen, laat zien. De technische bekwaamheid wordt aangetoond om daadwerkelijk impact te maken op de circulaire economie door het vinden van hoogwaardige afzet voor vrijkomende beton (constructies en/of elementen) bij een geamoveerd gebouw. Gegadigde dient genoemde competentie te bewijzen aan de hand van één referentieopdracht waarin dit wordt concreet gemaakt, geen abstracte termen, met: - De hoogwaardigheid van het hergebruik. Hoe hoger op de R-ladder (R3 t/m R8 waarbij R3 het hoogst is), hoe hoogwaardiger; - Omvang van het hergebruik (een grotere hoeveelheid in kg/ m2 en/of % ten opzichte van de totale hoeveelheid, is een hogere score); - Verschillende type betonnen constructie onderdelen zoals; vloeren, kolommen, wanden en liggers (meer typen Hoogwaardig hergebruikt is een hogere score); - Wijze van organiseren van de gevonden afzet zodanig dat de kans voor Hoogwaardig hergebruik aantoonbaar is gemaximaliseerd.	Aanbesteder wil Gegadigden partijen selecteren voor de dialoogfase die het meest geschikt zijn een aanbieding te doen die aansluit bij de projectambities en bij zal dragen aan het behalen van de projectdoelstellingen.
S3 Circulair delven	Eén referentie -welke niet ouder dan vijf jaar gerekend vanaf de sluitingsdatum van de Aanmelding welke de bekwaamheid van gegadigde met het Circulair delven van een gebouw laat zien. De referentie dient te voldoen aan de volgende kenmerken: - Maximaal één A4 aan toelichting met betrekking tot de referentie en de bijdrage van de Gegadigde hieraan;	De mate waarin de referentie Hoogwaardig hergebruiken van vrijgekomen producten, materialen en (grond)stoffen laat zien. Gegadigde dient genoemde competentie te bewijzen aan de hand van één referentieopdracht waarin de volgende aspecten tot uitdrukking komen: - De Gegadigde was verantwoordelijk voor en belast met het management en de uitvoering van de referentieopdracht;	Aanbesteder wil Gegadigden partijen selecteren voor de dialoogfase die het meest geschikt zijn een aanbieding te doen die aansluit bij de projectambities en bij zal dragen aan het behalen van de projectdoelstellingen.

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	- Tevredenheidsverklaring opdrachtgever referentie; - De referentieopdracht is niet ouder dan vijf jaar gerekend vanaf de sluitingsdatum van de Aanmelding; - De referentieopdracht is naar behoren uitgevoerd, zowel met betrekking tot de wijze van uitvoering als met betrekking tot het resultaat.	- Het slopen van een gebouw middels circulair delven -niet zijnde een bedrijfshal- met een omvang van ten minste 1.000 m2 BVO, welk gebouw geheel of gedeeltelijk bestaat uit ten minste 2 bovengrondse bouwlagen (een grotere omvang is een hogere score); - De referentieopdracht bevat voorbeelden van vrijkomende Materialen die hergebruikt zijn op niveau R3 t/m R8 van de R-ladder. Hoe hoger op de R-ladder (R3 t/m R8 waarbij R3 het hoogst is), hoe hoogwaardiger en grootschaliger hoe groter de score; - De mate waarin de bekwaamheid wordt aangetoond om als organisatie zelfstandig hoogwaardige afzet van vrijkomende Materialen te organiseren te bewijzen aan de hand van minimaal één voorbeeld waarin de volgende aspecten tot uitdrukking komt dat gegadigde afzet voor Hoogwaardig hergebruik (niveau R3 t/m R8 van de R-ladder) van vrijkomende Materialen kan organiseren door specifieke afzetkanalen aan te wenden.	

Algemene eisen referentieopdrachten ter onderbouwing van de selectiecriteria

- Eenzelfde referentieopdracht mag voor meerdere Selectiecriteria en Geschiktheidseis worden gebruikt.
- Per selectiecriterium mag maximaal één referentieopdracht worden opgevoerd.
- Indien een gegadigde een beroep doet op een derde(n) om de geëiste competentie aan te tonen, dan dient dit door de gegadigde te worden aangegeven in de eigen verklaring onder deel IIC.
- Indien een referentieopdracht in een combinatie of in onderaanneming is uitgevoerd, dan dient de gegadigde zijn eigen aandeel in de bijlage "Model opgave referentieopdrachten" te beschrijven. Het aandeel dat door de gegadigde is uitgevoerd, moet de geëiste competentie(s) aantonen.

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Beoordelingscijfer	Waardering
8	**Uitstekend:** uit de door de gegadigde verstrekte informatie blijkt dat er boven verwachting en meer dan volledig aan het doel van dit criterium wordt beantwoord. De inhoud is duidelijk, concreet en goed onderbouwd met bewijsstukken en praktijkvoorbeelden.

	De relevantie en meerwaarde voor dit criterium is integraal en overtuigend uitgewerkt
6	**Goed:** uit de door de gegadigde verstrekte informatie blijkt dat er volledig aan het doel van dit criterium wordt beantwoord. De inhoud is duidelijk, concreet en goed onderbouwd. De relevantie en meerwaarde voor dit criterium is goed en overtuigend uitgewerkt
4	**Ruim voldoende:** uit de door de gegadigde verstrekte informatie blijkt dat er in ruim voldoende mate aan het doel van dit criterium wordt beantwoord. De inhoud is duidelijk en concreet. De relevantie en meerwaarde voor dit criterium is ruim voldoende uitgewerkt
2	**Voldoende:** uit de door de gegadigde verstrekte informatie blijkt dat er in voldoende mate aan het doel van dit criterium wordt beantwoord. De inhoud is duidelijk en concreet. De relevantie en meerwaarde voor dit criterium is voldoende uitgewerkt
0	**Neutraal:** uit de door de gegadigde verstrekte informatie blijkt dat in onvoldoende mate aan het doel van dit criterium wordt beantwoord. De inhoud is niet volledig duidelijk en concreet en/of irrelevant. De relevantie en meerwaarde voor dit criterium is beperkt uitgewerkt.

Wegingsfactor
De wegingsfactor geeft het belang van het selectiecriterium weer. Hoe hoger de wegingsfactor, hoe belangrijker het selectiecriterium.

Totaalscore
De totaalscore wordt berekend door de scores per (afzonderlijk) selectiecriterium bij elkaar op te tellen.

Nr.	Selectiecriterium	Wegingsfactor
S1	Affiniteit met de circulaire economie	1,0
S2	Hoogwaardige afzet beton	3,0
S3	Circulair delven	2,0

Tabel weging selectiecriteria

Appendix VII – Internal process chain of demolition company

Process_chain_demol
ition_ company_Zuid_

Appendix VIII – Quotes used for analysing sub-question 3

Table 25 – Relevant quotes for sub-question NR 3

[Quote 10.6]	"Tim and I have talked to companies on the civil engineering side (bridges and large constructions) and they told us that it is very difficult from a quality assurance perspective to reuse stuff. They might have it but the dimensions are not right, and the quality is not high enough so they do not want to risk certain legal consequences. If you are not designing for circularity, they most likely will not fit a new project. So this perspective has to be there in the design phase/process. We have talked to the Waterschap and they have a lot of riet (reed plant) (10t a year) and if a construction knows that next year January they will receive this amount they can use it for insulation. But if you do not design with that material in it, then you lose this opportunity. So the connection between institutions that can benefit from each other."
[Quote 10.7]	" First thing is the quality, so quality assurance that the material lives up to certain standards. Time, this is also one of the USPs of our system/platform. When do you need a material, when it becomes available and matching those two data. These are very important data. Description of the element. What is in it, what is it made from. This I think is actually very important. (…) If you talk about a brick, what is its size colour and so on. These kinds of specifications. For a bridge, this is way more complicated. So the more information the easier it becomes to reuse."
[Quote 11.1]	"Making the connection between the right parties. This is the most important thing. Connection from a demand and supply point of view. We have to make sure that exactly at the right moment we can supply something that is in demand. For us, this is the most critical thing. Of course, we are more focused on the infrastructure part. That is a thing like the supply and demand exists. Some marketplaces are working with supply and demand, but the challenge is to know what is there in the coming year for example. Question: has the certainty anything to do with this? Answer: Yes! Also! Certainty and the that the quality is assured."
[Quote 11.2]	" Question: Based on what you have shown me on your platform, namely the possibility of meeting offer and demand. How did you get this information? Do you think this information can somehow be automated? Answer: That is our USP that we are on the programming side of building processes, so we know during the design phase that we are going to build 4 years from now. There are always long periods. We know that part. And we also know from our clients when assets can be harvested. For instance, a road is an easy example. The municipality has an agenda that says in 4 years we will take up this road. We know that we have this other project that needs building blocks for a road that is less used. Or we know that we have a temporary road while we are building and we can use those bricks for that temporary building road. Then we can make those connections quite easily. As we have data from both sides."
[Quote 11.6]	"Question: What about the availability of materials? Is this important for you? Answer: Yes it important. Currently we only know on the spot when some material is available. SO if someone of our clients decides to make a new building out of the old one. Then this is no problem. But when we need materials from another project and put it from client A to client B, then it si a bit of a problem. Because you never know when the material is available. There is no platform for that right now. We have a platform for second hand bridges (https://www.nationalebruggenbank.nl/). But for houses or offices there is nothing like this right now. Because it is too difficult to match offer and demand right now."
[Quote 11.8]	"The advantage of working on a small client is that the client can adjust the planning. If you know you do a certain activity this year and then the next in another moment, you can plan the supply and demand of the materials. It is one client and one wallet and this makes it easier. But when you build up a marketplace for all materials and you do that on a large scale. The problem is that you have so many influencing factors like weather, labour, the condition of the plot, and licences and those are all elements that influence the planning. And thus very hard to align them all and use the recovered material in one unique process. So take out and put in. It is possible if you would recover it, store in a hub and then put it in a building. But recovering and reusing between different clients/projects and considering the external factors outlined above, is extremely complicated to do."
[Quote 6.7]	"There are group of people thinking for 5 years about a project and then in 2 month we make the project. Like a sort of funnel."
[Quote 12.0]	"And this si a problem. It is not feasible to plan the last minute with the materials because these are bound to the whole design process starting years before."
[Quote 12.1]	"The information is the quality of the project. The measurements, the specs of materials the quantity, the planning is very important. Also the strength of the materials and required strength (static). These are the important elements as data information."
[Quote 6.8]	"The easiest is to reuse on the same project. And the planning can also be merged into one. But I think this is complicated on multiple sites. So you need a designer that knows what is available and what needs to be constructed. So your challenge as a designer is to use all these materials and to make a nice design out of it."
[Quote 12.9]	"(…) the material must be available at the time of construction. We are bound to the timing. If demolition starts in June we cannot wait for 3 or 4 months."
[Quote 13.4]	"(…) what it is really needed is the quality of the product, specs of the material and the availability of material (timing) and someone certifying it. Also, that the customer knows what to expect. Again, when people buy a new house they expect to have new components and not old ones. This is one of their largest investments and they want to be really sure about the quality of what they buy. When you buy it you buy it based on price not on the vision of reusing it. A lot of people buy things as a way for doing good to the world while a large part just buys it for the price of the final product. This should be taken into consideration."
[Quote 7.8]	"Question: You decide on site what material you can reuse for a new project ? Answer: Sometimes on site, but sometimes the demolisher sends pictures to us when we ask for it. We have a network of demolishment companies. When we need certain materials, we mail our network and wait for replies. They send us pictures and specs. Some demolishment companies have their own websites where they publish pictures of available materials. Sometimes we know the building owner or building user and get a tour in the building that soon will be demolished."
[Quote 13.9]	"Question: What are the exact challenges associated with working with reused materials?

	Answer: Planning. The materials you want to use should be available on the right moment that your project starts. Preferably without extra costs for extra transport and storage."
[Quote 14.4]	"And that time gap I would say is the biggest challenge we have right now when ti comes to reusing materials Ideally we would need the information of the property we want to demolish 2-3 years in advance."
[Quote 14.7]	"The lack of data and information that we have about the material is the biggest issue. If we stay with steel we do not know anything about that. Even if you have the data of the builder, or origin of steel 30-50years ago and give is to you right before starting. Steel gets old and if you use it for a long period of time in a building it gets old. So the material changes, you need to test it and see if it is of good quality. This costs money. Secondly, the problem we have just describe that the timeframe does not match. But there is third element as well and that is there no public marketplace through which these materials find their way. It might be that we have material that are perfect for new construction starting very soon. But if you do not know you don t know. So I guess the whole country is waiting for this big database that will arise magically and that will match demand and supply. You have marktplaast and insert which work for a sink but these websites do not provide enough information or information suitable for construction materials. Actually this is what Fabian is doing. The matching platform that he build that would be a huge solution if it would be scaled up. If that would work and all construction and demolition companies can link their data to this model so that this database could become very big then we would have a huge tool for matching offer and demand. Then the bigger the database with all materials and new products becomes, the smaller the timing issue becomes as well. The knives cut on both sides."
[Quote 15.9]	"We are working on an app that would help us to expand our knowledge about the material content of buildings. "We need to know the demand and also what is the offer. You need demand from the market about materials. For example now we have a high demand for concrete due to the environmental aspect but also because it is widely adopted in construction. IN the other way, it is also a product we see and demolish/dismantle a lot. But there also many other materials that are not present in every building but is also a not very demand driven product. But in the future it would interesting to have an overview about these. Right now these materials are forgotten. We are building a database and doing surveys before dismantling buildings and try to understand what is inside of it. We are not only mapping materials that we can recover and reuse/remanufacture and resell but also those that we can do nothing at the moment. We are putting this in a database and this will work on a very different scale. At the moment only on a building level but in the future we want to know use it as a model to determine " ok this building was constructed in 19xx and therefore we expect with 60% of certainty that 1,2,3 materials will be present and that are this old and that these could be reused in this way" So the data will help you to deal with this in a completely different way. Data is key but it does not provide insights if done on 1 building only. Once you run this analysis on 300 houses you could start to see a pattern in terms of material content (%) and use it as a predictive model. This is what we are doing at the moment."
[Quote 16.5]	"There are a lot of materials that can be resold and they are trying to make the network work. The issue is that you need to give them a lot of information."
[Quote 16.7]	"When I demolish a house and I want to make sure 90% is reused, then I need the information the construction ends. Because if I try to sell concrete plates to a constructor, he wants to know the dimensions, the year of construction, the pressure it can hold and for how long it can hold it. Even if I have all this info, it is not my decision as a demolition company. It is the decision of the client to decide what to do with the new house. When you demolish something you are your biggest customer. You need to get the information right for the people who are going to use it."
[Quote 16.8]	"So if you ask me what is needed for bringing this materials to new life, I would turn this around. When you decide to have a new building look a the building you currently have. SO you are going to demolish the building but you need to see what is the building made of, you made a whole material passport for yourself and you give this to the architect and tell him that you want in your building all these materials. Then the architect would call the company with experience in sawing concrete and taking things apart. Then we make a price on what you want. If you tell me you want to use this and this, we will not crush the concrete but cut it and tow it out. But this is not what people think about They go the traditional way of first planning the new house and then they demolish the house and get rid of the material."
[Quote 11.5]	"We need the specifications of materials/construction elements. This includes the quality of the element. The costs to recover them, because it is a different kind of work to selectively remove from demolishing. The design of the new building. IF you have an old building with small windows and you have a big one with large windows these would not fit. SO the design is an important thing. And lastly the status of materials"
[Quote 12.1]	"The information is the quality of the project. The measurements, the specs of materials the quantity, the planning is very important. Also the strength of the materials and required strength (static). These are the important elements as data information."
[Quote 12.7]	"The most important data are about the quality of the products. Because today the customer is used to get new products in his house with a warranty of 10-20 years while with the reusing of materials this is difficult. Who will give the guarantee that the material is of good quality ? Are there termites in the wood ? This is an important aspect to consider. If we take the product and it would not perform as the customer expects? The customer is paying for it and need to perform as it should and the customer needs to decide whether he wants it or not. When you buy a new car and you know it was used already people would not like it. When you buy a house with a new toilet and they see it is reused they would not want it. Although the next day it will be dirty anyways."
[Quote 12.8]	"The only thing that really matters is the quality of the element. You need to be sure that strength is maintained (or reduced by xx%) and that the dimensions match. So quality of product and its specs would be important."
[Quote 7.7]	"Question: How do you do this and what specific information/data do you need for undertaking these steps? Answer: We need dimensions, photos, sometimes we need to check the quality on site. (…)"
[Quote 13.5]	"Question: What information/data would from your perspective facilitate/improve this process now and in the future? Answer: We need specs about the material, like age, technical specs like constructional possibilities."
[Quote 14.0]	"Question: Would specific data increase the willingness of construction agencies to reuse materials/construction elements? What are these data ? Answer: For construction elements: Age of the materials and the way / amount in which they have been used / to what extent they are loaded with weights. For frames (doors/windows): Age and information about the type of glass used. But in most cases the glass panels are being removed and replaced anyway. So the quality of the wood or other materials (metal frame, rubber profiles) are important."
[Quote 14.2]	"Varies per product. For doors for instance it would be very handy to have data about fire resistance, sound dumping. For insulation you have the RC value. In general the technical data. For insutlation is is about sound and heat specs. These are the most important data that we never have but would eb helpful for selling products. Most of the other data we can find ourselves. Size of a door and other specs we can figure out ourselves. But more specific specs are quite difficult to obtain upfront."
[Quote 8.1]	"Next to this, the deconstruction company is only reusing products that are in potential profitable (look at the timber process on the circular building hub in Utrecht). So if many refurbishments steps are necessary and safely dismantling which can be costly, costs more than recycling and profit of selling them, then they won't do it."
[Quote 15.3]	"Nice example I found during my walks with the account manager who inventories reusable products: It was an office building in a big city in The Netherlands on the 20th floor. Which has been rented out for ten years and all new, nice furniture like carpet tiles, glass walls and doors was used. The account manager will look how the walls and doors are mounted and saw that these could be easily dismantled. The glass walls and doors could potential be reused and sold easily. However they do not fit the elevator, therefore a large crane should be rented €2000,- to get all

	elements downstairs. Because of this expense, these good reusable products are not reused which is a shame. Because of the costs/benefits analysis. Sometimes clients also don't give time for dismantling."
[Quote 15.6]	" (…) we choose partners within our collective because we all say in basis that we cannot give those guarantees about the materials. We guarantee that the partner who delivers our recycled concrete stay within pre-defined levels of quality. Otherwise we will not allow the distribution. But they are responsible for guaranteeing the quality and from a regulation perspective towards the final user. This is why we have a concrete/brick/gypsum partner. They are responsible as they are at the end selling the product that is going to be used in a building. We have some experience now because we do the same with concrete, wood and gypsum. Cocnrete has a lifespan of 100 years. IN this time span nothing happens to it. But sometimes we have to sign a guarantee of 20 years minimum. But when you go to wood, the material is more affected over time thus regulations are different and guarantee period is as well. So the partner needs to define what is the guarantee they can give to the client and we trust them as specialists on the matter."
[Quote 9.1]	" Question: do you decide with your partners what materials can be harvested and reused ? Do you also discuss specifically on a product (case-by-case) level? Answer: Yes in a short way. But let me give a mor concise example. For example the cable trail are easy because you do not have regulation about those, you just need to dust them off, remove the coating, and painting. Sometimes they put them high next to the ceiling and in those cases you have no issues in terms of regulations. With wood for example, we have different qualities defined (A,B,C products). The A goes to one specific partner and he has many requirements and the piece needs to comply to specific specs. Otherwise it becomes a B quality and so on. So we find different ways of reusing it (C for example can be shredded) In any case we tend to find ways of reusing them."
[Quote 15.7]	"Because you use wood of construction there is a lot of pressure on it and you have to reuse it again. Who will give the guarantee that it will hold for another 20 years. So you see a lot of shifting in regulation and how people think about the environment."
[Quote 16.0]	"Material content of the building. At the moment when we do a scan or survey of the building, the survey is very material driven. The scan checks also at the construction period, the drawings and how are pieces connected to each other, what kind of other materials are used , what are all the components put together. How were the materials put together ? For example a house from 1980 and 1940 the roof construction is very different and this has an implication for recovery. The drawings of the building BUT also the renovation that was conducted throughout the years. The material base: what was used in the renovation and how it was installed. All these data should be put in a database and these could help us. IN tender projects for 2025-26 we know already that certain buildings will be demolished and we would need such a big database that could help us in determining the material content of the building and decide how and where these could eb reused. The developer know that by taking out xyz materials in 2022 we can reuse them in project of 2026 and reuse them in a circular way. To recap: - Material content of buildings - Construction technology and design - Timing (when are building demolished and constructed)"
[Quote 16.1]	"(…) one more point. Also the level of reuse is important. IN the pas they never thought of dismantling building and reusing them. So we could also define the reusability level/index of materials. You have the 5Rs and you could add a layer and say that x-materials are for reuse and y-materials are for refurbish. This would help in deciding where the materials can be streamed after the demolition phase."
[Quote 16.6]	"But when you have construction materials it is difficult to say you can reuse them because you need the assessment of many parties in order to assess whether you can reuse it. You need to take it out, test it and decide whether you can reuse it. The producer then must say if it is cost effective compared to using virgin material."
[Quote 15.5]	"Only visual detectable information is often known. An 60 year old building has no BIM model. Is there asset management and maybe this could be used in the future? The inventarisation of these application could be done by my inventarisation application in my research which is being implemented. Policies are making it a challenge to also reuse facade elements."
[Quote 9.4]	"Question: Do you always recover the same materials ? or do you conduct an assessment before doing it ? Answer: It really depends which materials we are talking about because our electro technical partner (for the cable container) this is very simple to remove and install. They also do very complex installations like heating/cooling and ventilation. But due to regulations about safety and compliance, if we would put these in a new building who would take the responsibility if it burns down ? Therefore there are different ways and challenges about quality, regulations and compliance. With other elements like the cable tray this is very simple and the business case is quite consolidated and stable. We have calculated the added value, the environmental impact and the business feasibility and have arranged the logistics to support it. SO then we made the business case with the reversed logistics. We have to scope in/out how are we using the materials and how do we build the right business case. IN the material base many products can use the same structure. For example the sanitary have the business case as the cable tray, they just need slightly more cleaning. So you have the same business case that can be applied to different partners. So I think that once you set this up once you can replicate it more times with more and different partners. We have the experience and take the partner through the process. For the reuse percentage you can look it in 2 ways. Currently it is not possible to reuse elements a 100% because we don t have enough partners for reusing everything. Also there are some products that cannot reuse at the moment. Only if you have different thought of it and rearrange their configuration. Then you have to scope in on 2 levels: 1) if we have a material that we have a contract for with our partner the contract should say that if it has the right specs you should take it (think about gypsum is very vulnerable and can break very easy and this depends on building the dismantling and how the house is constructed) 2) Then you have the total scope of the materials we are currently recovering. Also this depends on the building. You have certain buildings with a lot of concrete or steel (which we do not recover) so the percentage (of recoverable) varies a lot per project. And we aa lot of materials right now that we can recover but at the moment we brought back to life 63 products and materials. I think at the moment that we have in a continuous flow we have 15/20 materials"
[Quote 15.4]	" Standardised ways of dismantling. Now only a few people in the company now how to do this. There is only one person who has all information, if someone has to take over, the decision making if a product will be dismantled for reuse will be different. So there is not current standard in the full process, also not in the process after selling till new construction site. I don't think its a data issue, more the connection with the new construction site and how the data can be transferred over (product passport (lite)). This should ofcourse not be done with an Excel or PDF, but should be on higher data standards like databases, which you could make automatic connections with."
[Quote 11.0]	"Question: the Madaster has a function for the design, planning and procurement (for material inventory). But after that has no direct purpose? Answer: it has a purpose if you have a government that wants to reuse. For example municipality of Leiden says that everything in their buildings that needs to be demolished must be harvested from a circular point of view. So I want that Madaster material passport and you have to recover from the building at least 75%. But if there isn't a party that is working circular, there is no incentive to do it. It might be cheaper to bring it down and sell the steel. Also because the demolition company is primarily focused on demolition and is focused on harvesting and reselling. Answer 2: but it does make it easier. Our question is what data would make it more effective. Well, the Madaster data does make it more cost-effective to regain those materials. It is a good thing to add here. And maybe not just for the owners, but also for the government as an owner it is good to have this info. The same goes for the demolition company. It might be more cost-effective for them to demolish with the material passport at hand."

[Quote 11.7]	"If you talk to a real designer and you have a 3d design. I think it should be possible to get a 3D BIM model of an old building and then say, we have 100 elements and some of these can be reused in my new design. Or what do I have to do for reusing them in my new design? I think that should be a very nice program and solution. The advantage of reusing is gone when you need to put it somewhere and then reuse it at a later stage. Then the economic advantage is gone because it costs too much. It is possible and efficient for one client."
[Quote 6.8]	"The easiest is to reuse on the same project. And the planning can also be merged into one. But I think this is complicated on multiple sites. So you need a designer that knows what is available and what needs to be constructed. So your challenge as a designer is to use all these materials and to make a nice design out of it."
[Quote 12.6]	"For the designer this was a bit difficult because we have very old drawings and not very detailed specs/measurements. So we had to make some assumptions which need to be verified by the government as well. This was slightly the challenge. You do not have the space for mistakes and so we had to take a lot of measurements and verify our assumptions. Also, there was another building next to ours so this made the process slightly harder for us."
[Quote 13.2]	"The bigger the project the more advantage you get from BIM. BIM is not really advantageous for repetitive building designs. ON the other hand, for the maintenance it would be great because you can identify the elements within the construction."
[Quote 14.3]	"Question: You can have element specific information which can differe for a door and insulation. SO ideally if you would have the product name it would be even better because you could check the official data of the element employed. Answer: in theory that would solve it but the buildings we are working on are very old. So it might be who produced the door is not even there yet. Yes iit would help and in some way it would be the solution but again if the door is 20 years old even if you know the producers and the producer doesn t have the spec on the website."
[Quote 14.8]	" (…) the material passport helps us to our customer that we actually did what we promised in a tender. Because with this passport you log all materials, of course different evel than ablockcahin, but you have 40t of steels logged before you start. At the end you have to prove that you used 40t of steel if all a sudden you have 20t in the building you have something to explain. So the material passport is a first step in order to make circularity and circual promsiese in a tender vague and that you can promise the world and then not do anything. But I agree that Blockchain can be a huge aspect in this."
[Quote 15.1]	"Question: Did you ever work in the past in close contact with construction/architects already during the demolition phase? And did this make a difference in the work flow and costs? Answer: in the perfect situation (and this is what we are asking customers) is to involve us as early as possible. IN the perfect situation we would make the inventory of the property and then we go to the develoeprs architects responsible for building on this specific plot, and show them what will be harvestable. This gets closer to the material driven design that we just talked about. They just store the material that they want to use. IN this way you can keep the material as close to the site as possible and you stimulate the architect to reuse them. We have quite some projects working like that Belmaar bij Amsterdam. Not everything went right but what we did is to make an inventory at an early stage, we discussed with the architect quite some elements we marked as reusable and they placed them in the design. (https://www.bajeskwartier.com/en/bajeskwartier/het-plan/) The issue is that with the traditional way we are too late. Developers start way before the moment of demolition and they think about big plans, with very cool architects and materials. They start with the paperwork and all the permissions and only later realize that the demolition part still needs to be performed. The client only then contacts the cheapest demolition company and goes ahead with the project. This is how it traditionally works. We are trying to educate custoemrs to involve us as parteners rather than just as dealing with this as a customer-supplier relationship."
[Quote 17.1]	" Question: putting a material passport on a marketplace and people reserve the product before you start even the demolition would make sense for you ? Answer: Yes that would be perfect because then we only have to take it apart and locate it in the place it needs to stay. For us this is even a better way that everyone gets a fair and balanced price. When there is request for quote you would be sure that the price gap would be similar between the companies. But now there are companies that say they can reuse everything and their quote can be significantly lower (also differences of 1 mio E). But then they increase the price afterwards to compensate. Companies make fake prices to win the tender and then increase the price for the final customers. Also they find loopholes in the contact and then they increase the price later. You get tenders also for houses because owned by large housing companies. We are a large companies with a big office and very smart people so our prices are higher than one-person company sitting at home. They can propose cheaper prices then us because they have way less costs then us. So I need to have minimum of 2k per house and they can do 500E per house."
[Quote 17.3]	" Question: If you would have also specifics about the smaller components (doors, windows and so on) in the building available before demolition and the possibility of having these materials claimed by other partners. Would this be beneficial for you. Answer: For now I am the database and I have to connect with the partners. But maybe later in the future such a large database could help. Right now I work with people that have been for so long in the business (like the guy who is selling wood for the last 40 years) they can just see it once and decide if they can reuse it. It is based on their experience. Question: so a large database will not change the industry? Answer: Not in the way we do demolition today. But if construction companies would be involved then yes, they would need all these specific information upfront. They have to make sure that whatever they build stands for the next 50-60 years. For me as a demolition company selling a wooden beam I can rely on my partners knowledge to assess whether it works or not."
[Quote 13.8]	"It is a challenge to work with construction elements that are used. You have to find a construction agency that wants to work with that material."
[Quote 10.4]	"With Madaster and municipalities that make policies about demolition and when there is something demolished they want to take it apart and you must harvest certain materials. But I am not even sure they know how these will be used."
[Quote 12.2]	"The problem I see is talking the same language of our clients. Many times we are ahead of their expectations and they pay the bill. So bringing the clients with us in this digitalization process, this is the challenge I see."
[Quote 12.3]	"In maintenance for example we are very ahead. We have drones, camera and digital scans everywhere. And then we go to a village and there the guy on the bike sees things through his phone. And we wonder how we can put his information in our system because this would help us a lot. But many people are not ready for this type of change and this generates friction. So in this case we are going faster than our clients. But we need to do this because our competitors are also going fast and we need to pick up. Also the client has many things to think about, sustainability, the money, that the process is running smoothly."
[Quote 12.4]	"Question: Do you see a difference in the tenders. Is sustainability taking a bigger role in this ? Answer: in 5 years time I think we do a lot of projects that are not only on money but also need to make a plan. If you get money from your plan and remove the part from the costs, then we compare prices. What I see is that in the last 10 years, when we started sustainability was an issue in 1/100 of the projects, now the ratio changed and you see that sustainability plays a role in 70/100 projects. What we see in sustainability is that our clients have systems to compare what we do. These are called MKI (ECI). We have a lot of tenders with MKI's and we have a special department for that. They calculate the MKI for us. SO that is what I see in the environmental arena. A problem I see is that one important element of sustainability, namely CO_2, is becoming very important (for example electrical machines). The problem

	with these is that their price is 2 times higher than normal prices. So the project are costing more money for our clients and therefore they can do less of them. This is the transition we are seeing right now.”
[Quote 12.5]	“Question: what about the importance of making your sustainability actions verifiable and trustful ? Answer: We call this verifiable project information. And this would help us because in every plan we write, we do measurements and we have to prove that it is working. So having a system that demonstrates that you have used reused materials than you can prove this works on other projects as well. With the MKI you certify that you are using certain materials. Every company goes to Switzerland with their materials and say they can do this and that. And this material is included in the database.”
[Quote 13.0]	“Question: How does the compliance between you and the material supplier work ? Who becomes responsible for the quality of the material ? Answer: In holland we have the Komo certificate. When present you know for sure that the quality of the product is guaranteed. ISO standards is related to processes. You write how you are going to do it, even if the product is terrible. Komo is more about the quality of the final product. The product needs to have a specific quality. Question: where do you verify the Komo certificate ? Answer: Most of the times we never check the Komo certificate because we trust the people we are working with. There is a new law coming out in 2023 (wet kwalititeits borging) that will say that you need to give a digital certification to the final customer that certifies the design and quality of products. You need to take a lot of pictures and show what and how you have used the products in the building. It is important to assure the quality of the final product. You will not have to add these info in a BIM model. You will just have to take a lot of pictures and drawings. Also, you will need to specifiy how the products need to be maintained. On a daily basis we know that the people we are working with are Komo certified. But we do not ask them every time. Bigger companies will ask them every time but for us being a small company trust is very important.”
[Quote 13.1]	“Question: what would happen if you would reuse a steel element and this fails. Whose responsibility is it? Answer: first our company is responsible. We are then going to talk to the people who made it/sold it and try to give them a bit of the costs associated. But at first it is always the constructions companies fault. Who puts the material in the building is responsible. So even if we get them from a demolition company we are then responsible about these elements. This is very true when we build for private consumers. When you build for other companies you can decide to make ad-hoc agreements. For example if they want to reuse materials we can make agreements about this project. We can agree to share responsibility. For our company this is a bit difficult as we are part of an insurance company which gives the guarantee when our company would get bankrupt. They would carry over the guarantee we gave to the final consumer. So the insurance company has us tied to some conditions we cannot overlook. But the issue lies also in managing accountability with multiple partners. You need to determine whether it is the material or the way it was installed? ”
[Quote 16.2]	“ The data is not available. Due to the age of the building BUT also it is outdated and not maintained (not reliable). In holland we do not have only one register/database: we have the MADASTER/BACH we have maybe 10 different databases. We would need a regulated one form the government, this is the one to use but it has to be capable of innovating. For example, Madaster is fine but it is not the best tool. There a lot of people excited about it but we are not so happy about it. This is why we are building our own database. This is why many other stakeholders are building their own database because as you see we find these 4 aspects important but other stakeholders see other aspects as important.”
[Quote 9.7]	“I first contact my network then I go on platform like Insert where you have only companies there and then you have marktplaats the website. When I say to people do you know insert they don’t . (…) I go first to my network because these are trusted partners. I am assured they will come and take it out by this date. If I contact people outside my network they make an offer but then they do not show up. This is the difficulty because I cannot trust them. I need to stick to a certain deadline and I cannot delay if people do not show up. The head of the project will tell me that we have to go ahead and things will eventually go to recycling.”
[Quote 17.4]	“What you say is correct. It is about making a circle work. If the material ends is function it must go back to the construction company. Many people have tried to make this connection in the past. Because with new buildings the material passport is already made and when I will be demolishing them in 40 years from now, I will now exactly what is in it. But when I demolish now, no one knows what is in there right now. Also current material passports are not reliable. We always make estimation from the floor plan of the buildings. Today a lot of companies produce material passports. Especially because municipalities and authorities request them so home owners make them. Insert des it for example, Madaster is a big one. There are so many right now. The issue is that everyone makes them in their own way. There is no standard way of doing them.”
[Quote 17.5]	“There are a lot of ghost companies used to basically win tenders. Because the company making an offer sells the material to this ghost company so they fill in the framework that they can basically reuse everything. This ghost company then acts as a material hub which will be financially in red because they will then pay to throw everything away. The issues is that no one can check this either. Of course there are some projects where you are obliged to share all the information of your contractors (who you are giving the material to) with address/invoice and phone number. We tend to do this with all our projects. But some companies use these ghost companies for winning the tenders and then dumping the materials.”
[Quote 17.6]	“A platform like insert which is a stitching (non-profit organization) there is always interest from other companies behind. No one does it for free. When you have a municipality that would organize this, with expert people on site looking after the materials. Then you would have a realistic hub and a realistic project. So having a third party institution with no hidden interest is important for making such a physical hub work. Insert for example there are people behind who need insight of the market for making their own product or make their own market better. But with a third party institution with no interest will make objective decisions for taking some materials. For example they would not buy a door knowing that there is no market for doors. Companies that have invested in insert might have interest in knowing who is demolishing what and for whom this is getting demolished. And as consequence understand what materials are becoming available. This gives them a lot of market insights.”
[Quote 10.5]	“We have a sister company that built a circular building in Utrecht near the train station. That was built with the steel H-frames. Also, bricks on the ground were reused and Glass and insulation were reused too. Even the heating system, and internal installation elements were reused. In this building, everything is bolded and made in such a way that everything can be taken apart in 10-15 years and reused elsewhere. But that is a specific project where from the beginning it was clear that it is temporary and must be 100% circular. So it is not really the case in 99% of the buildings but a nice example of what is possible.”
[Quote 7.0]	“What I find important is to have a project where we make our own designs. But oftentimes we develop projects for other clients. So where we have a developer and a building company the possibility of recovering and employing reused material would be more feasible. This is one of the very important parts. Because when we work on client’s designs, we are not able to adjust the design and make it fulfil certain needs.”
[Quote 7.1]	“A lot of them are not my decision because when we receive a project most of those decision are already taken by the architect and the owner of the building (commissionaire). Oftentimes they have already decided what is going to happen with the old and with the new building.”
[Quote 7.3]	“In the last project we have executed the construction. A part of the construction was maintained while another part was reused and integrated in the new building. Some years ago we have kept the basement of a building. This project was at the centre of an old town and there was not enough space to demolish the basement so we talked to the developer and the construction engineer. And we decided together to reuse it and we designed the new construction with the same plot.”

[Quote 14.5]	"Question: Your material hub is somehow solving this because if you store it for x years and archietects can look through the inventory, they can easily design for a future building and have the certainty to have the material available at the time of the construction. Answer: yeah but it solves it for very small part because you have very specific elements, let ssay construction elements like beams, we are not going to store them in the material hub because they are so specific and the chance of finding someone who will need it that exact that element at exactly a feew months from now, the chance is very small. SO we store elements which are not speicifi like a sink, a carpet and tiles door and stuff like that."
[Quote 9.8]	"Question: so it is about the use you make of the material after the demolition. SO you need the characteristics, the quality, the technical performance of a material. Assume you would take it out and keep this material, what info would you need to decide this. Answer: When we are on site we are already too late to make this decision. We have a deadline within which everything has to be out. The way it works today, they call an architect and get a plan, then the papers and then they think about the building still standing there. Then they call a demolition company and get a price for bringing it down."
[Quote 16.9]	"Question: Alex: so there are two processes. One where you get commissioned to reuse everything and one where you do this from your personal values a s company. SO it is very different the two perspectives Answer: Yes because you can also make a database of concrete elements where architects will look into it but because it no certain when these materials will come free then they will not be interested. Having a ground full of material is not a good use. You better use that ground for other purposes. To cut concrete pillars and to sell them it is not worth it. But if you build a new building and you reuse the materials from the old one then yes because then you only need to pay the workforce and not of materials. It is cheaper for a home owner to reuse its materials in the new building. You simply pay the work and not the material."
[Quote 17.0]	"For every projects you get now material passports, but because these are made by different companies there is no standard way of preparing them. There are so many parties nowadays making these, some with more information than others. When you get materials you need some wanting to buy them. From this perspective it makes more sense for the demolition company to make the material passports because we know what info our buyers need. While when other companies make a material passport they write that pretty much everything can be reused. So when the customer talks to us they think everything can be reused but there is actually no market for this. And they thing we want to charge them more. The issue is that these companies making material passports see only on internet and on pilots the possibility of reusing everything while they do not know the market. It depends on the market and on many other things. I have partners who buy glass façade from me but when they tell me that the market is not so strong right now and there is no demand because people want different things, then I cannot be assured that I can always sell these things. The market is dynamic."
[Quote 13.7]	"Question: When data are missing, do you go on site to assess them? Again, what data would prevent you from going on site? Answer: When the quality is poor, for example when the constructional elements appear to be hollow instead of massive, we do not go in site to asses them"
[Quote 10.8]	"If you look at how we have built in the last decades, we have all kinds of standardizations and quality standards for materials. So for building a bridge or a house all the parts that make that up to have to live up to a certain standard. NEN-9116 or the CE standards or ISO standards. So there are all kinds of standards. In that sense, things are already clear and the view is pretty clear on what material is used. Specifications are also standardised. So if you build a building we make the specifications down to the smallest element you need (as you do with lego). Each element is described and the element must be coherent with these standards. So there is a lot of data on the materials contained in a building. My point is that the infrastructure is in place, but what we put in is not circular yet.(…) Because if you look at Madaster you know what is in the building. But the building owner has no incentive during a demolition process to say to other parties "Hey do you want this material or construction element" . And this is also not in the culture of these people. They are not project developers so they do not know these things. So someone needs to make the connection."
[Quote 11.4]	"(…) The goal is to get stakeholders who are not used to working together and automate the information flows. I think an interesting thought is " should our government be a Blockchain provider?" Maybe a new role for the government is to provide these information supply chains and make sure that policy goals are implemented in those Blockchains. If you make parties responsible for a certain material, for the whole lifecycle it is also an incentive for the party to use it more sustainably. These types of ideas are very interesting indeed."
[Quote 11.9]	"(…) a big part of a project is the labour force. This is something you can plan. Because if these people are 10% f the building costs then no problem But in fact these people are very expensive and therefore if you start ana activity you need to finish it otherwise you incur in additional costs."
[Quote 6.6]	"My job is to inform BAM about incoming projects of our clients and there is no one project that we tender at the time the project starts. Usually it its month, years later the tender. Especially because of the elements outlined before. When there is one stakeholder that says I am agains this project-> you delay 1 year. If you find something in the ground, you need to do research and delay the project. This is the problem."
[Quote 10.3]	"Question: DO you check the BIM model /material passport of a building to take a preliminary decision? Answer: No, we do not. Since we do not use BIM yet. Since the building that we have retrieved materials from, didn't have a bim model or passport. Also we are not really familiair yet with BIM. Question Do you make material passports of the new buildings you design ? Answer: No"
[Quote 7.9]	"Question: DO you store somewhere the information of the material you have reused in a new project? Answer: We always make a document called 'harvest map'. This is a nice graphical overview in which the reused materials are visible. it would be great to put the technical specs there."
[Quote 16.3]	" So I see 2 solutions for the next future: -You have a regulated database with transparent information and data. You can use it as construction and demolition company. And it is managed by the government. -OR everybody is a specialist in what they do and can create 100 databases but then everybody must open-source the database and be transparent about the data and processes employed. IN this way the knowledge can be integrated. Circular construction can only work with sharing knowledge. Our company is very open and transparent with sharing certain knowledge. We have lived in a linear way with their own company and business. But in circularity we have to break those boundaries and make a more open and transparent. This is a very different way of thinking. Today they would think and be afraid about you making more money. Data is very important for unleashing this transition. But we need to make data transparent and all the layers within the construction should be connected."
[Quote 16.4]	"For small companies you have to pay a lot for license to get the data. Too standardized processes. If it is a centralized product/service it is not open to a lot of innovation. Innovation is faster than government. Not saying madaster is a governmental company. But my fear is that if you do not apply enough innovation the tool and processes behind it can stagnate a lot in relation to innovation required in the market."
[Quote 17.2]	"Question: what info would you need in a material passport . And do you even need it ? Answer: I do not need it for me. I can make a market to sell construction material, but this is not needed for a company whose core business is demolishing things. It can bee needed on a different level where also construction companies are included. They can say I have this material available and I can put it in the BIM model and use it for the new construction.

	Question: So the information alone is not relevant for you. It becomes relevant when put in a network of other partners/actors Answer: Yes correct."
[Quote 10.9]	"Question: So the Madaster project is not owned by the house owner but rather by the architect/engineering firm who has built it? Answer: Well, It is a building passport so the idea is that it is attached to the building. And when it gets demolished you can see that it contains specific parts/materials. But of course, an important driving factor is the owner of the house. If you design something and then build something and then you say goodbye it adds no value. I am now working with a project developer and they are building houses for elderly people and they want to build them most sustainably but also healthily. Our job is to supply sensor kits to measure the quality of the building. So once it is built the project developer is gone. So who is going to maintain the sensor data, who decide what to do once the sensor data says something? SO there should be an extra party. But there is always an issue with companies that are specialized and focused on a certain part of the process and then you move to the next process. So there are a few companies that are engaged with the whole life cycle of an object. For example, you have an investor from Russia. And he says I have 50mio and I want to invest in real estate. The project developer is building, there are using the cash from the investor to build and then the developer builds and he gives the keys to the investor, but he doesn't want to be there. So there is a maintenance party that does the management of buildings and then they are in charge. But their sole purpose is that the building does not fall apart, that the heating system is working and so on. But they do not have an incentive when something gets demolished to do it in a certain way. The Russian investor has no incentive in doing so either because he has invested for 50 years and made his money. So f it gets demolished he gets money for the land so it is very difficult to get parties/institutions who have no incentive to do something in the next phase. To invest in circularity for example. Why would I ? My sole purpose is to make sure that the heating system is on and that I make my money in this specific phase of the building."
[Quote 15.2]	"Question: do you have architect firms that refer you as partner and explain customers that you could work together? Answer: we have a few architects firms (like xxxx) that work like that. So it happens that architects brought us in in the tender process and not as a demolishing company but rather as supplier of materials. But this is a quite spatial situation. We sold quite some materials to xxxx but this is still quite exceptional. The hardest person to persuade is in fact the architect because he wants to have his design and touch for the building."
[Quote 11.3]	"Where we have all assets of municipalities, we have somewhat 50% of that market. So we know a lot of municipalities where all their assets are (down to trash bins, brick, trees ad so on). We have this in the system and we have this data. But we are only a small part of the municipality. The competitors have other parts of this information. Of course, there are other places where maintenance information and asset information are not there yet. Like the rijkswaterstaat has a lot of assets which are not mapped. A part of the market knows this information and for another part of the market, there is the challenge of writing this data down. There are a couple of challenges before everything can be automated. That is our USP that we have a lot of data we can already use and make an automated connection between supply and demand."
[Quote 13.6]	"Question: Are you currently employing Material passports/ do you review BIM models where possible ? Answer: No, not yet, we are planning to use BIM in the future."
[Quote 7.5]	"But currently for our renovation works we have no BIM models as these are too old and have no digital model."
[Quote 14.1]	"Question: If you had more information like exact material content of a building, technical specs, time when the material becomes available and so on, could this increase the amount of material/construction elements you can reuse ? Answer: Yes this would be handy, if there would be more tech specs available. But mostly we find them anyway by requesting the specs by the producer or by seeing the material and estimating it visually (what would be the age)"
[Quote 10.0]	"Question: What is the time window you have from when you get to project to when you decide to either sell or demolish everything Answer: We have no time. We set some internal deadlines and if we do not meet them then we decide to demolish everything."
[Quote 7.4]	"I think we are a bit late with the adoption of BIM. But we use it very little. Most of the designs we get from the architects/engineers is in BIM, so we use it but we make a lot of small projects, not big ones."
[Quote 13.3]	"Question: what does the government force you to keep track of ? Floor plan, material passport, BIM? Answer: Correct, the only thing that you really need to keep track of is the floor plan, but the rest is not really an obligation."
[Quote 14.6]	"Question: Ideally you could take a pillar and reuse it. But you need to make sure you can take it and sell it to someone ? Answer: exactly. With steel we are doing that now because with steel there is quite some experience on how to reuse that. So the market is becoming more comfortable with that. So at this moment if we see construction steel we extract it and bring it to our hub. Because we are quite confident that we are going to sell it."
[Quote 4.3]	" (…) we build all buildings with wood or concrete. Only construction plants are made with steel. But steel is already recycled quite well. I think until 5-6 years ago we did not have any good way of reusing concrete or a lot of wood in some sort of ways. Indeed still at this moment we do not have the knowledge and regulation on how to reuse wood."
[Quote 14.9]	" Question: What about the political part of the business and the value of information in the business. What is your opinion about that ? Answer: I think the demolition branch in holland in general is very competitive. I think the market is smaller than the number of companies. So everybody I very competitive for winning a tender. Especially if it a good one, for a nice customer. XXXX also works like that. We always want to be smarter than the rest. So yeah we always think about If I say this, what would the competition learn from this. Again, that is old thinking. So yes I have colleagues that think like this. But this is getting less and less. You see that construction companies are starting to work together. They are recognizing that the amount of innovation you need today for staying ahead of competition you cannot do it alone. XXX can sometimes do it alone because we are quite big. But especially for small ones it is impossible to do certain investment on their own., SO they get together and jointly do some investments. Insert is one of the ways for working together. But in general also XXXX is starting to work together with other companies. So it is not so old style as it was a while ago."
[Quote 15.0]	"Then again I think it can a bit tricky because the construction companies in Holland are also famous for calling each other and sharing what prices to put down for tenders. Some companies are also convicted for these practices. Again working with your competitors is good but also a bit dangerous if you take this in perspective."
[Quote 8.9]	"In a tender I present myself including all the circular innovations I can offer. So because of that I would like to invest in circular innovation because the more I do so, the more I can offer in the tender process and the more I can win these tenders. If I have exactly the same innovation as my competitors and then we have to present ourselves in the tender, we will not have a competitive advantage on each other. Then the only thing you can win on is labour costs and price."
[Quote 15.8]	"(…) , if you build a modular building you could redefine your business model. As I explained during the circular material hub, if your step over to modular building you know that you have n number fo building you could reuse materials again in 30-40 years. This requires to redefine the business model. Instead of selling everything they could try to keeping the materials owned by them and give it on a leasing basis. Maybe in 40 y they can reclaim certain parts of buildings and refurbish them and use them in new projects or in the same building. In this way the lifetime value of the building is extended to 100y instead of 50y it was thought of. I think there will be a complete new scope and new business models on how buildings will be designed and reused in the future."
[Quote 10.1]	"(…) material passport system that is connected to the tender. Basically in the tender you have to fill in the volumes of materials you will be reusing and this will give you a score and based on this you get the job or not. This is such a unreliable system. But more companies are getting into this mechanism now. But you are not sure whether you can resell this material on the market."

Appendix IX - Digital Construction Policies/Strategies across the EU-27

Countries	Type of Digital Construction Policy					
	Horizontal Policy/Strategy – does not comprise construction	Horizontal Policy/Strategy – comprises construction	Vertical Policy/Strategy – targets the construction sector	Comprehensiveness		
				Strategy	Action Plan	Financial instruments
Austria		√		√	√	√
Belgium	√			√	√	√
Bulgaria		√		√	√	√
Croatia		√		√	√	
Cyprus		√		√	√	√
Czech Republic		√		√	√	√
Denmark		√		√	√	√
Estonia			√	√	√	
Finland			√	√	√	√
France			√	√	√	√
Germany			√	√	√	
Greece			√	√	√	√
Hungary	√			√	√	√
Ireland			√	√	√	√
Italy	√			√	√	√
Latvia		*[310]				
Lithuania			√	√	√	√
Luxembourg			√	√	√	√
Malta	√			√	√	√
Netherlands	√					
Poland	√					

Figure 111 - Digital Construction Policies/Strategies across the EU-27 (source (European Construction Sector Observatory (ECSO), 2021))

Appendix X – Case studies under the RESOLVE framework

Regenerate

The objective here is to reduce negative externalities by reducing the consumption of resources and the generation of waste.

Examples, in this case, involve the use of low-impact designs and sustainable operations of buildings which lead to reduced emissions, air pollution and waste generation. Diverting waste from landfilling practices and adopting more sustainable materials and products can, besides improving the liveability of cities, also positively impact the reputation and image of construction and demolition companies operating this way. It is important that to allow for regenerative practices the built environment is also resilient to sudden shocks and changes, allowing for flexibility and redundancy when selecting materials and designs for construction. This can allow for future disassembly and reuse practices (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016).

For example, the initiative Madrid + Nature aimed at developing design solutions for regulating heat waves, flooding, water scarcity, loss of biodiversity and limited access to green spaces in the city of Madrid. The initiative included the creation of replicable and modular green infrastructures (green roofs, facades and natural areas). Parks, green facades and roofs and natural areas were built and interconnected, allowing to reach an average temperature decrease up to 4.5°C (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016)

Share

The optimization of asset use can lead to more efficient use of space and infrastructure. Person-to-Person (P2P) sharing services like BlaBlaCar or Uber are share models that allow increasing a service/utility with a lower number of assets. In the built environment building owners can rent out or share spaces (AirBnB), whole buildings, and construction material. By reducing the time an asset is empty or non-utilized, fewer resources are required for delivering the same service. This can have a direct impact on revenue and cost savings. For example, the Lloyds Banking Group has introduced flexible working hours for 18000 employees and this resulted in the removal of 1000 working spaces with a total saving of £10m. The business model adopted by companies like The Collective, Coliving, Common is very innovative in this perspective because they provide shared homes which can be converted into a bar or event spaces (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016).

Sharing can also be extended to information. For example, WikiHouse is an open-source design platform that allows architects to share their designs and users to customise their own houses. Such an approach requires standardised information-sharing practices and protocols. This can also enable modular construction designs that can facilitate disassembly. This can in turn enable recovery and reuse practices, who can stimulate collaboration between asset owners and other industry partners. Such an approach can result in technical innovations, reduction in costs and reduced employment of resources. Nevertheless, the collaboration between different stakeholders must be mutually beneficial for scaling up circular practices. Globechain is a platform that connects businesses and individuals willing to purchase or give away surplus equipment and goods in the construction (and other) sectors, thus encouraging reuse practices (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016).

Optimise

The key to achieving optimisation in the built environment is by allowing construction elements and components to retain their highest value through design and construction processes, reducing waste production and enhancing reuse and repurposing practices. Digitalization and innovative design principles like modularity can directly lead to reducing the production of on-site waste during construction as well as drastically reducing the use of virgin material. This can allow the reusing of construction elements in new buildings or repurposing them for other projects in the built environment, or completely different sectors (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016).

Also, designing for longevity can improve the durability of materials which can increase the life span of the construction element and in the long-term reduce maintenance costs associated with the building/structure. Off-site manufacturing of construction elements for example can increase the quality standards of the component, and reduce the risk of structural faults and waste products associated with the manufacturing process (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016).

An innovative construction process is being tested at the White Collar Factory in London. It entails the construction of a flexible building core which allows changing of the functional use of spaces, from commercial to residential use. Specifically, the commercial and residential spaces were designed with adaptable floor plates to allow flexible division of the spaces over time. This approach can significantly increase the lifetime of buildings (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016).

Waste can also be drastically reduced in C&D projects. This, however, requires a coordinated alignment between the architects, and construction and demolition firms. Reverse logistic practices enable closed-loop approaches through which end-of-life construction elements are retained. Return policies must however be incentivized for the reverse logistic to properly function. For example, Caterpillar uses a deposit system for ensuring that engines are returned to the company that can refurbish and resell them. Within a construction supply chain collaboration between the stakeholders is paramount for creating coordination as well as for reaching sufficient scale for enabling a reversed supply chain (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016).

Loop

Looping of construction elements requires coordination and alignment between the stakeholders present in the supply chain. The process starts with focusing on disassembly during the design phase and it culminates in disassembly practices during demolition. Monitoring and tracking of assets are fundamental to enabling looping practices. Integrating multiple construction and demolition sites and coupling this with modular designs can allow for disassembly and flexible design change and reduce construction waste. Recovering valuable construction materials can not only reduce waste but also increase the revenue of stakeholders across the supply chain (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016).

Tata Steel can be an interesting example with regards to designing for reuse. To address and be prepared for future potential supply chain disruption, the company has used a financial model for studying the value of reusing steel by building owners. The analysis has demonstrated that there are significantly more environmental and economic advantages to reusing rather than recycling steel. The economic savings ranged from 6-27% for warehouses, 2-10% for whole constructions and 9-43% for offices. Also, the average material costs would be impacted, leading to a saving potential of between 16-25% per tonne of steel (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016).

Virtualise

The virtual exchange of information and goods is making processes more efficient and less time-consuming. Building Information Modelling (BIM) is a digital ecosystem that allows representing digitally an asset and the communication of information about this asset throughout its lifecycle. It allows, for example, designers, and C&D firms to share information and collaborate on a project. It can also be adopted to collect data during the use phase of a building and to assess the need for maintenance thus supporting decision-making for applying modifications to the building's components. Incorporating and maintaining information about the construction elements embedded in the building, allows for efficient decision-making for recycling, remanufacturing and reuse opportunities (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016).

BIM was adopted throughout the design phase of the T-PARK, a sludge treatment facility in Hong Kong. 3D models were developed for the design to the use phase of the facility, thus allowing all involved stakeholders to visualize the facility in a virtual space and assess potential clashes, safety routed, delivery routes and other aspects, even before the construction was initiated. The approach significantly improved the collaboration between the different teams of specialists, thus speeding up any resolution of conflicts before and during the execution phase. Also, the model helped in designing the building with fewer resources and with the possibility of fully disassembling the construction in the future, making it become a real material bank. This is because a complete 3D BIM model provides full transparency about the material composition of a building (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016).

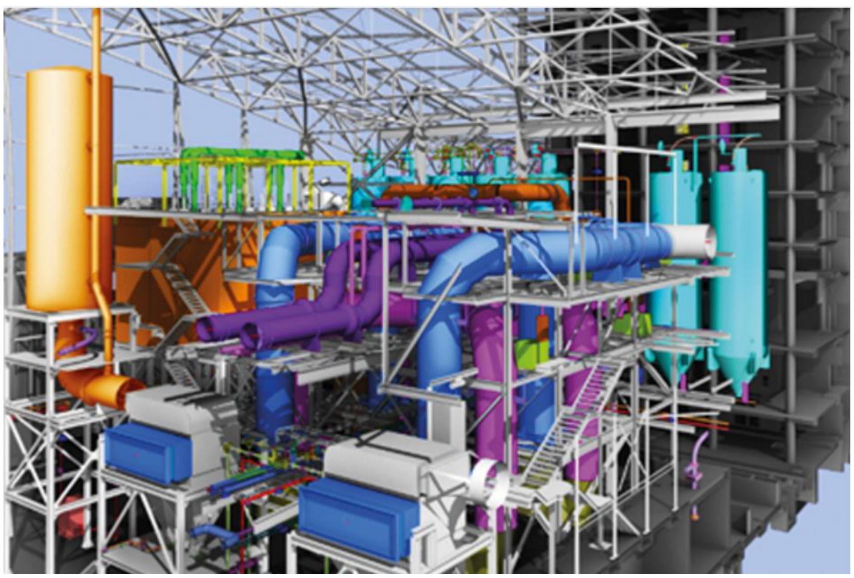

Figure 112 - BIM model of T-PARK (source (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016))

Exchange

The focus in this case is to provide sustainable materials that allow for flexible and user-centric designs. This transition is slowly replacing top-down and static processes and business models. For example, new business models entail leasing and performance-based agreements. New and disruptive technologies are paving the wave for new opportunities and ways of collaborating among stakeholders, leading to disruptive business modes and processes. The Sky Believe in Better Building project blended innovative pre-fabricated materials and construction methods, which incorporated sustainable means of energy generation. Additionally, the space was designed for flexible use, allowing to change spaces and adapt them to different situations. The innovative approach leads to substantial cost savings and reduced emissions (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016).

The Living project produced the first tower made of mushroom bricks back in 2014. Bricks were manufactured by Ecovative and were produced by using microscopic fungi bound to fibres. The final project employed 10000 bricks which at their end-of-life can be composted and returned to their biological cycle. Innovation in material sciences, design principles and business models are allowing to extend a building's lifetime, facilitating repair and maintenance activities as well as conducting cos-effective disassembly and space transformations (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016).

The service of performance-based contracts is also an innovative business and revenue model in the C&D sector. Similarly to a renting agreement, the building is leased to an owner for a specified time. The user does not own any assets in the building. This model has a positive impact on the management of resources and construction elements. Being the agreement is based on the service that the building needs to deliver, maintenance and repair activities are aimed at preserving the full integrity of the building while maintaining all embedded resources at their highest quality standard (Zimmann, R., O'Brien, H., Hargrave, J., Morrell, M., 2016)

Appendix XI – Blockchain application in different industries and case studies

Smart energy

As of 2016, power producers and distribution companies were responsible for 94% of the electricity production in the European market (Murkin, J., Chitchyan, R., Byrne, A., 2016). The reduced cost of sustainable energy generation technologies has boosted and increased the overall energy generation and sharing by citizens. This new approach is moving the market to a new model in which individual households can generate and sell the excess energy directly to the grid or their neighbours. Trades were so far still managed by power producers and distributors, but new micro-grids systems managed through DLT are allowing to run such transactions in a decentralized manner, directly between producer and consumer without the need for a third party (Li, J., Greenwood, D., & Kassem, M., 2019) (Castellanos, J. A. F., Coll-Mayor, D., Notholt, J. A., 2017).

IoT devices can be coupled to smart contracts and operated on a DLT. This approach allows for better managing the distribution and demand of electricity. For example, they can employ smart contracts for automatically regulating power usage or for informing users about their electricity consumption and about feasible alternatives that could make their energy consumption more sustainable (Mylrea, M., Gourisetti, S. N. G., 2017) (Pieroni, A., Scarpato, N., Di Nunzio, L., Fallucchi, F., Raso, M., 2018).

Microgeneration of electricity and micro-grid technologies are also revolutionizing how people and communities leave together. DLT has allowed to design and run of mechanisms for automated auctions between members of a community. In this way, energy providers and consumers can passively exchange energy, following pre-conditions they have set in the system. Communities can in this way become more independent from centralized energy grids and generate extra revenues from the surplus energy they can sell to their neighbours (Hahn, A., Singh, R., Liu, C. C., Chen, S., 2017) (Murkin, J., Chitchyan, R., Byrne, A., 2016) (Li, J., Greenwood, D., & Kassem, M., 2019).

Current limitations related to the lack of regulations for the adoption of smart contract and DLT technologies in this context are hindering wide adoption (Park, L. W., Lee, S., Chang, H., 2018).

Smart cities and sharing economy

The smart city concept entails the integration of resources and technological systems that allow human and social capital to interact with each other in an intertwined way (Pieroni, A., Scarpato, N., Di Nunzio, L., Fallucchi, F., Raso, M., 2018)

Innovations and advancements in the field of information and communication technology (ICT), together with the widespread of IoT devices, have enabled practices that will become the basis for a so-called sharing economy. The integration of these technologies will allow having live data about the metabolism of cities/urban areas and to take data-driven decisions. This model allows having a data-driven economy in which offer and supply are put into relation to each other allowing for further innovation and growth opportunities, from a social-ecological as well as technological point of view (Huckle, S., Bhattacharya, R., White, M., Beloff, N., 2016) (Pazaitis, A., De Filippi, P., Kostakis, V., 2017).

(Ibba, S., Pinna, A., Seu, M., Pani, F. E., 2017) have illustrated how smart devices, IoT and Blockchain can be employed for monitoring and controlling air quality throughout a city.

Decentralised autonomous organizations (DAOs) together with DLT-based distributed applications (DApps) have been proven to allow users to monetize their assets when these are either not used or not at full capacity (Huckle, S., Bhattacharya, R., White, M., Beloff, N., 2016) (Sun, J., Yan, J., Zhang, K. Z., 2016).

Because information sharing is extremely intensive in a smart city, thus posing some risk to security and privacy, (Biswas, K., Muthukkumarasamy, V., 2016) proposed the adoption of Blockchain technology for developing a security framework that can make the communication between platforms and entities more private and secure.

The application of DLT technology for enabling smart city concepts to work is very diverse. Case studies include monitoring demographics, secure access to health records, improved participation during democratic elections, and improvement of government and municipality operations through the reduction of bureaucratic processes. Estonia for example is the first country to employ a Blockchain-based ID system which allows the person to authenticate his/her identity as well as provide digital signatures. This system allows a citizen to purchase and collect medicines at pharmacies (Li, J., Greenwood, D., & Kassem, M., 2019) (Rivera, R., Robledo, J. G., Larios, V. M., Avalos, J. M., 2017)

The deal breaker for the sharing economy is that Blockchain allows communities to create a proprietary value system on a DLT in which sharing of services and resources (productive process) is based on business models and logic that can be fully conceived and defined by the community itself without the need of a third party auditing the behaviour of community members (Pazaitis, A., De Filippi, P., Kostakis, V., 2017).

(Swan, M., 2018) discusses the fundamental innovation that Blockchain can bring about. Citizens have the possibility of taking back control of society through the creation of the so-called "Cryptopolis". The new social structure should be a trusting society based on DLT and four pillars "*economic self-definition, the civic responsibility of the crypto citizen, a social theory of dignity for mutual coexistence, and the future of work"*.

Smart governments

Many countries around the globe, including but not limited to United Arab Emirates, United States, Sweden, United Kingdom and Denmark are investigating and sometimes employing DLT and related technologies (Li, J., Greenwood, D., & Kassem, M., 2019) (Nordrum, A., 2017).

The application range from autonomous-executing administration, and building governance that can enable direct democracy to concepts such as distributed autonomous government (DAG). Other applications employ also smart contracts and deal with automating tax collection processes, property and land registration, ID management, public records management (P. Boucher, S. Nascimento, M. Kritikos, 2017), regulatory compliance (Engin, Z., Treleaven, P., 2019) and health care services (Alketbi, A., Nasir, Q., Talib, M. A., 2018) (Jun, M., 2018).

The key benefit of Blockchain, namely transparency combined with data immutability, can allow for automation in bureaucracy without losing accountability and trust (Nordrum, A., 2017).

China is testing the adoption of DLT to authenticate individual data which can then be used for providing mutual and trustworthy information exchange for credit systems (Hou, H., 2017).

Adopting Blockchain technology for electoral voting has also been tested. The benefits identified by (Kovic, M., 2017) is that a Blockchain-based e-voting system would allow bringing the voting service to people in remote areas while at the same time reducing fraud risks associated with the manipulation of traditional databases.

(Atzori, M., 2015) has thoroughly studied the challenges and potential consequences that can result from the decentralization of governance in which the power is shifted from a physical central body to a decentralized body of unknown people with no accountability and with ideally unlimited political power. The risk is the rise of anarchistic states or groups which could threaten the economic order (Maupin, J., 2017).

Other challenges relate primarily to the immaturity of the technology, its high development and implementation costs as well as the long-term preservation of records. To overcome these barriers, some solutions were proposed. These include standardised Blockchain models, clarification of governance practices around Blockchain as well as building robust security and privacy mechanisms within the Blockchain model (Hou, H., 2017).

Smart homes

It is expected that due to the widespread of IoT and smart technologies, smart homes will become the blueprint for new homes (Li, J., Greenwood, D., & Kassem, M., 2019).

In a recent study, (Dorri, A., Kanhere, S. S., Jurdak, R., 2017) tested the use of Blockchain for monitoring and reducing energy consumption, especially with the large utilization of home appliances.

(Dorri, A., Kanhere, S. S., Jurdak, R., Gauravaram, P., 2017) instead, have investigated the use of Blockchain for security and privacy reasons concerning IoT home appliances. Although the up-front costs are high the benefits are considered to be significant.

Smart homes are usually complemented with monitoring systems that can identify suspicious activities within the premises. Adopting digital signatures through Blockchain technology can allow the house owner and other third parties to control the house conditions remotely and act accordingly (Zhu, X., Badr, Y., Pacheco, J., Hariri, S., 2017).

(Lazaroiu, C., Roscia, M., 2017) have also investigated the application of Blockchain technology to smart districts. Smart districts are an extension of smart homes. They provide recreational areas where children can generate energy through swings and slides, the presence of interactive tables that allow reading news, watching tv and much more. Also, the district offers smart charging and parking services, bike sharing and car sharing options. The Blockchain system can manage all the energy transactions that occur within the district. The only limiting factor is the interoperability with certain devices as product manufacturers are not supportive of collaborating and sharing data with other devices.

Smart transport

If combined with smart energy systems and IoT technologies, DLT can provide attractive applications to the transport industry too (Kang, J., Yu, R., Huang, X., Maharjan, S., Zhang, Y., Hossain, E., 2017).

Modern vehicles collect and exchange a large amount of data with third parties. For example, vehicles receive remote software updates by the manufacturer or can collect data for flexible insurance contracts based on driving behaviour (speed, breaking etc.). Also, modern vehicles can be charged at optimum times when the price of electricity is cheapest or based on the driver’s behaviour. Additionally, these vehicles allow remote car sharing when the car is not in use. In all these approaches Blockchain can provide more control over the data to the car owner, in the last case for example smart contracts can regulate the transaction as well as the unlocking of the car and the authorization for its use (Dorri, A., Steger, M., Kanhere, S. S., Jurdak, R., 2017) (Cebe, M., Erdin, E., Akkaya, K., Aksu, H., Uluagac, S., 2018).

Blockchain is also employed for enabling payments associated with recharging electric vehicles (Kim, N. H., Kang, S. M., Hong, C. S., 2017). For example, (Hou, Y., Chen, Y., Jiao, Y., Zhao, J., Ouyang, H., Zhu, P., Liu, Y., 2017) have investigated the possibility of coupling Blockchain with smart leasing contracts for leasing private charging stations and ensuring data privacy of transactions without the need of third parties.

An interesting approach is presented by (Yuan, Y., Wang, F. Y., 2016). In this case, Blockchain and smart contracts lay at the basis of a ride-sharing application named "La'zooz". The application rewards users who share their driving data with specific tokens called "zooz". These can be used for paying for future journeys. The more people decide to make their data crowdsourced, the better the performance of the tool becomes. Similarly, (Yang, Z., Zheng, K., Yang, K., Leung, V. C., 2017) conceived a crowdsourced data system about traffic conditions in the city.

Blockchain has also been conceived for bidding systems applied to charging stations. Users can bid for specific prices at certain charging stations (Knirsch, F., Unterweger, A., Engel, D., 2018). In a similar study conducted by (Pedrosa, A. R., Pau, G., 2018), the charging station can be employed by allocating a predefined amount of tokens.

(Strugar, D., Hussain, R., Mazzara, M., Rivera, V., Lee, J. Y., Mustafin, R., 2018) have developed an interesting concept on the IOTA distributed ledger. Their concept facilitates billing activities, charging of electric vehicles and vehicle-to-vehicle communication.