# Digital Solutions for a Circular Façade Economy

## A framework to integrate Industry 4.0 concepts in the lifecycle of a façade to enable extended producer responsibility of the Dutch Façade Industry.

MASTER THESIS – P2 REPORT

BUILDING TECHNOLOGY MASTER TRACK

Faculty of Architecture and the Built Environment

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# List of Abbreviations

BIM: Building Information Modelling

DT: Digital Twin

VDC: Virtual Design Construction

PSS: Product Service System

AI: Artificial Intelligence

IoT: Internet of Things

CE: Circular Economy

MP: Material passport

CDW: Construction and demolition waste

DFD: Design for Disassembly

VR: Virtual Reality

AR: Augmented Reality

RFID: Radio Frequency Identification

IT: Information Technology

DBFMO: Design, Build, Finance, Maintain, Operate

MFA: Material Flow Analysis

MCI: Material Circularity Indicator

LCA: Lifecycle Analysis

API: Application Programming Interface

IFC: Industry Foundation Classes

AEC: Architecture Engineering and Construction

LOD: Level of Detail

STEP: Standard for the Exchange of Product Data

IDS: Information Delivery Specification

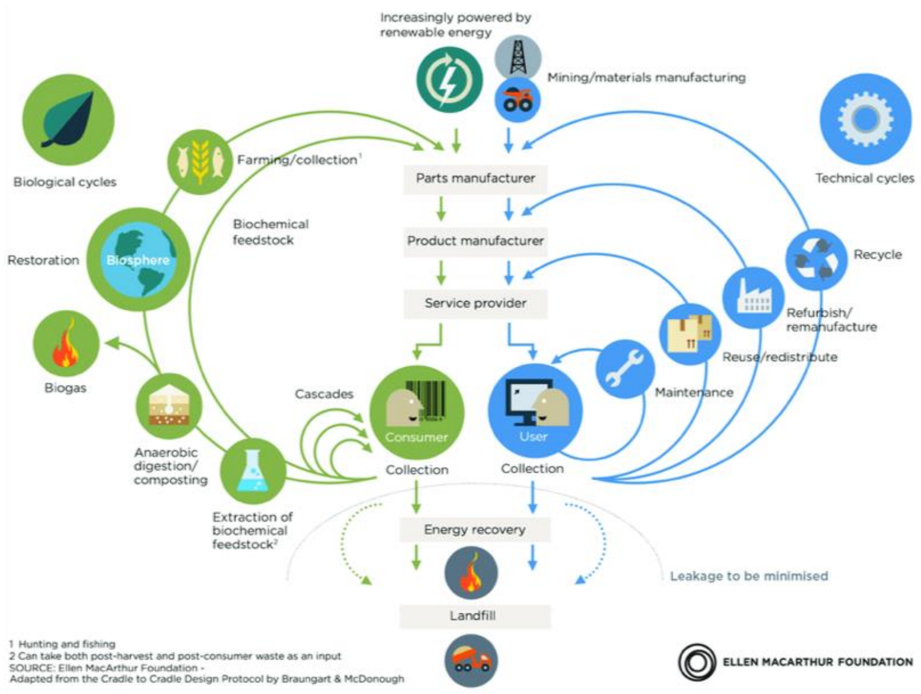
MVD: Model View Definitions

# Contents

# 1 Research Framework

## 1.1 Background

The Circular Economy arose from the necessity of utilizing waste flows more effectively, reducing our demand for raw materials. The EMF , a UK based charitable organization actively working on frameworks for the circular economy concept, defines it as follows:" A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles". The building industry at present mainly concerns with the technical cycles. As seen in Figure 1, the system diagram indicates the biological and technical cycle's material flows in a circular economy.

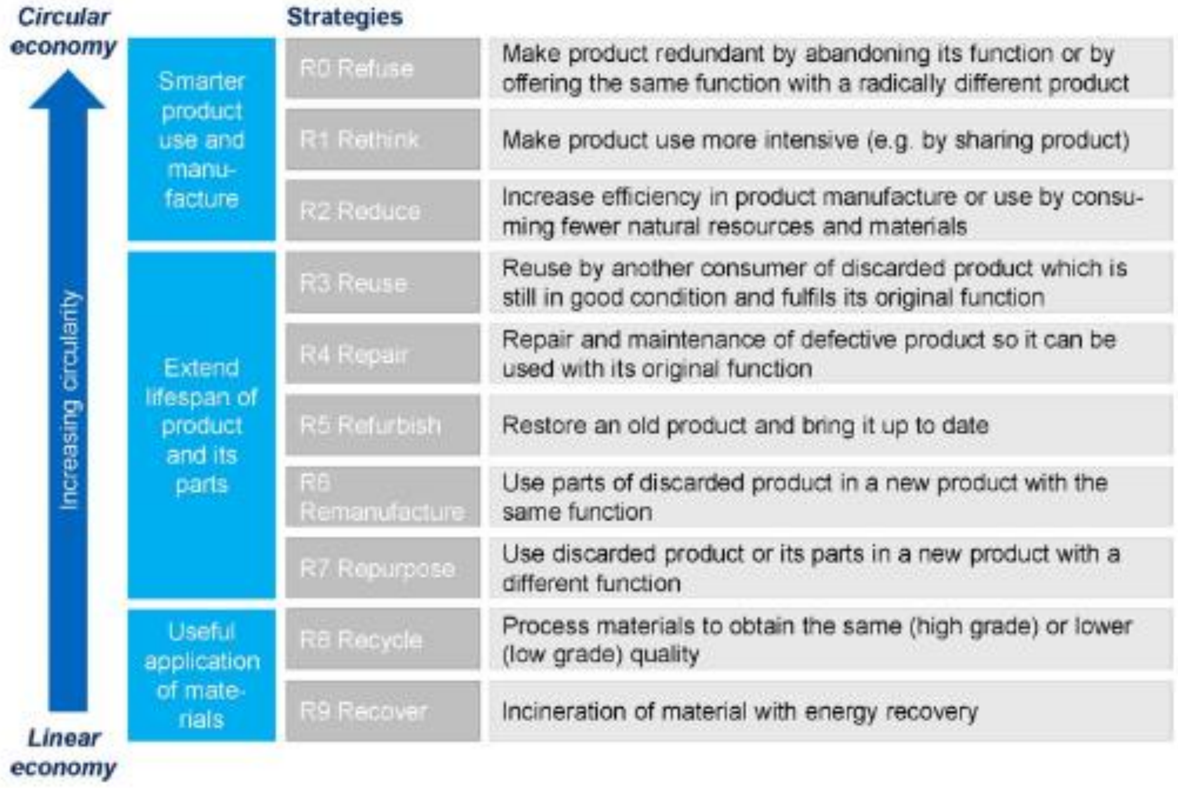


1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input
SOURCE: Ellen MacArthur Foundation -
Adapted from the Cradle to Cradle Design Protocol by Braungart & McDonough

*Figure 1: System Diagram of the Circular Economy indicating the various loops in the technical and biological cycles. Source: EMF*

For implementing circular material flows in the technical cycle, the 9R Framework by Potting, Hekkert, and Worrell (2017), as seen in Figure 2, details the different circular strategies employed. Strategies, named from R-0 to R-9, are organized in a hierarchy, indicating their circularity potential. These strategies are under three groups: Smarter Product Use and Manufacture, Extend Lifespan of Product and Parts, Useful Application of Materials. While strategies R0, R1, and R2 under Smarter Product use and manufacturing can be employed during the design stage or use stage of a project, strategies R3 to R9 are employed during the operation phase or end of life a project. According to a report by(Delolite, 2017), which aimed at investing the current CDW management practices in EU member states detailed in Figure 3, many E.U. countries are still struggling to use the lowest preferable strategies, i.e., recovery and recycling for construction and demolition waste. Simultaneously, the Netherlands is recycling 86% of the recovered construction waste(CDW) and is striving to move towards more circular strategies of dealing with construction waste. This is done in context to a document, "A Circular Economy in the Netherlands by 2050," published in 2016 by The Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs, which gives an overview of a Government-wide program aimed at developing a

Circular Economy in the Netherlands by 2050. The primary objective stated is to reduce 50% of primary raw materials by 2030 to ensure that, by 2050, raw materials can be used and reused efficiently without harmful emissions to the environment. These goals need to be achieved in parallel to the fourth Industrial Revolution (Industry 4.0), which includes an increased effort towards automation, connectivity, and Artificial Intelligence-driven technologies in the manufacturing industry and is expected to extend into the construction industry.



**Circular economy**

Increasing circularity

**Linear economy**

| | **Strategies** | |
|---|---|---|
| Smarter product use and manufacture | R0 Refuse | Make product redundant by abandoning its function or by offering the same function with a radically different product |
| | R1 Rethink | Make product use more intensive (e.g. by sharing product) |
| | R2 Reduce | Increase efficiency in product manufacture or use by consuming fewer natural resources and materials |
| Extend lifespan of product and its parts | R3 Reuse | Reuse by another consumer of discarded product which is still in good condition and fulfils its original function |
| | R4 Repair | Repair and maintenance of defective product so it can be used with its original function |
| | R5 Refurbish | Restore an old product and bring it up to date |
| | R6 Remanufacture | Use parts of discarded product in a new product with the same function |
| | R7 Repurpose | Use discarded product or its parts in a new product with a different function |
| Useful application of materials | R8 Recycle | Process materials to obtain the same (high grade) or lower (low grade) quality |
| | R9 Recover | Incineration of material with energy recovery |

*Figure 2: The 9R Framework adapted from Potting et al. (2017).*

To achieve the Dutch goals, several Circular Business Models are developed. Industry 4.0 technology can drastically improve the implementation of Circular Business Models in construction practice . One such business model, developed by T.U.Delft and several other partners are aimed at supplying Facades as a service rather than a product. This would ensure manufacturers retail full ownership of the product throughout the Lifecycle, which has many associated benefits in achieving circular goals. VMRG, the Dutch Metal Façade Industry branch organization, and other industry partners, including T.U. Delft has initiated several pilot projects to facilitate the implementation of these business strategies. As a result of these collaborations, initial feasibility studies on applying an extended form of DBMFO (Design, Build, Manufacture, Finance and Operate) contracts are being explored with several façade companies in the Netherlands. These contracts require information between the different departments of the organization to be transparent and linked, which require extensive use of technology and should be able to track and trace the components of the façade throughout its Lifecycle. For example, A façade Identification system (FIS) project was initiated by VMRG, which resulted in a web-based application 'Cirlinq', which acts as an asset management platform to monitor the health of buildings and facades and determine its value. The platform enables information about buildings and building objects to be located and stored in a centralized platform for various stakeholders to use, including companies that have leased out facades as a service. This would result in a database of information which is termed as a ‘Material Passport’, a key facilitator for transitioning to the Circular Economy as it serves as an inventory of information about all components in a project. Another initiative, Façade Service Application (FaSA), has also been developed along with 39 other partners to support data collection for facades' maintenance using sensors, drones, and AI. Data collected by FaSa can also be linked and viewed in Cirlinq. These technological applications, therefore, can be seen as early integrations of Industry 4.0 technologies applied to achieving circular building.

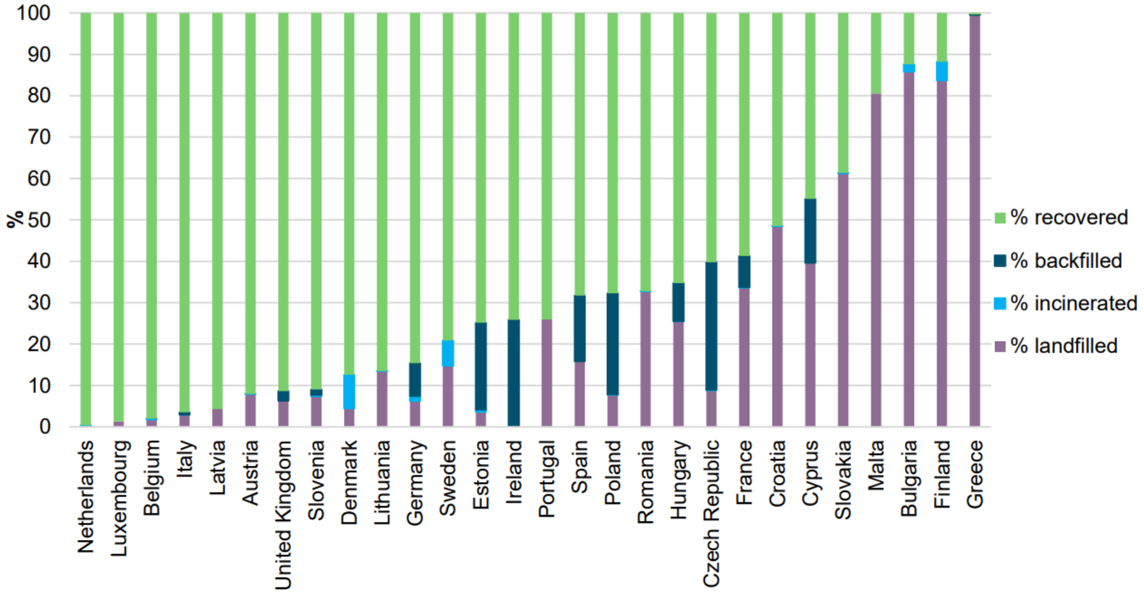


*Figure 3 - Waste Management summary of EU nations(2012). Source:  (Delolite, 2017)*

## 1.2 Problem Statement

As the recycling rates in the Netherlands are relatively high, it still needs to be noted that report measures waste by weight and not by Embodied Co2 or emissions. Hence, this statistic does not give a full picture of the impact of Global Climate change. This would imply that the recycling of materials with high embodied energy can continually contribute to CO2 emissions. Therefore, more effective strategies need to be employed to extend the product lifespan as part of the 9R framework developed by Potting et al. (2017), which implies a shift towards reuse, remanufacturing, refurbishing, repurposing, repairing, and maintaining facades. These strategies come with several challenges: lack of policies, economic challenges, enforcement of labor taxes, and other technical barriers such as lack of data or methods to facilitate these goals as per a report by (Alba-Concepts, 2020). While the government can only address the lack of policies and taxes at a national level, there is a potential of solving the economic challenges and lack of data with Circular Business Models and strong stakeholder collaborations. The Façade Leasing project by TU Delft in collaboration with other industry partners indicates that A Product Service System (PSS) with a fully integrated façade is one such possibility. This model ensures the façade producer's responsibility throughout the lifecycle and is rewarded with financial incentives as they retain full ownership of the materials even after its end of service, enabling them to remanufacture and use them for other projects. Implementation of such a business model requires integrating Industry 4.0 technology for efficient tracking, tracing, predicting, and optimizing information about facades' material flows and performance. Several pilots of these are active within the Netherlands, and one such example is the Cirlinq (an asset management platform) and FaSa (data collection for maintaining facades) co-initiated by VMRG, an association for Dutch Façade builders. As these pilots are still in the early development stage, progress has already been made towards specific data collection methods but is not integrated into an overall framework for how this data can be organized, analyzed, and used for effective outcomes, such as extending the façade producers responsibility.

## 1.3 Objectives

The main objective is to develop a conceptual framework that maps out the use of digital methods, technologies, and data flows by different stakeholders in the lifecycle of a façade.

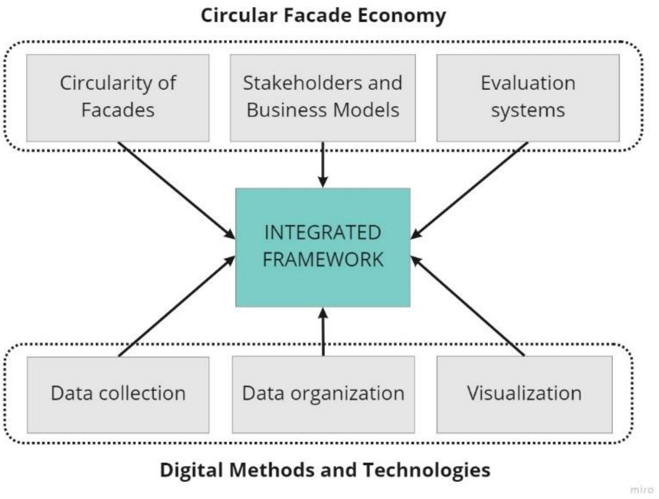


*Figure 4 - Positioning of the Research Topic. Source: Author*

### 1.3.1 Sub Objectives

1. Identify what kind of data required in different stages of the Lifecycle of a façade to promote a circular façade economy.

2. To develop a data categorization standard to organize the data.

3. To identify digital methods and technologies to collect, manage, Access, and analyze this Data.

4. To identify the different stakeholders involved in the Lifecycle of a façade and what kind of data from a material passport would be utilized.

5. To identify a case study, map out the lifecycle stages and stakeholder involvement, and demonstrate data utilization methods to promote reuse/remanufacturing.

6. Interviews with industry experts to understand production processes employed, challenges faced, and barriers to implement Industry 4.0 concepts into their products.

### *1.3.2 Products*

1. **Integrated Framework:** A framework comprises state-of-the-art literature reviews and an organizational map of the lifecycle, stakeholder, and data interaction at different stages of a project. This framework would be a result of several diagrams, guidelines, tables, and conceptual flowcharts.

2. **Tool Demonstration:** Conceptual flowcharts and wireframes of a computational tool, demonstrating the framework's application onto the case study facade, to execute appropriate reverse logistics strategies using the available data.

## 1.4 Research Questions

How can a framework be developed to map out the use of digital methods, technologies and data flows by stakeholders involved in the life cycle of a façade in order to accelerate progress towards a circular façade economy?

1. What are the various stages involved in the circular lifecycle of a façade?

2. Who are the stakeholders involved in the circular lifecycle of a façade?

3. What are the digital methods and technologies used at the different stages of a facade's lifecycle to ensure circular flows?

4. What are the resulting data flows with implementing this technology in a circular lifecycle of a façade?

5. How can the resulting data be structured and organized into a material passport?

6. How can this data in a material passport be interpreted and utilized by the different stakeholders to promote the circular lifecycle of a façade?

## 1.5 Design Questions

How can the data in a material passport of a case study façade be structured to enable a façade producer to promote its reuse or remanufacturing at its end of service?

1. What are the main design criteria that make a façade reusable at the end of life, and how can the relevant data be included in the material passport?

2. What kind of data is known about by a façade in the current situation, and what needs to be included to ensure appropriate reverse logistics processes?

3. How can the tool be designed and visualized to ensure all the relevant information is present to go about the decision-making process?

## 1.6 Methodology

The program's methodology consists of state-of-the-art literature reviews, interviews with industry experts, case study applications, and visual demonstrations of the findings. The different aspects inform each other but are conducted mostly sequentially, answering different research areas as indicated below.

1. **State of the art literature reviews:** The state-of-the-art literature reviews are conducted to get a perspective on the current research and envision future perspectives. As the research question involves developing a theoretical framework, combining two distinct disciplines, the review's initial phases of the research are more exploratory to establish standard links and develop a conceptual framework. As areas of the framework are validated through industry experts at later stages, additional literature reviews would improve the framework. The standard search terms for the Digital methods and Technologies included: Digital frameworks, Digital Twins, Smart Manufacturing, Industry 4.0, with an affix of search terms such as 'Circular Economy,' 'Design,' 'Manufacturing,' 'Logistics", 'Supply Chain Management," 'Building Industry.' Search terms for Circular Façade Economic Included: ' Circular Economic,' 'Design for Disassembly, 'Circular evaluators,' 'Reuse of Facades', etc. The research material included previous thesis' reports, Ph.D. results, Thesis reports' of other universities and various Journals and was organized into groups of BIM, Circular Business Models, Circular Economy, Digital Frameworks, Digital Twins, Circularity Evaluations, Building facades and Material Passports.

2. **Interviews with industry experts:** The interviews with industry experts are conducted to gain a perspective on the circular façade economy, the opportunities they see, and the barriers they currently encounter. This would help establish gaps between current knowledge present in literature reviews and on-ground conditions to identify where companies are currently positioned to integrate the framework. Case studies will also be requested during the interviews to base the implementation on a real project.

3. **Implementation of the framework to a case study facade:** This phase of the project will involve focusing on specific areas of the framework and applying it to a case study. As data acquisition and transparency is key, case studies will be requested during the interviews. A computational workflow will be developed using Rhino, grasshopper with links to a customized excel database. Additional plugins to make Rhino BIM compatible such as Visual Arq and Geometry gym, will be explored, depending on the nature of the findings. This phase will be treated as an experiment to simulate the framework and determine how different stakeholders can use the data.

4. **Visual demonstration:** The research findings will be summarized using mock wireframes of a computational tool, for example, a web-based platform such as Figma, in combination with visualizations extracted from the case study experiments. Conceptual flowcharts will be made for specific computational methods to support the intended functionality of the tool.

Stage 1 and 2 would answer most of the leading research questions. Stage 3 and 4 will help in answering the design questions. The last stage will be focused on conclusions and proposing a roadmap for integration based on the findings of the other stages. Figure 5 gives a thematic organization of the research methodology.

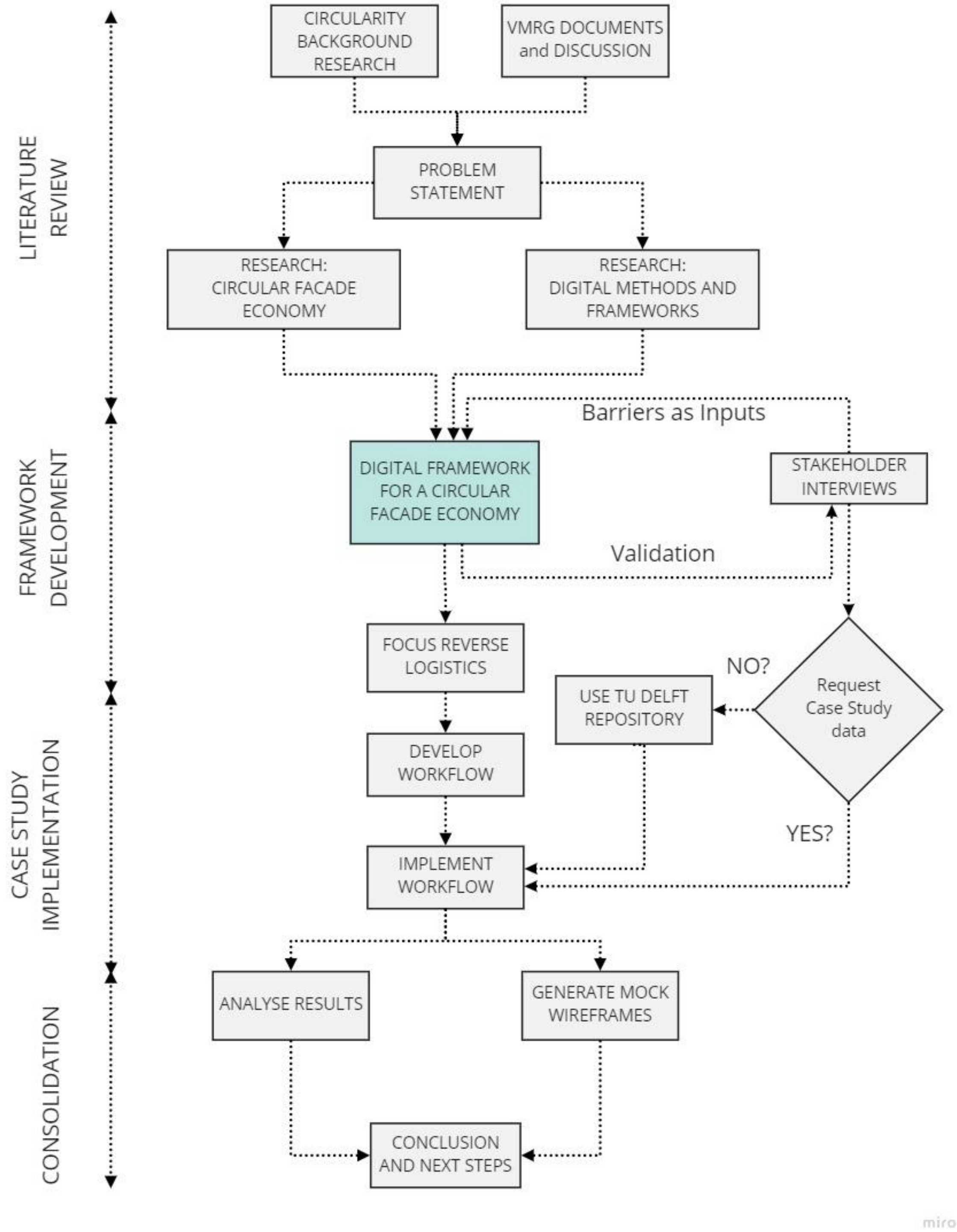
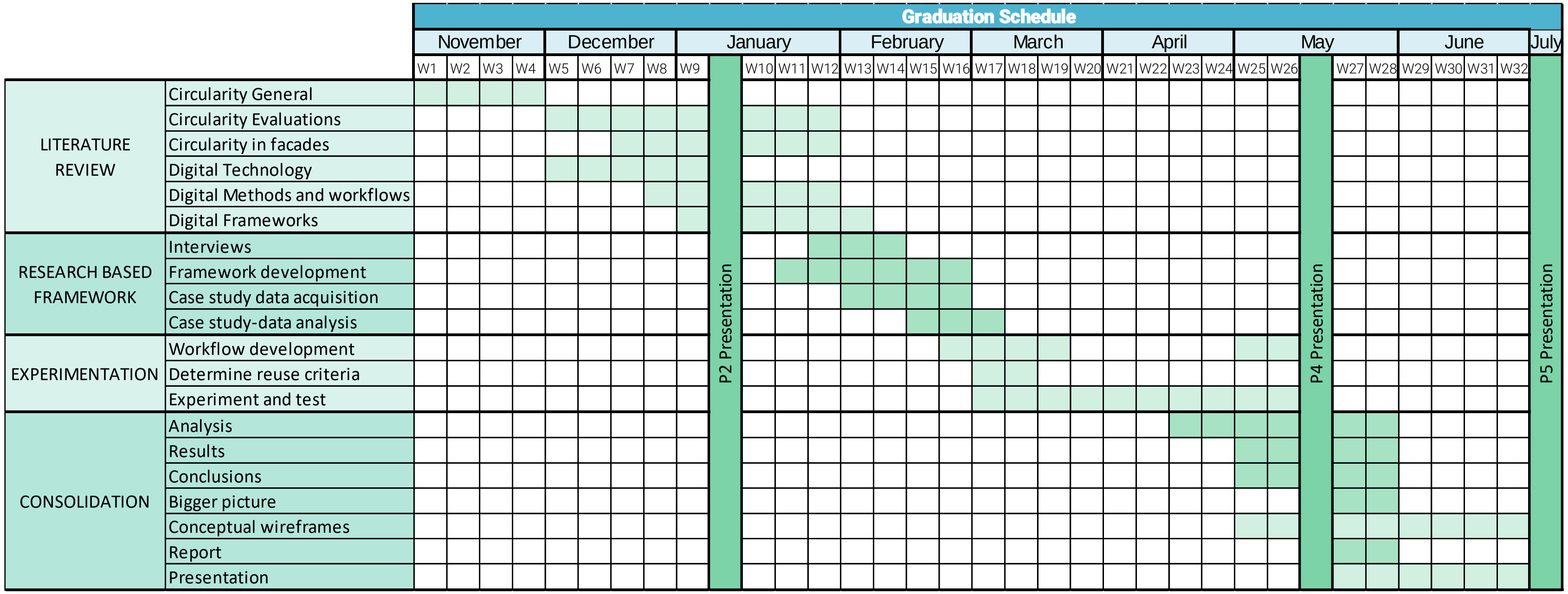


*Figure 5 - Thematic organization of the research. Source: Author*

## 1.7 Timeline



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## 1.8 Relevance

### 1.8.1 *Scientific relevance*

The topic falls under the realm of determining the technological implications of moving to a circular economy. As the topic is quite broad, a focus is made on building facades as it has a significant impact in terms of types and the impact of material used and the complexity in which it is arranged. For the Dutch façade industry to move towards a Circular Façade economy, there is an ongoing project by TU Delft and other industry stakeholders to develop a Product Service System (PSS) to extend producer responsibility. For successful implementation of this business strategy, the design of the façade changes and technologies to quantify, track, and monitor materials throughout the supply chain and ensure a data-driven decision is taken at its end of life. The building industry has always lagged in keeping up with emerging technologies, due to a dynamic and fragmented market, with multiple stakeholders involved in the decision-making process. In contrast, other related industries (automotive, aerospace, logistics) have proven successful integration due to the early adoption of these business practices. Therefore, the topic can act as a framework for the digital methods and technologies available and propose a roadmap of how the Dutch Façade Industry can integrate them into their current working methods.

### 1.8.2 *Professional Relevance*

As the topic is initiated initially by VMRG, an association of Façade Builders, the professional field's relevance is undoubted. Numerous companies in the Netherlands (MADASTER, Circular Cloud, New Horizon) and abroad are developing various methods, strategies, and roadmaps to integrate digital technologies to implement a Circular Economy. Nevertheless, most of them address the issues at the scale of a building. Building construction often involves many stakeholders, and the dynamics of interactions and collaborations differ from contract to contract. Therefore, it is challenging to develop a common framework applicable to all cases. Therefore, a focus on the façade industry, especially linking several ongoing initiatives, would help develop a more in-depth assessment. Reflections from the research can then be used to apply to other building components and domains.

### 1.8.3 *Social relevance*

With every industrial revolution, there has always been a focus on people being removed from menial and risky jobs in the quest for efficiency. This would also be the case with respect to the current industrial revolution with the development of Artificial Intelligence(AI). Therefore, the way these technologies are integrated into society can directly impact the quality of life. Many industries have already employed these technologies, and it is only expected to continue to grow. As the IT industry spearheads most of the developments, while other industries play ‘catch up’, a framework from a perspective of industry requirements can facilitate a more appropriated and meaningful integration of these techniques to current issues. The research aims to bridge the gap between the IT industry and the building industry and develop a meaningful framework with both disciplines to arrive at a common ground. Resource depletion and climate change is an issue which needs to be tackled by all industries. A recent survey from climatecare.org equates the footprint of a single google search to boiling a teacup. Therefore, efficient use of data is of paramount importance and, therefore, even technology appropriation.

## 1.9 Limitations of the research

1. As most information about facades, such as sources of material, types, and other details, are confidential, the demonstration of the framework on a case study is highly dependent on

the cooperation of the participating companies and stakeholder willingness to share information.

2. As most of the computational methods and workflows mentioned cannot be developed within the time frame, the demonstrations will only be a visual representation with a high-level flowchart that indicates the different processes.
3. The framework will encompass only Stakeholders directly involved in the lifecycle of a façade. Indirect stakeholders(banks, financial institutions, govt etc.) will be mentioned, but details of what information can be useful for them are beyond the project's scope.
4. As the project aims to bridge gaps between the construction and the digital industry, two distinct and vast fields, an attempt will be made to ensure the framework is understood by both disciplines and can be treated as the common language.

# 2 Circular Façade Economy

## 2.1 Introduction

In Buildings, resources are used by different parts of the building, and they have different lifecycles. Brand (1994) illustrates this as the shearing layers of change where facades have a lifespan of 20+ years. However, this is much smaller than the main structure of the building, which is assigned a range from 30-300 years. This lower lifespan can be either attributed to extended wear and tear due to exposure to weather or replacement of the façade to adapt to new trends and standards. Design for Disassembly (DFD) is one way to achieve a circular building, which ensures materials can be separable from each other at the End of life. When viewing Brand's layers with the perspective of the building being circular, it can be presumed that each of the layers needs to be separable from each other. This approach has resulted in modern building constructions, especially facades, move towards prefabricated building techniques.

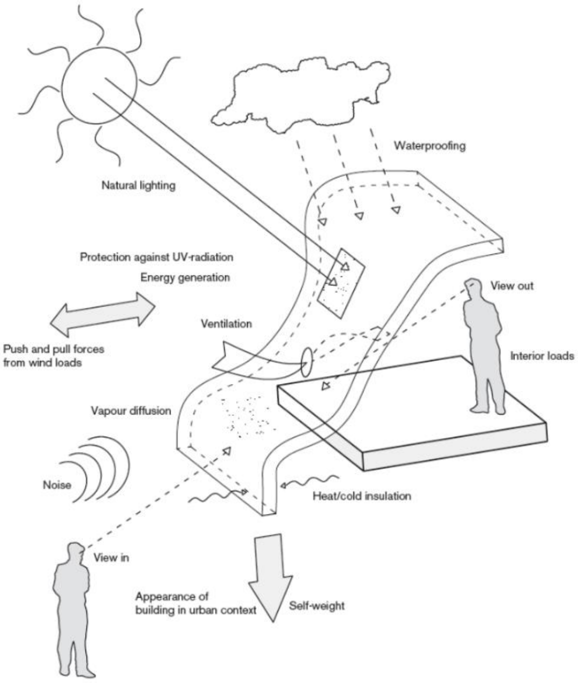


*Figure 7 - Functions of a facade. Taken from Knaack, Klein, Bilow, and Auer (2007)*

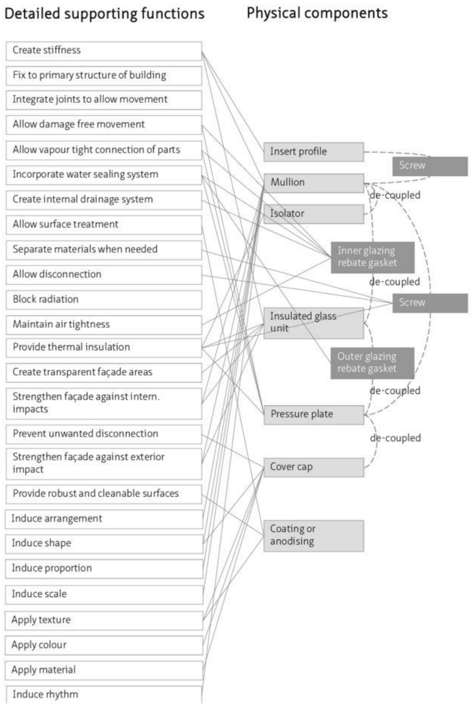


*Figure 6 - Function structure of a typical curtain wall. Taken from Klien (2013)*

Prefabrication can be mainly attributed to the high level of precision, complexity, and detailing in contemporary facades(Klien, 2013). Where other building parts can have tolerances in cm, tolerances in building facades are in millimeters (Klien, 2013). Therefore, components need to be prefabricated and require pre-assembly in controlled environments to ensure quality is retained. Apart from the lower lifespan, facades can contribute to at least 20% of the cost of construction, can have a surface to floor area ration of around 40% for most tall buildings (Parker, Wood, 2013), and serves as an external protection layer with a host of functions as detailed in Figure 7, which results in a complex, intricate assembly of materials as detailed in the function structure in Figure 6. The parameters mentioned above and a drastic impact on operational energy, and therefore the impact of facades in the building's overall footprint, cannot be underestimated. Therefore due to the number of components and the prefabricated nature of facades, along with its unquestionable impact on the carbon emissions, progress can be made towards developing circular strategies for facades.

## 2.2 The life cycle of a façade

### *2.2.1 Forward Logistics*

The different phases of an architectural project, as shown in Figure 8.

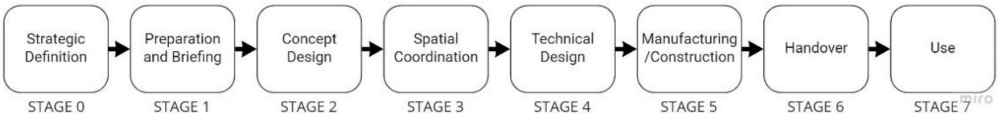


*Figure 8 - Stages of a construction project. Adapted from RIBA (2020, p. 40)*

Although the technical Lifecycle of a façade technically starts at stage 6, when the parts are being manufactured and installed, the material selection, which has a significant impact on the Lifecycle of the facade, can start at the early stages of design, i.e., stage 2 or 3. The decisions were taken during the concept, and technical design stages can contribute to 80% of the environmental impact of the building (Morini, Ribeiro, & Hotza, 2019). Depending on the structure of the contract, a façade designer and producer can be involved at an earlier or later stage of the project, and this can also impact the overall quality. The Lifecycle of a typical façade is shown in Figure 9. These stages run parallel to the Stages of the rest of the project in Figure 8.

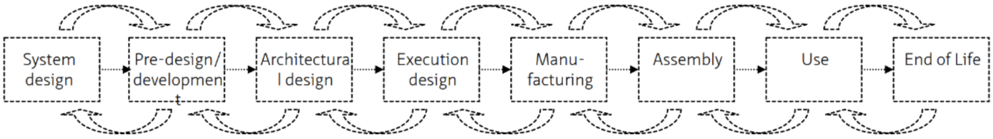


*Figure 9 – The Design and construction process for a curtain wall. Source (Klien, 2013, p. 40)*

Different stakeholders are involved in various stages of the building, again highly dependent on the structure of the contract, but a generalization is shown in Figure 10. While the involvement of stakeholders during the design stage is significantly high, it is interesting to see no stakeholder involved at the End-of-life stage. This was confirmed by Klien (2013) during interviews with different façade builders, who seemed to show a poor understanding of the stages after End of life. The interviews have shown that most façade builders do not have an understanding of the proper End of life of a façade.

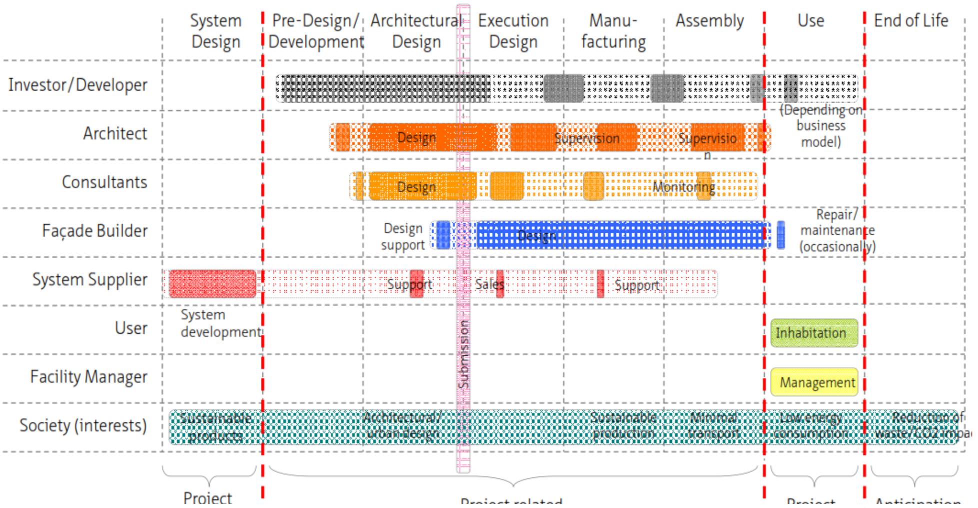


*Figure 10 - Stakeholder involvement in the lifecycle of a façade. Source: Klien (2013)*

### 2.2.2 *Reverse Logistics*

According to a report published by Alba-Concepts (2020), who addressed the possibilities of Producer responsibility for facades, with the short lifecycles of facades, it can be assumed that every existing aluminum façade will be replaced once in the period between 2020-2095. This was done with the assumption of the Lifecycle of aluminum at around 75 years. Furthermore, considering the lack of involvement by stakeholders at the End of life, as stated earlier, there is still ambiguity about the right processes to take place at this stage of a project. According to (Schultmann and Sunke, 20015), reverse logistics processes can be categorized into the collection, inspection, sorting, reprocessing, and redistribution. A more detailed reverse logistics derived from the Butterfly diagram is illustrated in Figure 11.

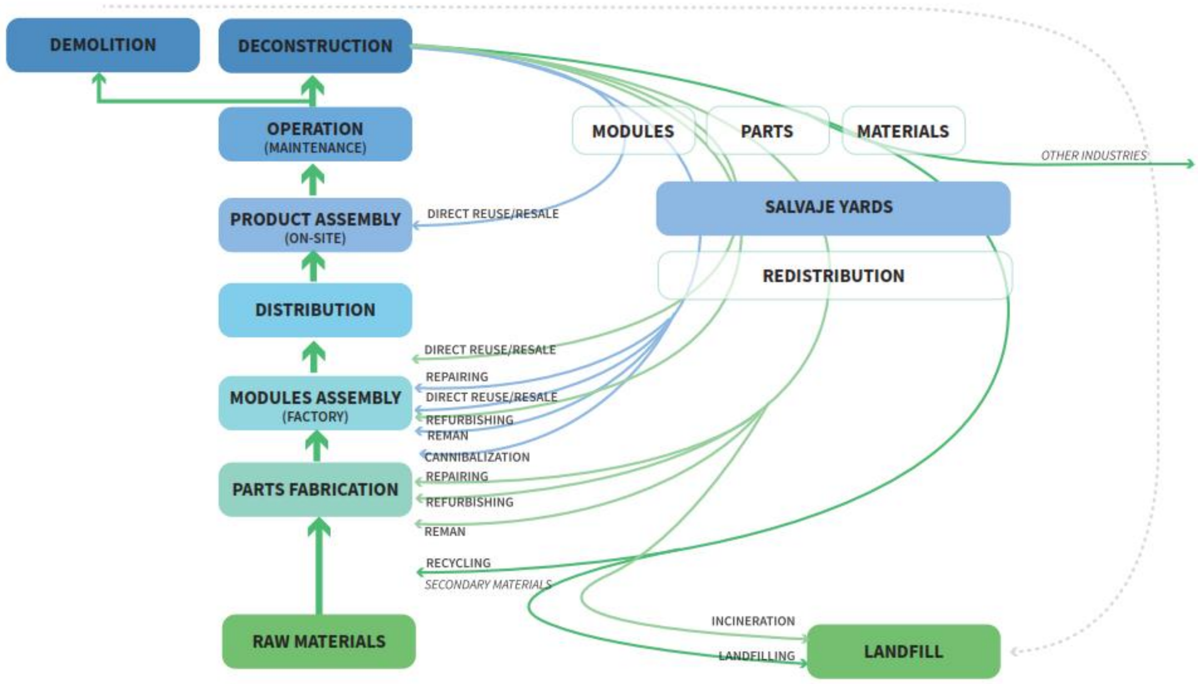


*Figure 11 - Facade Reverse logistics based on the Butterfly diagram. Source (J.M.Leos, 2020)*

### 2.2.3 *Circular Lifecycle of a façade*

Based on Figure 4 and 6, the forward and reverse logistics process involved in a façade can be combined to derive a circular lifecycle diagram of a façade can as shown in Figure 12.

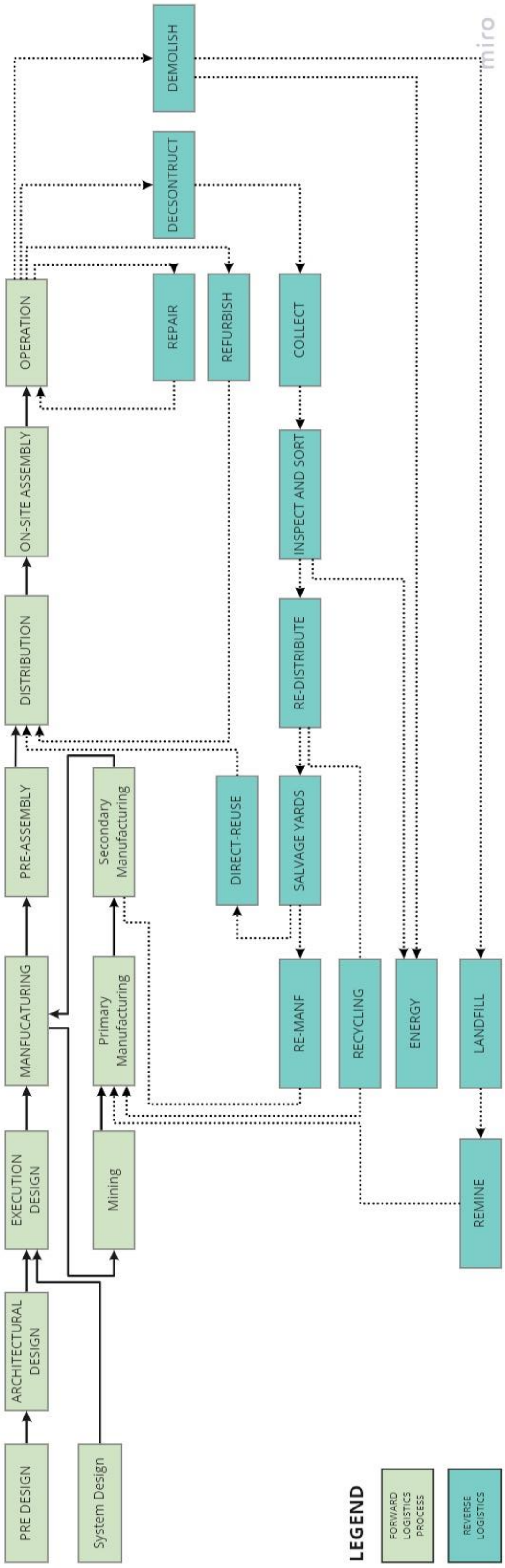


*Figure 12 - The circular Lifecycle of a facade. Source: Author*

## 2.3 Business Models

Implementation of a circular façade economy has drastic implications in the way business models are structured. As the current building and manufacturing industry implement a linear process, a long term collaboration between stakeholders such as supply tiers, contractors, and clients are not promoted(Azcárate-Aguerre, den Heijer, & Klein, 2018). There would be numerous challenges for designers and business strategists to facilitate this transformation from a take-make-dispose to a more circular model(Bocken, Bakker, & de Pauw, 2015). Therefore, to implement a circular façade economy, there is no doubt that most of the innovation can be driven by an appropriate business strategy.

According to (Chesbrough, 2010), the same product innovation implemented through different business models can lead to different economic outcomes. This logic is equally valid with circular business models. Bocken et al. (2015) categorize these business models into two main categories, slowing product loops, and closing product loops, as shown in Figure 13. Slowing resource loops deal with keeping the products we have in use for longer and closing loops deal explicitly with closing the loop between post use and production.

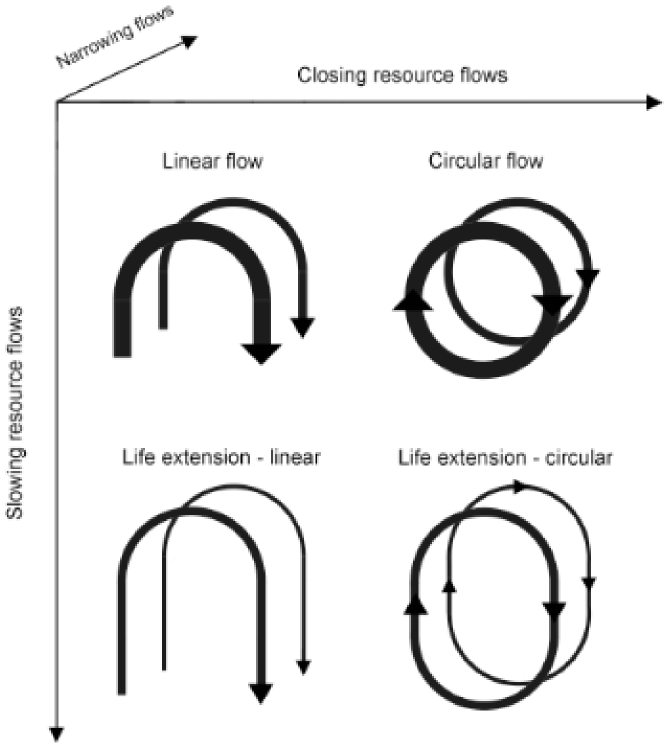
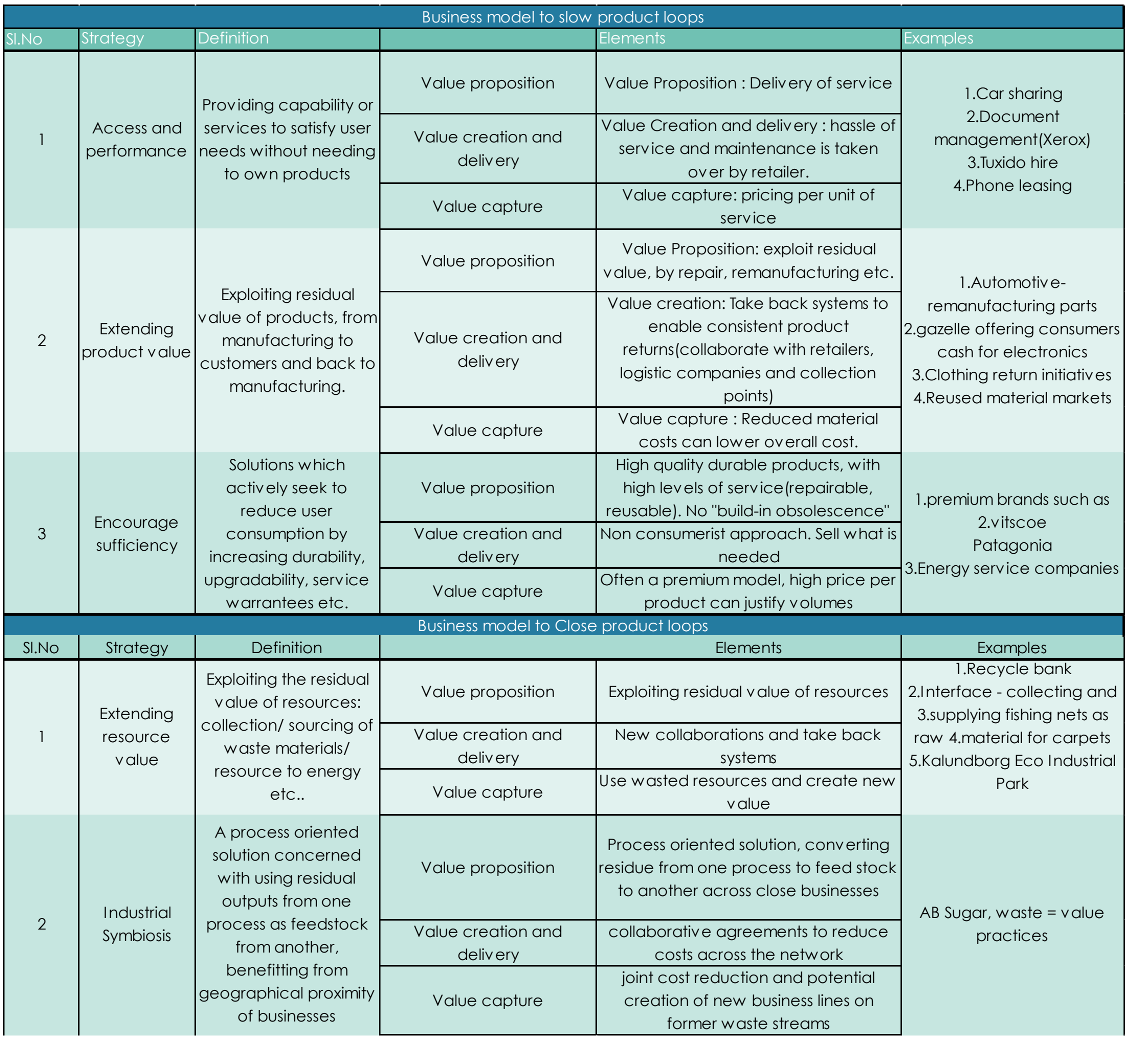


*Figure 13 - Categorization of Business models. Source: Bocken et al. (2015).*

Based on these categories, a list of business models is detailed in Figure 14.



| Business model to slow product loops | | | | | |
|---|---|---|---|---|---|
| Sl.No | Strategy | Definition | Elements | | Examples |
| 1 | Access and performance | Providing capability or services to satisfy user needs without needing to own products | Value proposition | Value Proposition : Delivery of service | 1.Car sharing<br>2.Document management(Xerox)<br>3.Tuxido hire<br>4.Phone leasing |
| | | | Value creation and delivery | Value Creation and delivery : hassle of service and maintenance is taken over by retailer. | |
| | | | Value capture | Value capture: pricing per unit of service | |
| 2 | Extending product value | Exploiting residual value of products, from manufacturing to customers and back to manufacturing. | Value proposition | Value Proposition: exploit residual value, by repair, remanufacturing etc. | 1.Automotive-remanufacturing parts<br>2.gazelle offering consumers cash for electronics<br>3.Clothing return initiatives<br>4.Reused material markets |
| | | | Value creation and delivery | Value creation: Take back systems to enable consistent product returns(collaborate with retailers, logistic companies and collection points) | |
| | | | Value capture | Value capture : Reduced material costs can lower overall cost. | |
| 3 | Encourage sufficiency | Solutions which actively seek to reduce user consumption by increasing durability, upgradability, service warrantees etc. | Value proposition | High quality durable products, with high levels of service(repairable, reusable). No "build-in obsolescence" | 1.premium brands such as<br>2.vitscoe<br>Patagonia<br>3.Energy service companies |
| | | | Value creation and delivery | Non consumerist approach. Sell what is needed | |
| | | | Value capture | Often a premium model, high price per product can justify volumes | |
| Business model to Close product loops | | | | | |
| Sl.No | Strategy | Definition | Elements | | Examples |
| 1 | Extending resource value | Exploiting the residual value of resources: collection/ sourcing of waste materials/ resource to energy etc.. | Value proposition | Exploiting residual value of resources | 1.Recycle bank<br>2.Interface - collecting and<br>3.supplying fishing nets as raw 4.material for carpets<br>5.Kalundborg Eco Industrial Park |
| | | | Value creation and delivery | New collaborations and take back systems | |
| | | | Value capture | Use wasted resources and create new value | |
| 2 | Industrial Symbiosis | A process oriented solution concerned with using residual outputs from one process as feedstock from another, benefitting from geographical proximity of businesses | Value proposition | Process oriented solution, converting residue from one process to feed stock to another across close businesses | AB Sugar, waste = value practices |
| | | | Value creation and delivery | collaborative agreements to reduce costs across the network | |
| | | | Value capture | joint cost reduction and potential creation of new business lines on former waste streams | |

*Figure 14 - Overview of Different Business models and examples Source: adapted from (Bocken et al., 2015).*

While the table gives an overview of the different possibilities, it can be noted that 1 or 2 approaches between the two main categories can combine or collaborate to create an industrial symbiosis of sorts. For example, a recycle bank that is mainly concerned about extending the value of resources can collaborate with Access and a performance-based company to receive unfunctional material and supply finished products.

## 2.4 Towards a Product-Service System (PSS) for Facades

There is ongoing work in treating building facades as a service to extend producer responsibility. A scheme of this is indicated in Figure 15. As per Azcárate-Aguerre (2014), in the typical business model, the client would be the owner of the façade but would not have the technical know-how of how to maintain it, and therefore, facades can go neglected during the operation phase. In a Product Service System(PSS), the producer can ensure he can provide service for the whole period for a lower price. In a typical PSS-oriented business model, all stakeholders are tied materially and financially to the building's optimum performance throughout its service life, including the End of service decision making(Azcárate-Aguerre et al., 2018). These business models would can fall under the Access and Performance category or the encourage sufficiency models as per the categorization in Figure 14. The value addition can either be that facades are supplied as a pay per service or designed with durable material to reduce maintenance costs, or a combination of both. In either case, servicing is carried out by the supplier through its use as part of the contract. One of the main reasons is that the performance of a façade or a mechanical system in a building is dependent on the performance of each of the individual systems and so do they have similar life spans. Therefore, employing such business models would change stakeholders' engagement terms responsible for designing and manufacturing façades. Facades would be designed to be more robust, efficient, serviceable, and possibly integrated with mechanical systems. Due to most modern façade components' modular nature, they are interchangeable, enabling clients, service providers, and manufacturers to make short-term decisions with lower investments. (Azcárate-Aguerre, 2014).

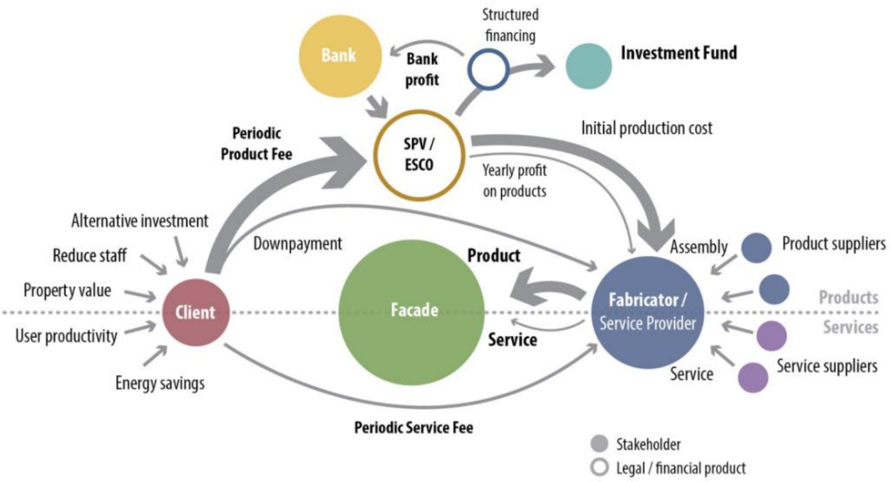
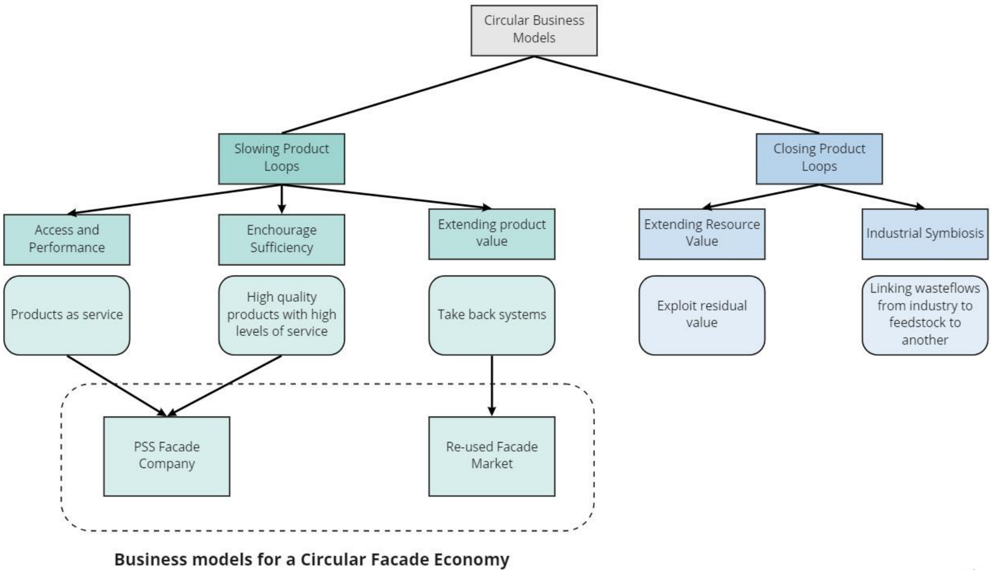


*Figure 15 - A facade leasing scheme is indicating stakeholder involvement. Source: Azcarate et al. (2018)*

A truly Circular PSS System needs to be an extension of a typical DBFMO contract (Design, Build, Finance, Maintain and Operate) contract which many new builders operate with. While employing such a business model would require redesigning of current facades, including the way building services are structured, it



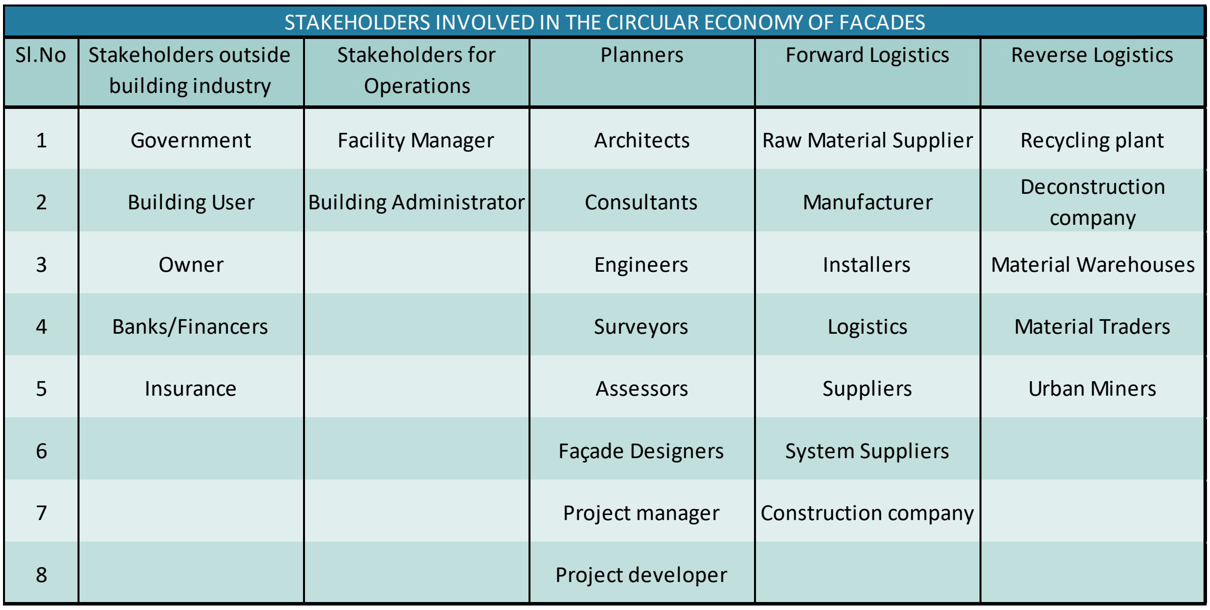
**Business models for a Circular Facade Economy**

*Figure 16 - Categorization of Business models which can be explored under the Circular Facade Economy. Source: Author*

could be a high capital route to facilitate circular principles. An alternative model can be developed where the remanufacturing is done by an enterprise who collects façade parts from various sources, remanufactures and re-sells it in the open market at a competitive price. The various dynamics involved in such a model still needs to be explored as shown in Figure 16.

## 2.5 Stakeholders

The involvement of stakeholders in a typical lifecycle of a façade was indicated in Figure 10 under chapter 2.2.1. which more generalized and for primarily forward logistics processes. Circular Business models or contracts would also require additional stakeholders to be involved even in the reverse logistics process. Typically a logistics manager appointed during the End of life stage takes care of transportation, storage, and distribution of building components, but in a circular economy, more stakeholders such as deconstructor, collector, and recycling companies can be involved (Heinrich & Werner, 2019). Moreover, the implications of Circular thinking extend beyond the realm of the building industry. They can also include the end-users, city inhabitants, regulatory bodies, infrastructure providers, and countless others. (Azcárate-Aguerre et al., 2018). Therefore, it is difficult to identify all the stakeholders in a value chain and differ based on location, contract model employed, regulations, and project type. A more generalized list of the different actors is formulated in Figure 17. The list is developed based and categorized based on an extensive material passports framework developed by Heinrich and Werner (2019), Figure 10 under chapter 2.2.1, and common knowledge and eventually be validated by Industry Experts. Specific actors involved in P.S.S-based contracts for facades can be considered a subset of this list. The grouping is done based on each stakeholder's roles in the lifecycle of the façade and can be refined further based on other parameters. T



STAKEHOLDERS INVOLVED IN THE CIRCULAR ECONOMY OF FACADES

| Sl.No | Stakeholders outside building industry | Stakeholders for Operations | Planners | Forward Logistics | Reverse Logistics |
|---|---|---|---|---|---|
| 1 | Government | Facility Manager | Architects | Raw Material Supplier | Recycling plant |
| 2 | Building User | Building Administrator | Consultants | Manufacturer | Deconstruction company |
| 3 | Owner |  | Engineers | Installers | Material Warehouses |
| 4 | Banks/Financers |  | Surveyors | Logistics | Material Traders |
| 5 | Insurance |  | Assessors | Suppliers | Urban Miners |
| 6 |  |  | Façade Designers | System Suppliers |  |
| 7 |  |  | Project manager | Construction company |  |
| 8 |  |  | Project developer |  |  |

*Figure 17- Stakeholders Involved in the Circular Lifecycle of a Building. Source: adapted from Heinrich and Werner (2019, p. 51)*

## 2.6 Barriers to implementing Circular principles in Facades

Among the various reverse logistics options, recycling is the most commonly preferred option for building facades, as it can ensure facades can be redesigned based on the trends and standards of the time. A study on the Dutch Façade Portfolio was carried out by Alba-Concepts (2020), which involved interviewing several façade producers and installers. Some of the few barriers to reusing façade components based on the market survey are given below. High labor costs and time associated with deconstruction compared to demolition processes.

1. **Real value of products:** Materials do not reflect real value, lack of integration of environmental and social impact into costs.

2. **Keeping up with standards:** Change of standards, so older frames do not match the current standards and requirements. An example is a ban on using lead-bearing PVC, which makes recycling difficult.

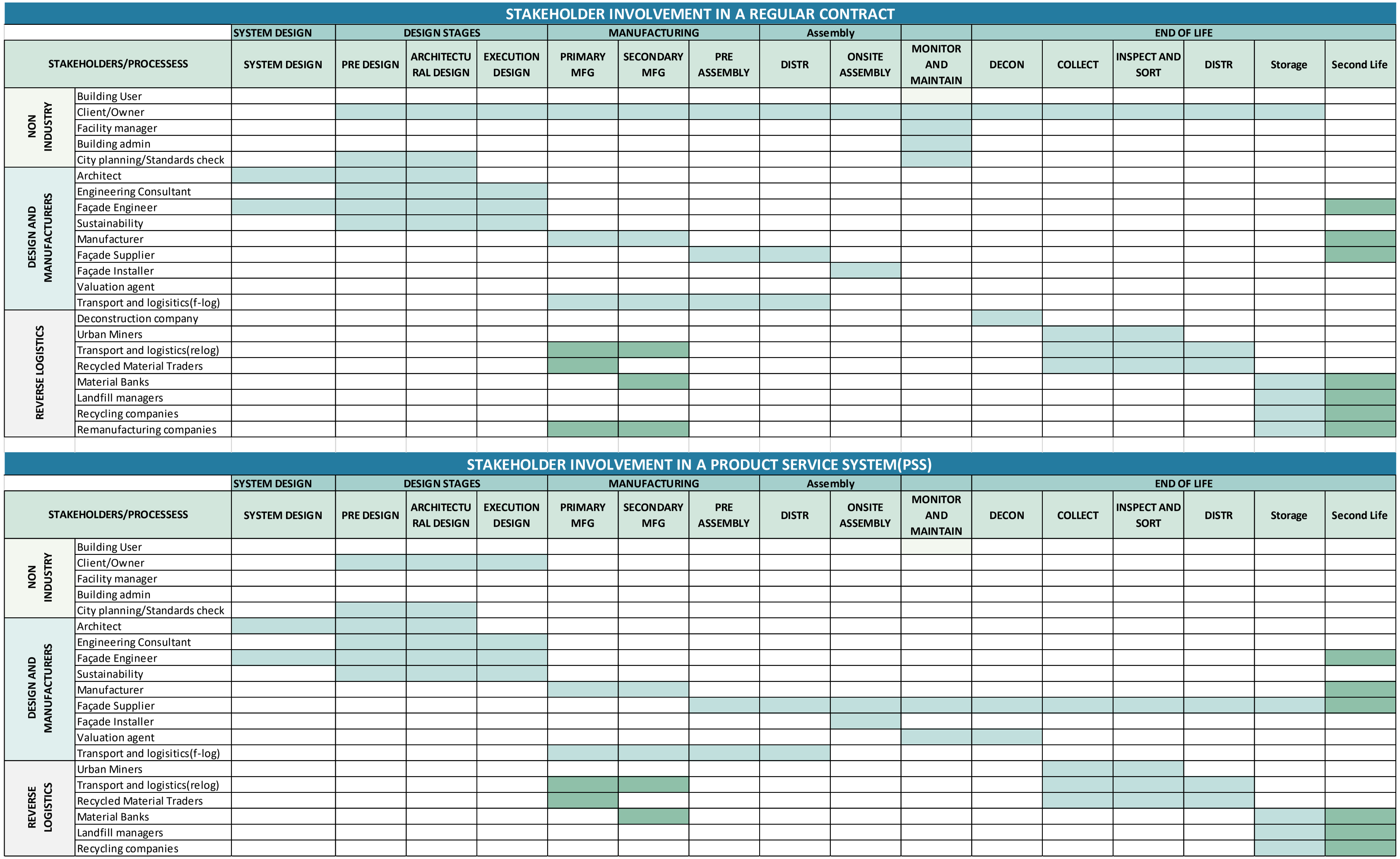
3. **Lack of data:** Lack of data about the existing condition/performance or disassembly potential of the façade.

4. **Lack of demand:** Lack of a market to resell or reuse the existing frames.

Problems 1 and 2 can be to be addressed as a strategic or policy level implementation, for example, implementing carbon tax measures or incentivizing reuse with the change of labor tax. According to (CPB/PBL, 2016), Co2 price in 2030 can be around 100-500 euros/ton. Therefore strategies like Co2 point exchange, where companies with higher Co2 can trade-off points, invest in green technologies (Azcárate-Aguerre, 2014) can benefit companies. Problems 3 and 4 can be solved with innovative solutions, business models, and other technological developments. While the façade industry is over-cautious to implementing new technologies due to the smaller scale of projects, a small portfolio could be open to new business models to extend their involvement and create continuous revenue schemes. (Azcárate-Aguerre et al., 2018).

## 2.7 Conclusions

The chapter addressed the context of why implementing circular principles in building facades is crucial and challenging. For successful implementation, the Lifecycle of a façade must include forward and reverse logistics processes, which results in a circular lifecycle of a façade. Various stakeholders are involved at different stages of the Lifecycle bound together by circular business models and contracts. While in traditional contracts, technical stakeholders who know the façade disconnect from the project even before the use stage, business models such as a Product Service system (PSS) can ensure stakeholder interaction through the use stage and at the end of life. As these business models have not yet been fully implemented in the market, the stakeholder involvement in the project's lifecycle can only be assumed and validated with interviews during the research. There is also financial merit for this involvement as the materials are owned by the company which installs it to ensure the material is recovered in the right order. Figure 18 shows the stakeholder involvement in the circular lifecycle of a façade and the stakeholder involvement in the case of a PSS system. Nonetheless, there are specific barriers to move towards this model, which are summarized in chapter 2.6. Some barriers require a policy level implementation, but progress can be made on improving the other barriers mentioned.



| STAKEHOLDER INVOLVEMENT IN A REGULAR CONTRACT | | SYSTEM DESIGN | DESIGN STAGES | | | MANUFACTURING | | | Assembly | | | END OF LIFE | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STAKEHOLDERS/PROCESSESS | | SYSTEM DESIGN | PRE DESIGN | ARCHITECTURAL DESIGN | EXECUTION DESIGN | PRIMARY MFG | SECONDARY MFG | PRE ASSEMBLY | DISTR | ONSITE ASSEMBLY | MONITOR AND MAINTAIN | DECON | COLLECT | INSPECT AND SORT | DISTR | Storage | Second Life |
| NON INDUSTRY | Building User | | | | | | | | | | | | | | | | |
| | Client/Owner | | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ | |
| | Facility manager | | | | | | | | | | ░ | | | | | | |
| | Building admin | | | | | | | | | | ░ | | | | | | |
| | City planning/Standards check | | ░ | ░ | | | | | | | ░ | | | | | | |
| DESIGN AND MANUFACTURERS | Architect | ░ | ░ | ░ | | | | | | | | | | | | | |
| | Engineering Consultant | | ░ | ░ | ░ | | | | | | | | | | | | |
| | Façade Engineer | ░ | ░ | ░ | ░ | | | | | | | | | | | | ▓ |
| | Sustainability | | ░ | ░ | ░ | | | | | | | | | | | | |
| | Manufacturer | | | | | ░ | ░ | | | | | | | | | | ▓ |
| | Façade Supplier | | | | | | | ░ | ░ | | | | | | | | ▓ |
| | Façade Installer | | | | | | | | | ░ | | | | | | | |
| | Valuation agent | | | | | | | | | | | | | | | | |
| | Transport and logisitics(f-log) | | | | | ░ | ░ | ░ | ░ | | | | | | | | |
| REVERSE LOGISTICS | Deconstruction company | | | | | | | | | | | ░ | | | | | |
| | Urban Miners | | | | | | | | | | | | ░ | ░ | | | |
| | Transport and logistics(relog) | | | | | ▓ | ▓ | | | | | | ░ | ░ | ░ | | |
| | Recycled Material Traders | | | | | ▓ | | | | | | | ░ | ░ | ░ | | |
| | Material Banks | | | | | | ▓ | | | | | | | | | ░ | ▓ |
| | Landfill managers | | | | | | | | | | | | | | | ░ | ▓ |
| | Recycling companies | | | | | | | | | | | | | | | ░ | ▓ |
| | Remanufacturing companies | | | | | ▓ | ▓ | | | | | | | | | ░ | ▓ |

| STAKEHOLDER INVOLVEMENT IN A PRODUCT SERVICE SYSTEM(PSS) | | SYSTEM DESIGN | DESIGN STAGES | | | MANUFACTURING | | | Assembly | | | END OF LIFE | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STAKEHOLDERS/PROCESSESS | | SYSTEM DESIGN | PRE DESIGN | ARCHITECTURAL DESIGN | EXECUTION DESIGN | PRIMARY MFG | SECONDARY MFG | PRE ASSEMBLY | DISTR | ONSITE ASSEMBLY | MONITOR AND MAINTAIN | DECON | COLLECT | INSPECT AND SORT | DISTR | Storage | Second Life |
| NON INDUSTRY | Building User | | | | | | | | | | | | | | | | |
| | Client/Owner | | ░ | ░ | ░ | | | | | | | | | | | | |
| | Facility manager | | | | | | | | | | | | | | | | |
| | Building admin | | | | | | | | | | | | | | | | |
| | City planning/Standards check | | ░ | ░ | | | | | | | | | | | | | |
| DESIGN AND MANUFACTURERS | Architect | ░ | ░ | ░ | | | | | | | | | | | | | |
| | Engineering Consultant | | ░ | ░ | ░ | | | | | | | | | | | | |
| | Façade Engineer | ░ | ░ | ░ | ░ | | | | | | | | | | | | ▓ |
| | Sustainability | | ░ | ░ | ░ | | | | | | | | | | | | |
| | Manufacturer | | | | | ░ | ░ | | | | | | | | | | ▓ |
| | Façade Supplier | | | | | | | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ░ | ▓ |
| | Façade Installer | | | | | | | | | ░ | | | | | | | |
| | Valuation agent | | | | | | | | | | ░ | ░ | | | | | |
| | Transport and logisitics(f-log) | | | | | ░ | ░ | ░ | ░ | | | | | | | | |
| REVERSE LOGISTICS | Urban Miners | | | | | | | | | | | | ░ | ░ | | | |
| | Transport and logistics(relog) | | | | | ▓ | ▓ | | | | | | ░ | ░ | ░ | | |
| | Recycled Material Traders | | | | | ▓ | | | | | | | ░ | ░ | ░ | | |
| | Material Banks | | | | | | ▓ | | | | | | | | | ░ | ▓ |
| | Landfill managers | | | | | | | | | | | | | | | ░ | ▓ |
| | Recycling companies | | | | | | | | | | | | | | | ░ | ▓ |

*Figure 18 - Stakeholder involvment in regular contracts vs Product Service System(PSS). Source : Author, to be valided by Industry experts.*

# 3 Circularity indices

## 3.1 About C.E. Indices

According to Corona, Shen, Reike, Rosales Carreón, and Worrell (2019), circularity indicators can play an essential role in increasing public awareness. A need for indicators was also raised by the European Commission's action plan (E.C.,2015) as follows : "to assess progress towards a more circular economy and the effectiveness of action at E.U. and national level, it is important to have a set of reliable indicators." The tools can help all the stakeholders, such as academics, industrialists. Politicians and decision-makers to be more aware of C.E. principles and manage the transition at different systemic levels.

Several circularity indices and measurement frameworks have been established. Each methodology takes into account different inputs and is calculated using formulas or an online/offline computational tool. Most of these indices aim to represent the level of Circularity in a product and are represented from a number ranging from 0 to 1(Corona et al., 2019). These indices can be used either for labeling products based on performance metrics or to instigate regulatory change. However, these indices' primary objective should be to evaluate the circular flow materials and not focus on other aspects such as environmental impact (Linder, Sarasini, & van Loon, 2017). The assessments can be addressed at different spatial levels, such as macro, meso, and micro. Each of these levels can correspond to different evaluation methods and techniques(Saidani, Yannou, Leroy, & Cluzel, 2017).

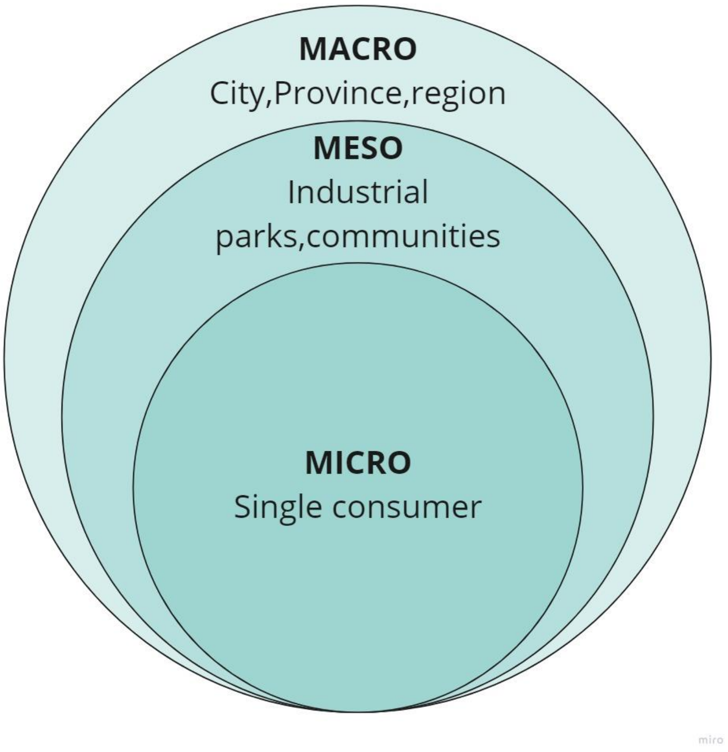


*Figure 19 - Different spatial levels of evaluating Circularity as defined by Saidani et al. (2017). Source: Own*

## 3.2 Comparisons

According to Linder et al. (2017), there is not only a need for a robust assessment method but also a requirement to consolidate the different options and compare them for strengths and weaknesses. Therefore, the research on these comparative evaluations was identified in a way to identify which methodology would be most useful when assessing the Circularity of building facades. The first paper by Linder et al. (2017) compared different tools to identify weaknesses and aim to derive a new metric for quantifying product-level circularity. The main contribution is to clarify the fuzzy logic of current indicators and understand their usability in an organized manner (Linder et al., 2017). They assessed the various tools to Construct Validity, reliability, Transparency, Generality, and Aggregation Principles, and the results are summarized in Figure 20. The results found that none of the metrics they compared score well on all criteria. Although MFA and MCI provide useful starting points, the methods seem to be problematic during accurate quantification of the inputs (Linder et al., 2017). Although the Eco-Efficient Value Ratio ranks the highest, the differences between the results are not significant enough to rule out the other indicators.

| | Construct Validity | Reliability | Transparency | Generality | Aggregation Principles | Total Score |
|---|---|---|---|---|---|---|
| Eco Efficient Value Ratio | 1 | 1 | 2 | 3 | 3 | 10 |
| Material Circularity Indiacator | 2 | 1 | 1 | 3 | 2 | 9 |
| Circular Economy Index | 1 | 3 | 3 | 1 | 0 | 8 |
| Repro | 1 | 1 | 2 | 2 | 1 | 7 |
| Material Reutilization Part(C2C) | 2 | 0 | 1 | 3 | 1 | 7 |

*Figure 20 - Evaluation of the table based on numerical values. Source: adapted from Linder et al. (2017).*

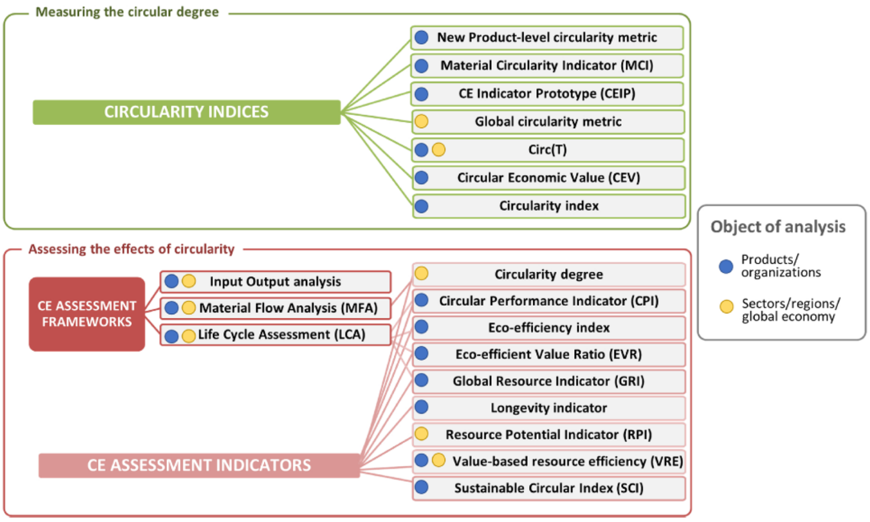
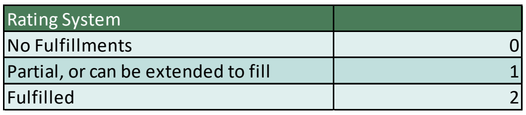


**Fig. 1.** Classification of reviewed circularity metrics. *Additional indicators applied within the assessment frameworks are described in detail in Table 2.

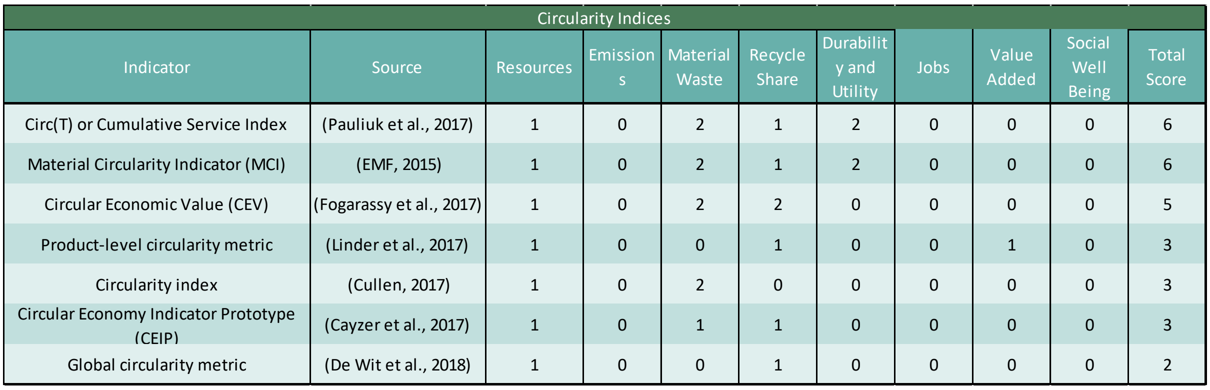
*Figure 21 - Classification of the reviewed metrics. Source: Corona et al. (2019).*

Linder et al. (2017) defined a new evaluation method called the Product level Circularity metric, which is based on the use of product parts' economic value as a basis for aggregating recirculated and non-recirculated elements into a combined measure for product circularity. However, even this new method had its limitations, as evaluated by Corona et al. (2019), who categorized various assessment methods into two groups: assessment indices and assessment tools, as shown in Figure 21. The first group, termed 'Circularity measurement Indices are methods to provide one value ranging from 0 to 100%, representing the circularity degree. The second group, termed 'Circularity Assessment Tools' was analyzed to contribute strategies to the principles of Circular Economic and was further subdivided into CE Assessment Indicators and CE assessment Frameworks. All these different methods are evaluated for their environmental, ecological, and societal considerations. The criteria were evaluated for the level of fulfillment as partial, total, or no fulfillment. These ratings were converted to points and tabulated, as shown in Figure 22. The results of the research are summarized in in Figure 23 and Figure 24.



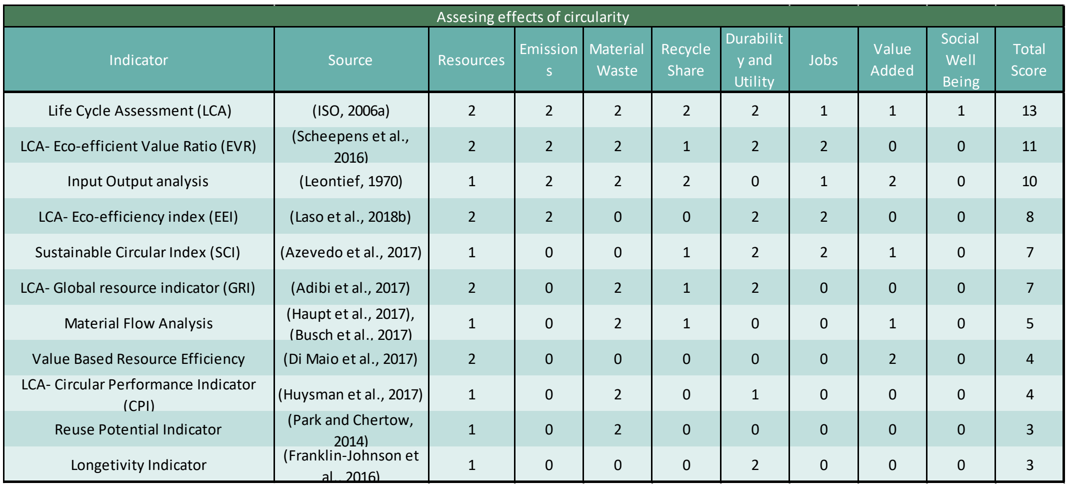
| Rating System | |
|---|---|
| No Fulfillments | 0 |
| Partial, or can be extended to fill | 1 |
| Fulfilled | 2 |

*Figure 22 – Assignment of points based on fulfillment level. Source: Author*



| Circularity Indices | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Indicator | Source | Resources | Emissions | Material Waste | Recycle Share | Durability and Utility | Jobs | Value Added | Social Well Being | Total Score |
| Circ(T) or Cumulative Service Index | (Pauliuk et al., 2017) | 1 | 0 | 2 | 1 | 2 | 0 | 0 | 0 | 6 |
| Material Circularity Indicator (MCI) | (EMF, 2015) | 1 | 0 | 2 | 1 | 2 | 0 | 0 | 0 | 6 |
| Circular Economic Value (CEV) | (Fogarassy et al., 2017) | 1 | 0 | 2 | 2 | 0 | 0 | 0 | 0 | 5 |
| Product-level circularity metric | (Linder et al., 2017) | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 3 |
| Circularity index | (Cullen, 2017) | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 3 |
| Circular Economy Indicator Prototype (CEIP) | (Cayzer et al., 2017) | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 3 |
| Global circularity metric | (De Wit et al., 2018) | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 2 |

*Figure 23 - Results of the evaluation of circularity indices, ranked from highest to lowest fulfillment levels. Source: adapted from Corona et al. (2019).*

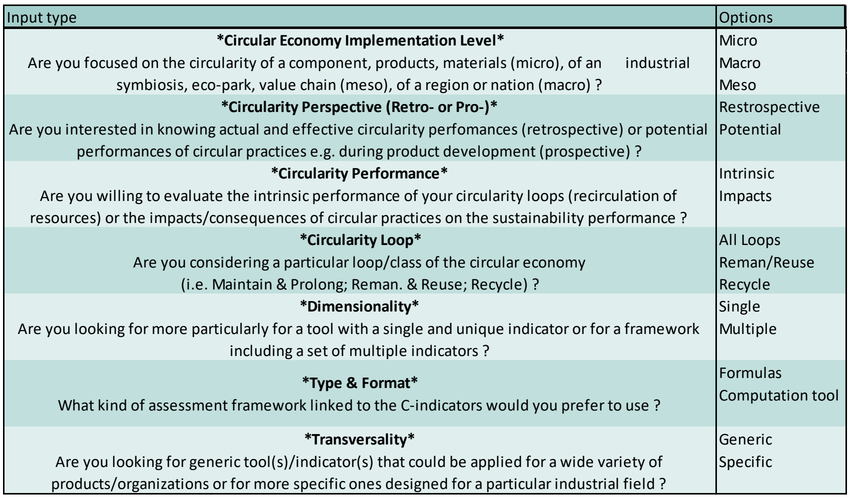


| Assesing effects of circularity | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Indicator | Source | Resources | Emissions | Material Waste | Recycle Share | Durability and Utility | Jobs | Value Added | Social Well Being | Total Score |
| Life Cycle Assessment (LCA) | (ISO, 2006a) | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 13 |
| LCA- Eco-efficient Value Ratio (EVR) | (Scheepens et al., 2016) | 2 | 2 | 2 | 1 | 2 | 2 | 0 | 0 | 11 |
| Input Output analysis | (Leontief, 1970) | 1 | 2 | 2 | 2 | 0 | 1 | 2 | 0 | 10 |
| LCA- Eco-efficiency index (EEI) | (Laso et al., 2018b) | 2 | 2 | 0 | 0 | 2 | 2 | 0 | 0 | 8 |
| Sustainable Circular Index (SCI) | (Azevedo et al., 2017) | 1 | 0 | 0 | 1 | 2 | 2 | 1 | 0 | 7 |
| LCA- Global resource indicator (GRI) | (Adibi et al., 2017) | 2 | 0 | 2 | 1 | 2 | 0 | 0 | 0 | 7 |
| Material Flow Analysis | (Haupt et al., 2017), (Busch et al., 2017) | 1 | 0 | 2 | 1 | 0 | 0 | 1 | 0 | 5 |
| Value Based Resource Efficiency | (Di Maio et al., 2017) | 2 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 4 |
| LCA- Circular Performance Indicator (CPI) | (Huysman et al., 2017) | 1 | 0 | 2 | 0 | 1 | 0 | 0 | 0 | 4 |
| Reuse Potential Indicator | (Park and Chertow, 2014) | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 3 |
| Longetivity Indicator | (Franklin-Johnson et al., 2016) | 1 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 3 |

*Figure 24 - Results of the evaluation of assessment frameworks, ranked from highest to lowest fulfillment levels. Source: adapted from Corona et al. (2019).*

The results show that none of the metrics are addressing all the criteria they have identified, and the differences in the total results are quite drastic. They attribute this issue to the diverse understanding of the C.E. concept, which is oversimplified in many cases. The criticality of resources is not taken into account. Therefore, social and environmental externalities are not integrated and therefore fail to represent the scarcity, emission levels, or socio-economic impacts (Corona et al., 2019). Among all assessment methods, LCA has shown a high potential to assess Circularity's goals at the product and service level, but the results still need to be translated at a product or service level. However, this directly contradicts (Linder et al., 2017) position on circularity metrics being purely focused on the circular economy concepts and not be boarded to accommodate other requirements.

Therefore, it can be concluded that, while there is still not a single indicator assessing all of the circularity principles and much contradicting viewpoints exist about what an indicator should or should not take into account. Therefore a combination of multiple assessments could be a way forward for Example, LCA, in combination with MCI, or Circ(T). As metrics are usually used contextually based on the stakeholders' needs, the stakeholder can generate different metrics if the available data is met. Another paper by Saidani, Yannou, Leroy, Cluzel, and Kendall (2019), who evaluated  55 indicators from diverse sources were analyzed. Their goal was to propose a taxonomy of circular indicators as different indicators could be used for a different purpose. Even Saidani et al. (2019)conclude the lack of reliability of most current indicators as they state, to provide a more holistic approach considering both intrinsic Circularity and its effects on the three pillars of sustainability, i.e., Social, Economic, and Environmental parameters. The research resulted in an excel tool that can be used to identify the different metrics. The data inputs required and other parameters where subjective comparisons can be made. A set of Inputs as shown in Figure 25, are asked to be entered, for which results are tabulated. Using the excel tool, a preliminary search was conducted to identify potential methods, usage, and required data.The results are tabulated in Figure 26.



| Input type | Options |
|---|---|
| ***Circular Economy Implementation Level***<br>Are you focused on the circularity of a component, products, materials (micro), of an industrial symbiosis, eco-park, value chain (meso), of a region or nation (macro) ? | Micro<br>Macro<br>Meso |
| ***Circularity Perspective (Retro- or Pro-)***<br>Are you interested in knowing actual and effective circularity perfomances (retrospective) or potential performances of circular practices e.g. during product development (prospective) ? | Restrospective<br>Potential |
| ***Circularity Performance***<br>Are you willing to evaluate the intrinsic performance of your circularity loops (recirculation of resources) or the impacts/consequences of circular practices on the sustainability performance ? | Intrinsic<br>Impacts |
| ***Circularity Loop***<br>Are you considering a particular loop/class of the circular economy (i.e. Maintain & Prolong; Reman. & Reuse; Recycle) ? | All Loops<br>Reman/Reuse<br>Recycle |
| ***Dimensionality***<br>Are you looking for more particularly for a tool with a single and unique indicator or for a framework including a set of multiple indicators ? | Single<br>Multiple |
| ***Type & Format***<br>What kind of assessment framework linked to the C-indicators would you prefer to use ? | Formulas<br>Computation tool |
| ***Transversality***<br>Are you looking for generic tool(s)/indicator(s) that could be applied for a wide variety of products/organizations or for more specific ones designed for a particular industrial field ? | Generic<br>Specific |

*Figure 25 - Input options of the excel tool to find suitable indicators. Source:  adapted from tool developed by Saidani et al. (2019).*

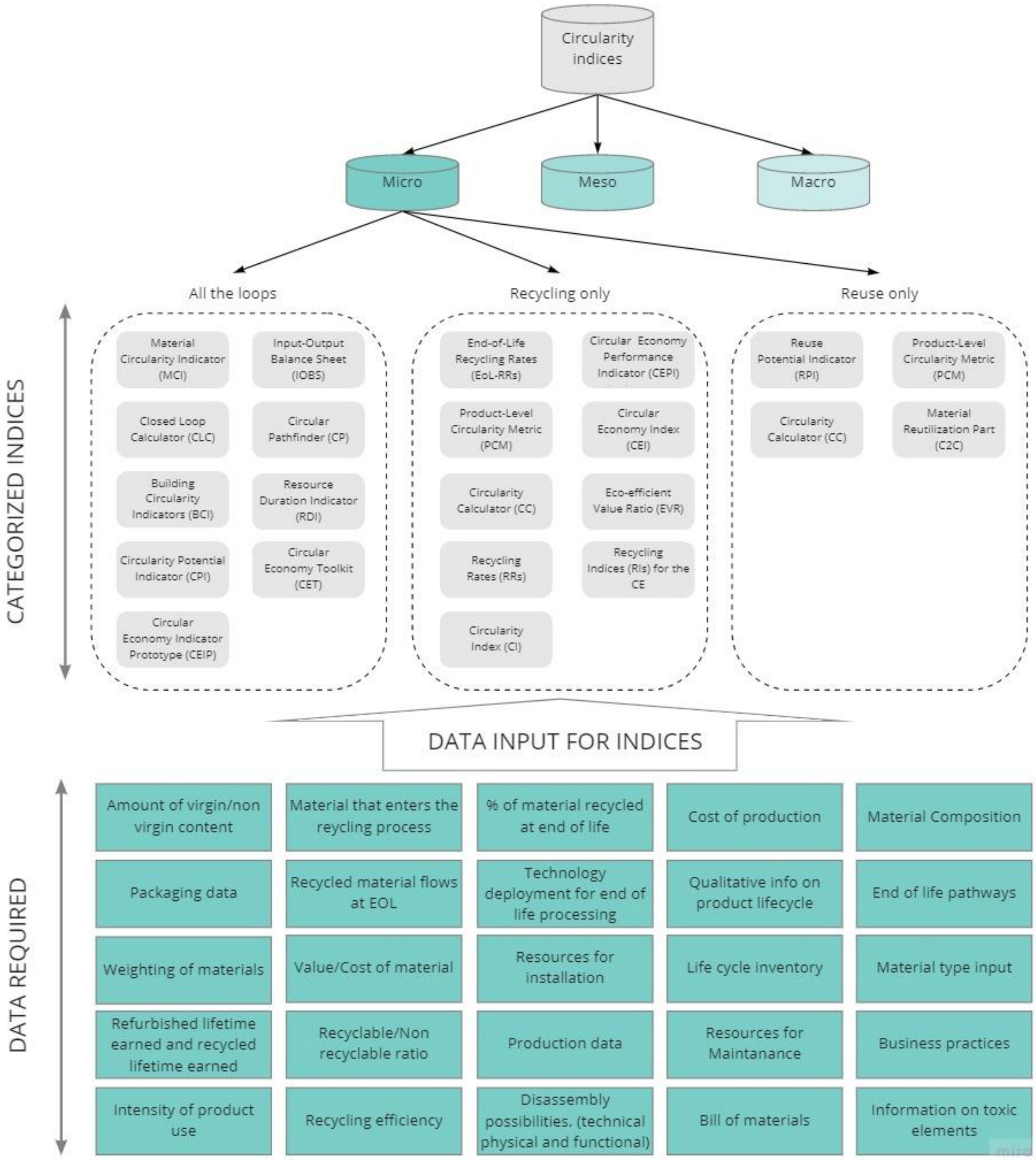


*Figure 26 - Categorization of results from the excel tool and a summerization of all the required data input for performing the calculations. Source: Author*

## 3.3 Other parameters influencing Circularity

Apart from the above indicators, which give the recycling and reuse potential, additional assessments need to be carried out, specific to building facades. The morphological matrix is a method to assess disassembly and design for adaptability criteria in building facades. Each façade is categorized into subsystems and components and is further divided and identified. Disassembly schemes with the component/element name, product levels, clustering, and type of connections are developed, as shown in Figure 27 and Figure 28. These factors are analyzed through a diagram and evaluated at the system level, sub-system level, and component level against 21 criteria indicating relative Circularity or linearity. Although the result cannot be quantified numerically, it can still be used as early indicators to compare facades.

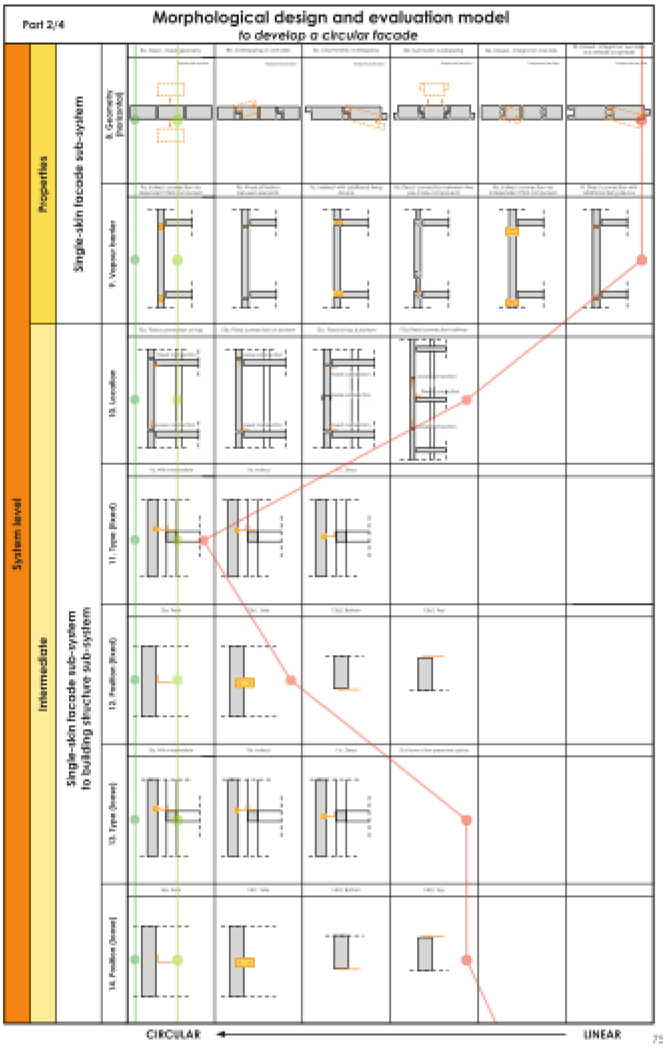


*Figure 27 - The Morphological matrix developed indicating the level of circularity of a facade based on 21 properties. Source. (Beurskens & Bakx, 2015)*

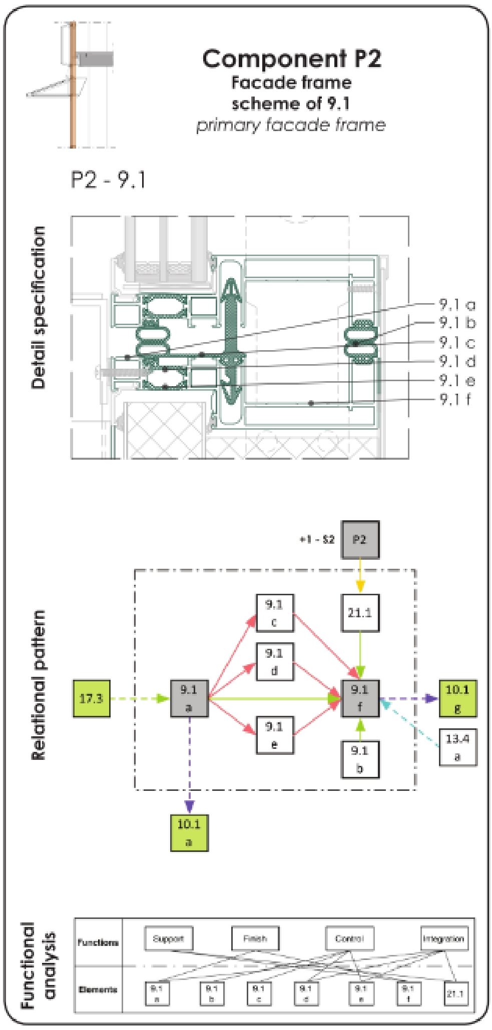


*Figure 28 - Evaluation steps of a case study facade. Source: (Beurskens & Bakx, 2015)*

## 3.4 Conclusions

While it is evident that there is more than one method for evaluating Circularity, and none of them cover the concepts in full, the vast number of assessments available indicates significant progress in developing methods to analyze. A good indicator needs to be specified through the entire lifecycle of products, from design, production, consumption, and End of life (EEA, 2016). Even during this research, it was identified that most of these tools are only available upon request to the authors, and some are not offered without a financial incentive (e.g., C2C), which brings a degree of unreliability of the indicators.

In order to compute indicators accurately, there is a requirement for the various need of data all along the value chain (Saidani et al., 2019). Even Lützkendorf and Balouktsi (2017) state a need to focus on the data required to feed the indicators. Therefore, the information is difficult to obtain and must be provided by the product chain actors (Potting et al., 2017). Most assessment tools need objective data with sufficient reliability to give results that match the intended purpose (Rahla , Braganca, & Mateus, 2019). As the number of data sources increases, it can result in Big Data which can drastically change the way Circularity assessments are made (Rahla et al., 2019). While several industries such as automotive, aeronautical, logistics have already integrated the utilization of Big data into their operations, the building industry has only begun to scratch the surface of the various potentials it has to offer. This can be attributed to the somewhat fragmented market space, where most businesses are too small or conservative in implementing new methods and technologies, or there is not much of a demand. But what is clear is that with Big Data, there can be an availability of entirely new data sets, especially at the micro-level, to assess the circularity performance of products, components, and materials in the entire life cycle (Saidani et al., 2019).

# 4 Material Passport (MP)

## 4.1 Defining a Material Passport

Various names have been given to Material Passports, such as Circularity Passports, Product Passports, Resource Passports and others. While resource passports deal with raw materials, products, circularity, and material passports deal with components or products after the manufacturing stage. As defined by Mullhall et al. (2017, p. 3), "Material Passports are digital sets of data describing defined characteristics of materials and components in products and systems that give them value for present use, recovery, and reuse." They are part of a larger group of data sets, such as the building cadaster of a region or city. They are differentiated from building passports and energy passports, as shown in Figure 29. The nature of application and scale characterizes the differences between them. Material passports describe characteristics focusing on the value of materials in reuse or recovery (Heinrich & Werner, 2019), energy passports can be used to communicate the energy performance of a building (Virta, Hovorka, & Lippo, 2012), and building passports can be used to capture information on building quality as well as environmental properties and performance data (Blum, 2001). Essentially material passports become a tool for tracking materials and documenting the residual value of materials and is a powerful component to support circular building initiatives.

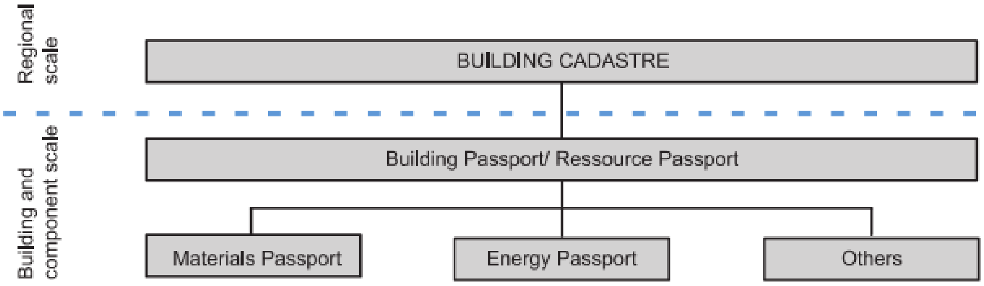


*Figure 29 - Classification of Materials Passports. Source: Heinrich and Werner (2019)*

## 4.2 Material Passport Contents

While there are several definitions of material passports, a standardized format for its contents has not yet established. In most cases, passports are developed more like a document with information concerning the use case. They can be an extension of an ingredients list with additional information such as material health, disassembly, positioning, location, reverse logistics, etc. (Luscuere, 2017). Heinrich and Werner (2019) released an extensive document titled "Materials Passports – Best Practice, " which indicates a materials passport's various contents. The document gives an overview of the different types of information included in the material passport, the actors and stakeholders involved, and types of material and product-related information. The primary data categorization is Material Data, Lifecycle management, and Assessment and Certification, with several subcategories as shown in Figure 30. Based on this extensive list, an overview of the different information included is generated, as shown in Figure 31.

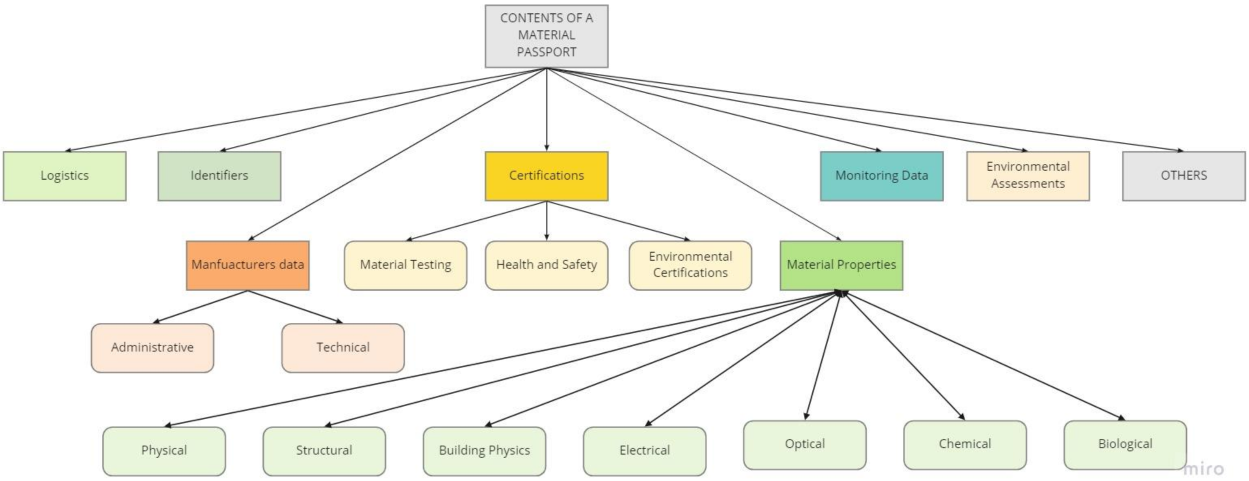


*Figure 30 – Categorization of the contents of the material passport. Source: partially adapted from (Heinrich & Werner, 2019)*

1. **Identifiers:** These refer to various Unique identification systems used to identify the particular component in the building.
2. **Manufacturers Data:** These refer to data sets relating to production-related information, which can be subcategorized as Administrative data, such as registrations, dates, etc., and Technical data, which have more specific details about production processes and so on.
3. **Monitoring data:** These refer to data collected once the product is installed and operational. It can be structural fatigue, thermal properties such as temperature, anything that would help understand the wear and tear of the product to predict its maintenance, performance, or expected lifespan.
4. **Logistics:** Data used during the transportation of material from different nodes of the supply chain.
5. **Certifications:** Contains All the various certifications and standards the material needs approval from
6. **Material Properties:** These are technical information on the various properties of materials such as thermal, optical, structural, building physics, biological, etc.
7. **Environmental assessments:** These can be values extracted from databases or eco inventories or calculated based on inputs from other data within the material passport. Examples are LCA ratings, Circularity indices, Carbon footprint, and so on, depending on the standard employed by the organization or country.

| MATERIAL PASSPORT DATA CATEGORIZATION | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sl. No | Identifiers | Manufacturers Data | | Monitoring data | Logistics | Certifications | | | Material Properties | | | | | | | Environmental Impacts |
| | | General Info | Technical Data | | | Material Testing Cerifications | Health and Safety | Environmental Certifications | Physical Characteristics | Structural Data | Building Physics | Electrical Properties | Optical | Chemical Composition | Biological Properties | |
| 1 | GTIN | Registration number | Production processess | Temperature | Packaging requirements | Energy Labelling | Occupant Wellbeing | Breeam | Size | Compressive Strength | Transparency | Electrical Resistivity | Colour | Material Name | Renewable/non-renewable | LCA rating |
| 2 | GS1 | Country of registration | Handing and installation | Humidity | Supply chain management | Structural | Emissions | LEED | Geometry | Tensile Strength | Hygroscopicity | Electrical Conductivity | Structure | Surface Treatmenets | Untreated/treat ed | LCC |
| 3 | Article Number | Manufacturing date | Disassembly instructions | Structural data | Transportation Requirements | Emission | Toxicity | EPD | Density | Youngs Modulus | Sound Insulation and transfer | | Surface | Composition | Decomposability | SLCA |
| 4 | CAS Number | Expected lifetime | Technical drawings | Energy | Other | Compliance | Emissions | C2C Certification | Weight | Specific stiffness | Fire protection | | Transmission | Adhesives | | MCI |
| 5 | BIM Identification | Year of dataset | BIM Model | Water | Storage requirements | Fire Testing | MSDS | Performance Declaration | Thicnkess | Yeild Strength | Ventilation and Air Tightness | | Transparecy | | | Material Criticality |
| 7 | Product name | Company Certification | Cleaning and Maintanance | Others | RFID Tags | | | | | Specific strength | Daylighting and Illumination Props | | Reflectivity | | | Recycling and reuse potentials |
| 6 | Manufacturer name | | | Location | Barcodes | | | | | Elongation | Fire Resistance | | | | | Lifespan |
| 7 | Active Functions | | | | | | | | | Compressive strength | U value | | | | | Embodied Energy |
| 8 | Location in Building | | | | | | | | | Flexural modulus | Thermal conductivity | | | | | Embodied CO 2 |
| 9 | Product level | | | | | | | | | Flexural Strength | Vapour diffusion | | | | | Processing Energy |
| 10 | Description | | | | | | | | | Shear Modulus | Porosity | | | | | Recycled content |
| 11 | | | | | | | | | | Bulk Modulus | Acoustics | | | | | Resonsible sourcing |
| 12 | | | | | | | | | | Poisson ratio | Maximum Service Temperature | | | | | MFA |
| 13 | | | | | | | | | | Shape factor | Minimum Service Temperature | | | | | Carbon footprint |
| 14 | | | | | | | | | | Hardness | Heat Transfer Coefficient | | | | | |
| 15 | | | | | | | | | | Fracture Toughness | Thermal mass | | | | | |
| 16 | | | | | | | | | | Toughness | Absorption | | | | | |
| 17 | | | | | | | | | | Wind Resistance(DIN 12210) | Heat Protection | | | | | |
| 18 | | | | | | | | | | | Airtightness(DIN 12207) | | | | | |
| 19 | | | | | | | | | | | Water tightness(DIN EN 12208) | | | | | |

*Figure 31 - Contents of a Material Passport. Source: Author.*

Apart from the general material properties, properties such as recycling potential, separability, and accessibility aspects also need to be included (Honic, Kovacic, & Rechberger, 2019b). While recycling potential can be calculated using an indicator, separability and accessibility aspects could be more qualitative information in the form of drawings/diagrams or visual indication of location within a building. The location and context of a component are extremely crucial to determine the end of life scenarios (Luscuere, 2017). This could be an Identifier linked to a central BIM Model. An example of the contextual information in the case of Building facades is the schematization models developed by Durmisevic (2006) is shown in Figure X. These can also be used to represent assembly and disassembly sequences and interconnectivity between various components. A product-level systematization, as shown in Figure X, can also give an indicator for the separability of the façade. A function structure would be useful to know what the function of each component is.

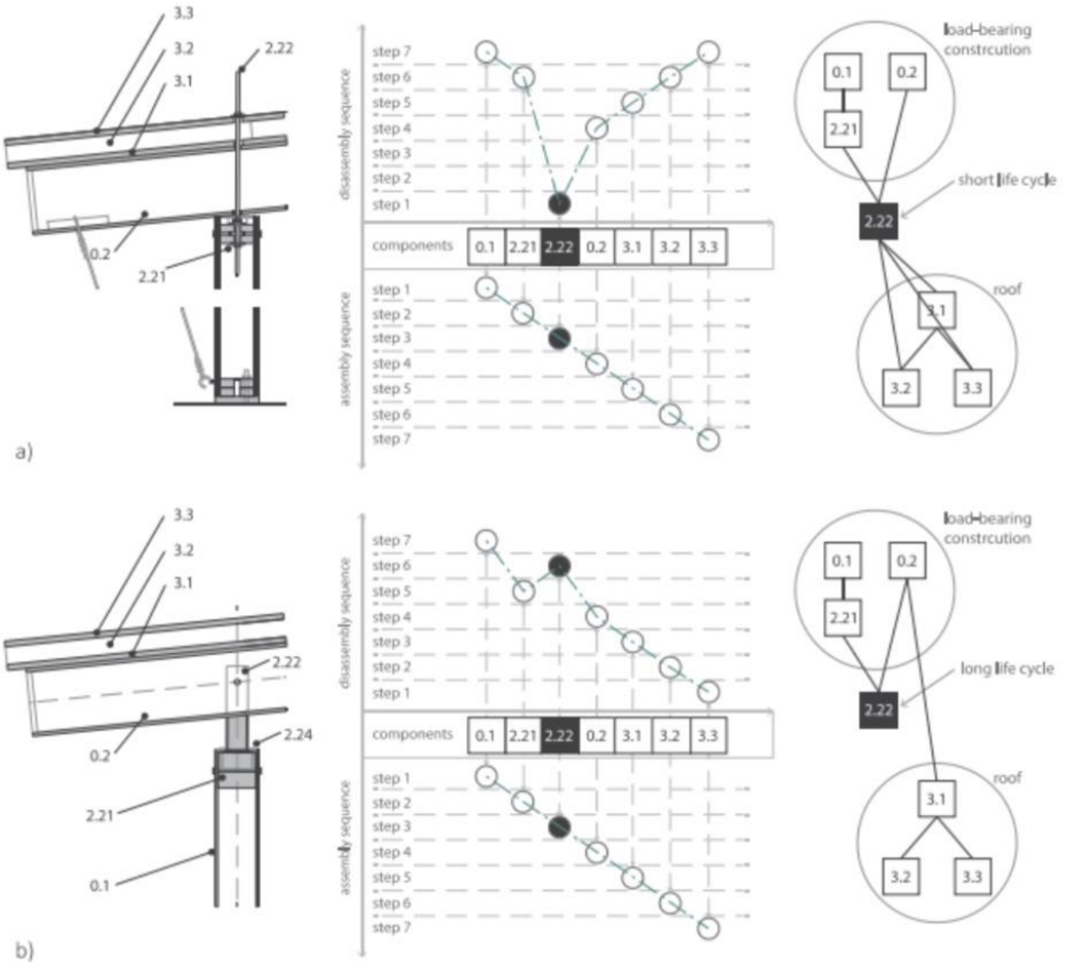


*Figure 32 - Systematization of Facades for assembly/disassembly sequencing. Source: (Durmisevic, 2006)*

An automated way of generating these systems by creating these relational diagrams from the BIM Model using graph theories and social network analysis is proposed (Denis, Temmerman, & Rammer, 2017) but yet to be implemented.

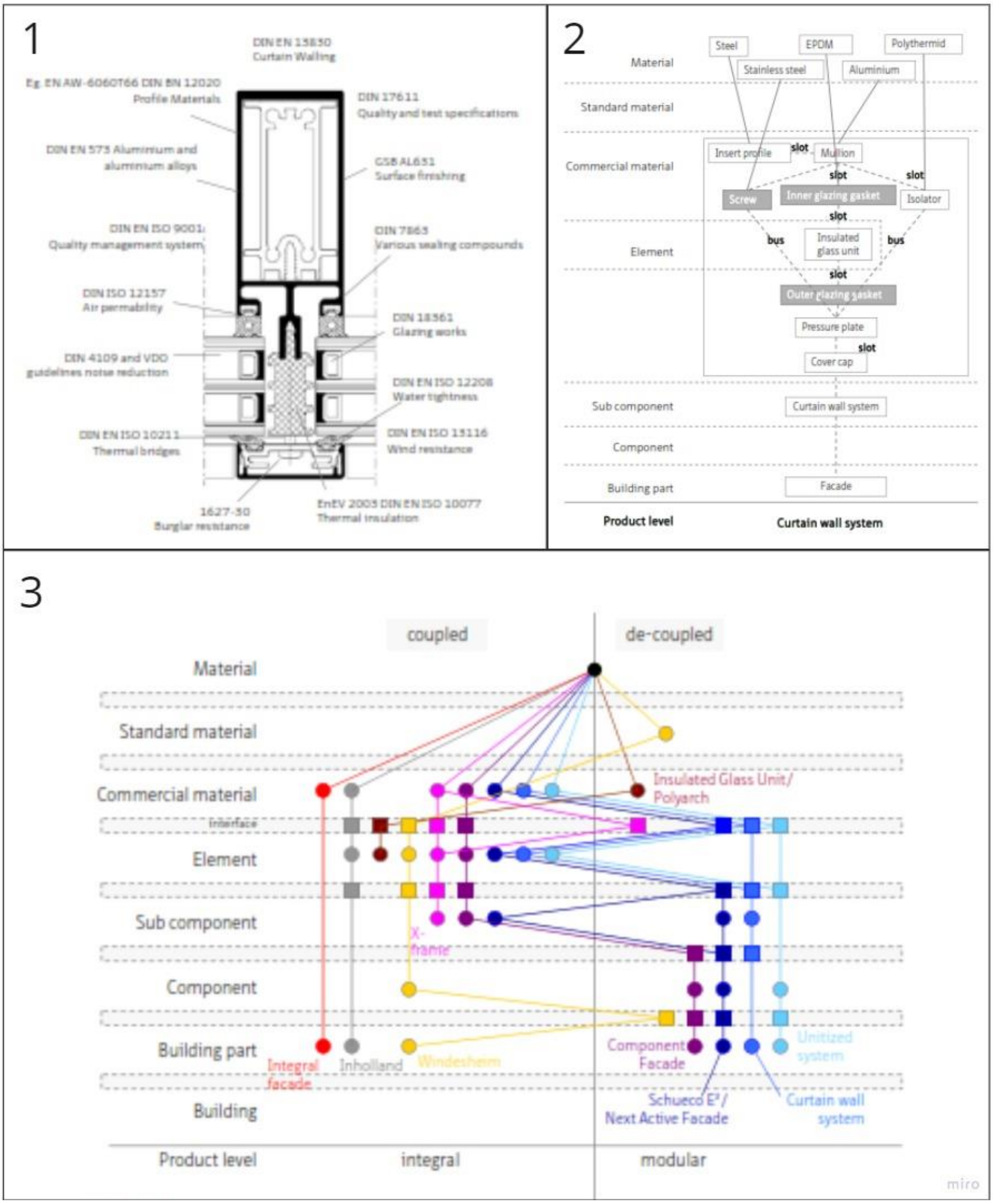


*Figure 33  1-Drawing of a typical Curtain wall, 2 the product levels and relational diagram, 3- comparisons of product profiles of multiple facades studied as part of the research. Source:  Own interpretation adapted from (Klien, 2013)*

## 4.3 Uses

The detailed specification of materials during the building design and construction phase is a major factor determining the level of re-usability of materials at the end of life (Akanbi et al., 2017). This technology needs to be addressed with high fidelity for implementing product services systems in the circular economy. Materials Passports help in achieving these goals. The uses and users of materials passports are varied throughout the circular life cycle of a product. In the early design stages, the Materials Passports can serve as an optimization tool serving as an important decision support tool. (Copeland & Bilec, 2020),(Honic, Kovacic, et al., 2019b). During tendering and documentation stages, the passports can become part of the inventory giving an overview of the various materials and components. Depending on the implementation level and information included in the passport, they can also be used during the supply chain and logistics process for tracking location in the supply chain and within the building and is a useful component for construction and site management (Heinrich & Werner, 2019). During the use phase, they can record information such as maintenance schedules, service life, and live performance monitoring. Finally, the passports with all the aggregated data about materials can help decide the best possible reverse logistic strategy for the end-of-life stage.

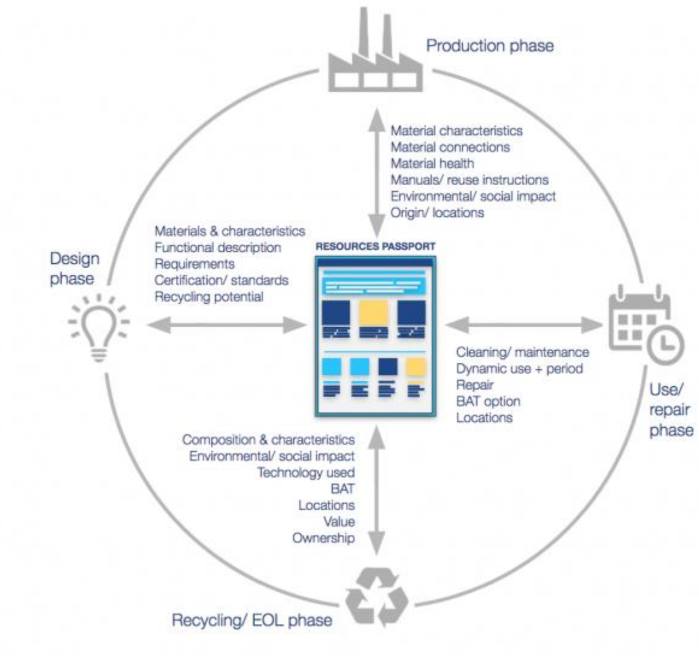


*Figure 35 - Uses of a Materials Passport in the lifecycle o a product. Source : excessmaterialsexchange.com*

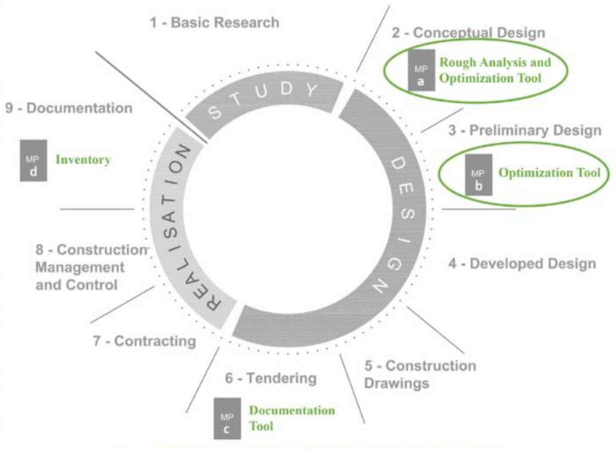


Fig. 1. The Material Passport along the life cycle of a building.

*Figure 34 - Uses of material Passport in various stages. Sournce: Copeland and Bilec (2020)*

## 4.4 Stakeholder interaction Framework

While material passports can be described as an equivalent of a nutritional label, they can do more than just be an ingredients list as they can contain data from different sources and provide information to different sources(Luscuere, 2017). This becomes one of the most critical aspects of the material passport, as not every stakeholder requires all the information simultaneously. This requires a stakeholder interaction framework and a standardized technological framework. Copeland and Bilec (2020) developed a data, stakeholder management framework for creating a BIM-based material passport as shown in Figure 36. They propose an additional stakeholder, an MP consultant who is responsible for entering relevant data into the BIM process by linking databases, analysis tools, and the BIM model. As the workflow they propose include data refrences from eco inventories and external libraries, they stress harmonizing data between eco inventories, the building elements specifications, and product declaration data. This is to ensure data can be linked more seamlessly with an automated process. A strong collaboration between MP consultants, designers, and BIM managers are needed.

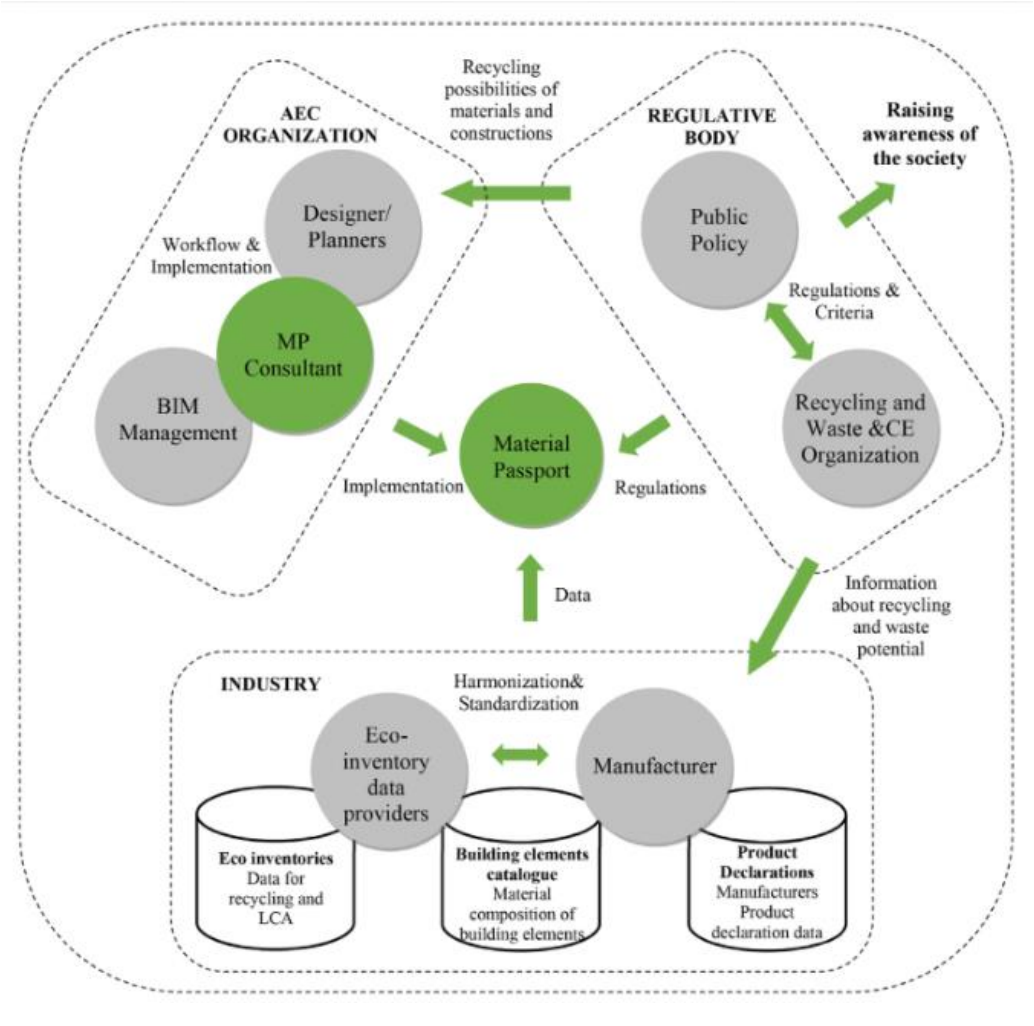


*Figure 36 - Data and stakeholder management framework. Source: Figure 31 - Introduction of a material passport consultant as a mediator for linking data between the designer and BIM manager. Source: (Copeland & Bilec, 2020)*

## 4.5 Technological framework

As materials passports are digital datasets, a technological framework needs to be defined. Currently, most material passports that are active is owned by private enterprises, and therefore, the back end functionality of the passports is not easily accessible. However, a generic framework for this is proposed by Mullhall et al. (2017), as shown in Figure 37. It breaks down the passport into three components, data, input, processing, and output of customized passports. There is a Data Input with different sources, a data processing component that works as a web-based platform, and the generation of customized material passports for various stakeholders to use.

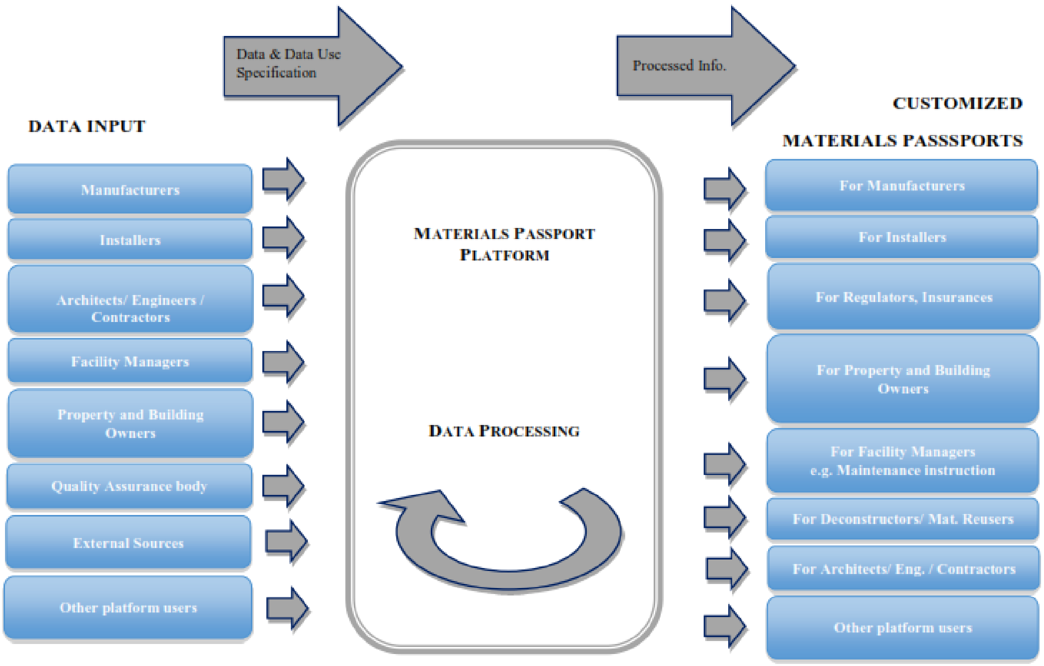


*Figure 37 - Conceptual framework for a material passport. Source:(Mullhall et al., 2017).*

### 4.5.1 Data acquisition

Different stakeholders involved in the value chain are responsible for the input of data. The methods can be either manual or automatically generated. Nonetheless, within each stakeholder group, one person needs to be responsible for the data collection method, such as an MP consultant as it to have specific know-how in data management and handling, building materials, eco indicators, and relevant repositories(Honic, Kovacic, Sibenik, & Rechberger, 2019). One study has explored the automated generation of material passports using laser scanners, ground-penetrating radar, and BIM (Honic, Kovacic, Gilmutdinov, & Wimmer, 2020). Other forms of automated data collection are explored using links to databases, with a standardized nomenclature, live readings of connected sensors via IoT (Internet of things), and RFID scans for location-specific information.

### 4.5.2 Data Processing and Storage

Here the data from the various sources are then categorized and organized as a database. The processing component can happen on either side of the data storage component. On the input side, the processing would mainly include algorithms used to link the various sources of the data, create relations, and perform other calculations required for information display. On the output side, the processing will be customized based on each stakeholder's needs. Data visualization, analytics, AI, and machine learning algorithms can be considered as possible processing at the output end.

For the storage component, many papers refer to blockchain technology as a means to store material information. This would ensure transparency and security, as it allows for changes as a transaction ledger is maintained for every change by a stakeholder, and the entire blockchain will be regenerated for only that particular user (Heiskanen, 2017). Due to their decentralized nature, the data here is safer from manipulation than it could ever be in a centralized platform(Arup, 2019). Therefore, it will provide the entire stakeholder network to know who made what change at a particular time. RFID information can also be stored in a blockchain to track the location of the material throughout its lifecycle(Copeland & Bilec, 2020). A material passport should allow confidential data to only be accessible to specific users in the platform. The provider of confidential data, often the manufacturer, should be able to define who has access to this information (Copeland & Bilec, 2020). There are cases where the information is important but does not need to be fully transparent to all stakeholders, as long as the evaluation of the information can be presented transparently (Luscuere, 2016).

Another criterion to consider is the level of detail the information needs to be documented. As buildings can be broken down into several product levels, as defined in Figure 39, a similar clustering of information can be be applied to material passports. Therefore material passports can be scaled down or scaled up based on four levels of products, ingredients, subcomponents, products, and systems, and relations between them need to be defined (Mullhall et al., 2017). An example of this aggregation of relation applied in a material passport data structure is illustrated in Figure 38.

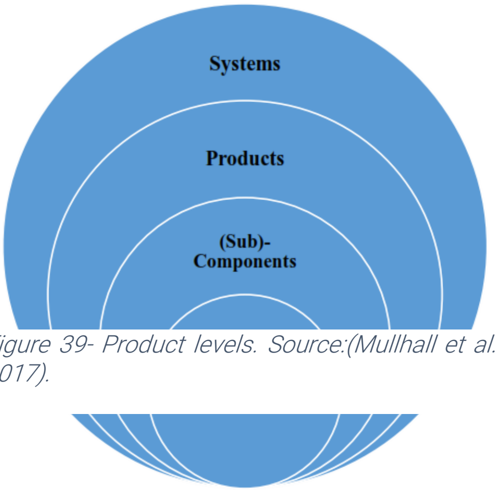


*Figure 39- Product levels. Source:(Mullhall et al., 2017).*

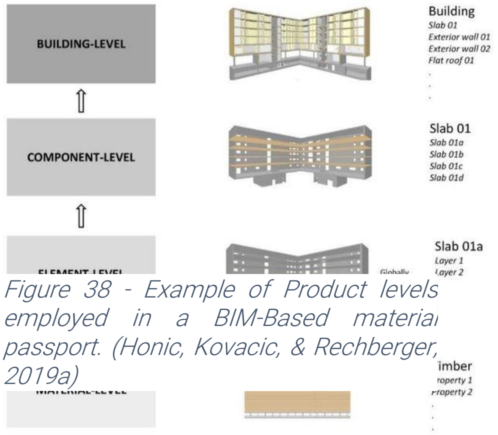


*Figure 38 - Example of Product levels employed in a BIM-Based material passport. (Honic, Kovacic, & Rechberger, 2019a)*

### 4.5.3 Data visualization

A web-based API has already been employed by Material Passport companies such as Madaster, Cirlinq, and Circular Cloud to access information. An Application Programming Interface (API), as defined by Mullhall et al. (2017, p. 7), is "a series of protocols, definitions, and tools to enable systems to communicate with the platform. A web-based platform's advantage is that access to the platform can be from any given location, so stakeholders from all locations can use it.

### 4.5.4 Example workflows

As scientific literature on the technological implications of material passports is sparse, workflows of fully implemented passports are kept confidential. Therefore, papers were referred to who define their own local material passport for the research were referred to. Honic, Kovacic, Sibenik, et al. (2019) defined a workflow where a BIM Supported material passport was created to assess the recycling potential and environmental impacts of building materials. Revit was used as a BIM software, used for modeling, and

Building One (BO), a material inventory and analysis tool as an addon was used as a data management as shown in Figure 40. BO was used as an external data handling program due to a lack of direct data handling in the BIM software package. A modeling guide based on the Austrian Norm “Digital Building Documentation: BIM-Level 3iBM” was used as a BIM model reference. A control tool, in this case, the Solibri model checker, checks the BIM model to verify if predefined elements are used.

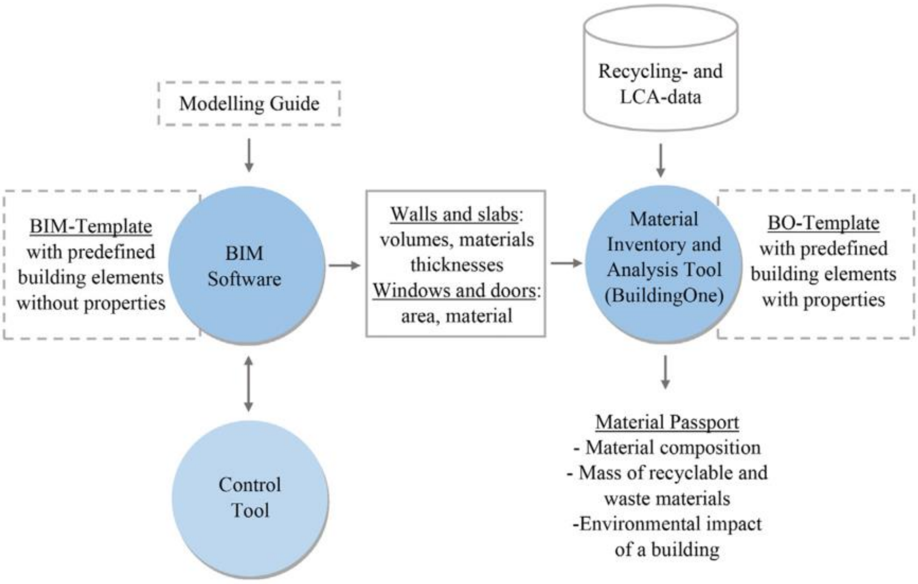


*Figure 40 - Workflow employed for a BIM-Based material Passport. Source: Honic, Kovacic, Sibenik, et al. (2019).*

Based on this workflow, several inferences were made.

1. Matching data from different sources can be time-consuming and requires specific knowledge, therefore requiring an additional stakeholder termed MP consultant.
2. The limitations of using predefined elements help in better categorization and matching of data but limit the design space.
3. Building elements are mono-layered to keep the design space open, but this would give rise to inaccuracy, and the approach is most suited for early design-based evaluations.
4. Material Passport assessments are difficult as indicators on recycling, and Lifecycle Analysis was not defined.

## 4.6 Conclusions

From the various literature review shown, it is clear that a material passport is more than just a collection of data sets and has far-reaching technological implications, and hence an exact boundary of what is a material passport cannot be defined. However, what can be established from the above is that a material passport can:

1. Have a standardized data entry method, mutually agreed upon by all stakeholders or standardized at a national level.

2. Different sources of information can be connected via an IoT network and integrated into a cloud-based platform.

3. Information can be collected and viewed in different product levels and interlinked as a relational database.

4. Blockchain technology can be used to manage and store the information so changes can be recorded and tracked, ensuring transparency while maintaining security.

5. Data can be edited and accessed and visualized using a web-based API where the front-End GUI can be customized to the stakeholder's needs.

6. It can be used as a tool to influence different stages of a lifecycle of a façade.

Based on the literature, a conceptual framework is proposed, as shown in Figure 41.

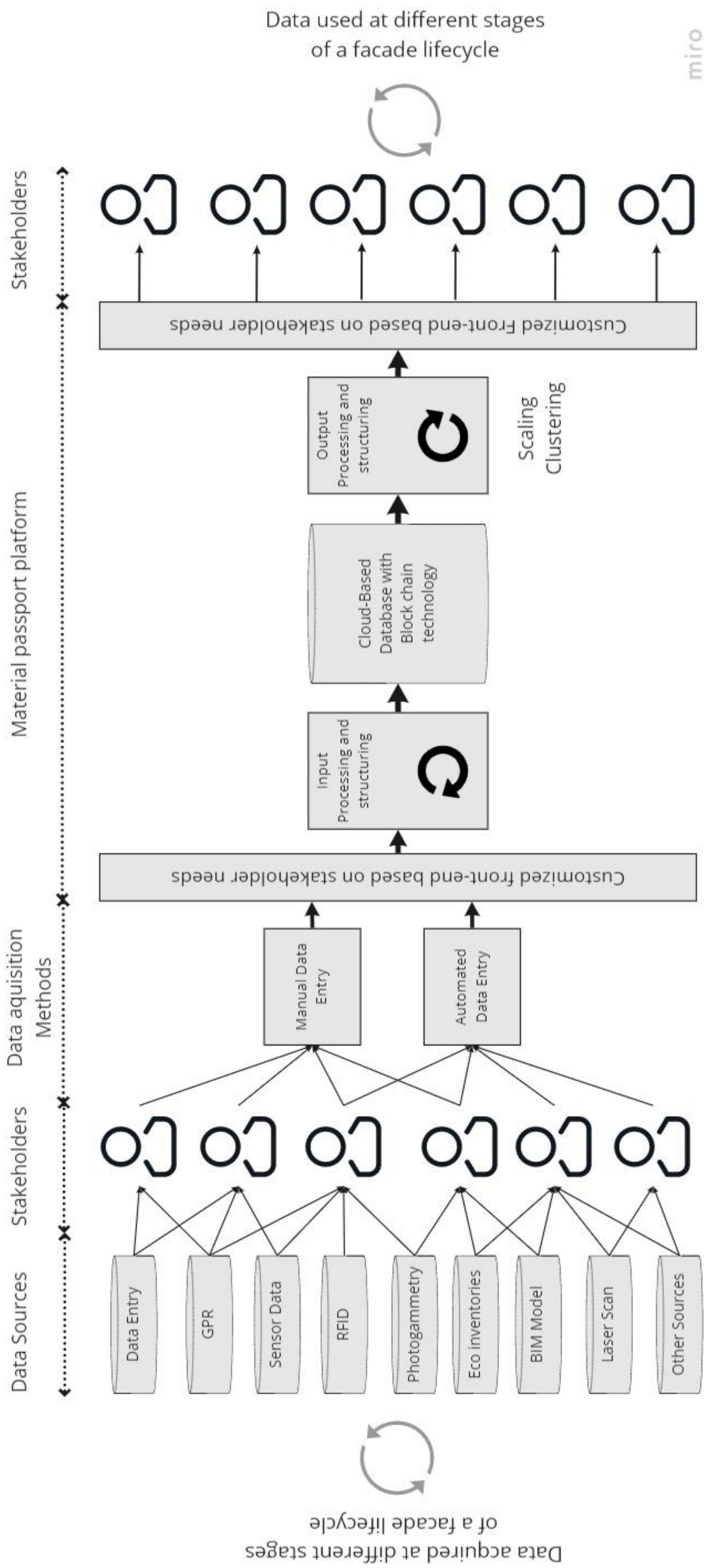


*Figure 41 - A framework for a material passport for a circular lifecycle of a facade. Source: Author's interpretation adapted from (Mullhall et al., 2017).*

# 5 Building Information Modelling (BIM)

## 5.1 Context

According to Tchana, Ducellier, and Remy (2019), Building Information Modelling(BIM) is a model-based approach to the design, construction, operation, and maintenance of buildings. But BIM, as we know it with all its capabilities, was implemented in 1987 with the development of ArchiCAD, released in 1987. Currently, BIM has been adapted at a national level in over nine countries as shown in Figure 42.

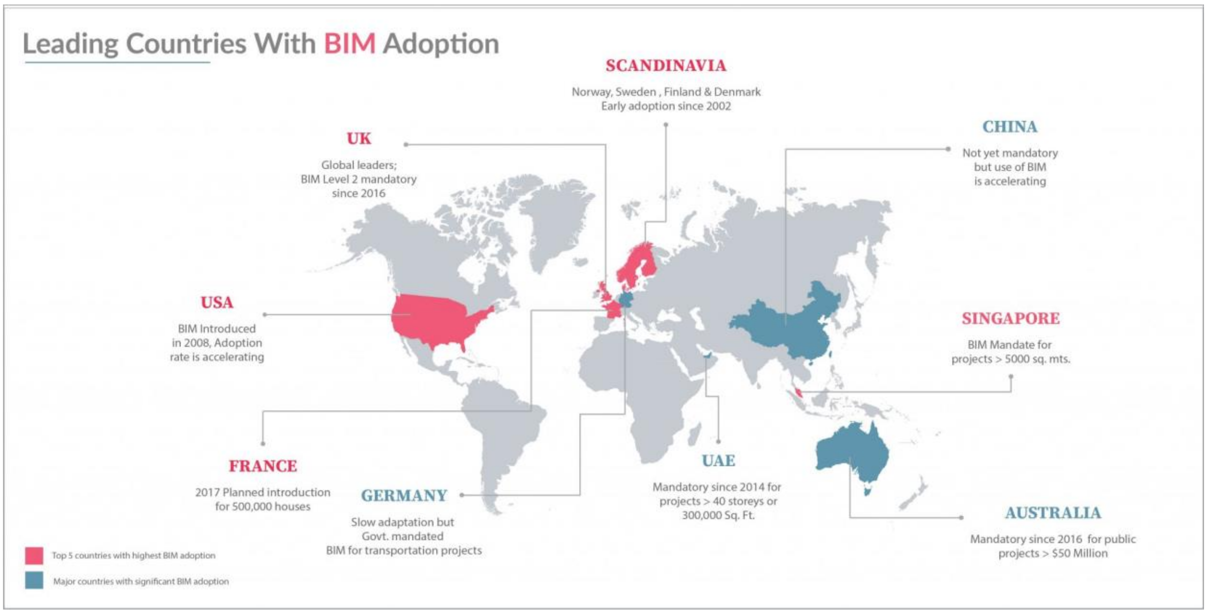


*Figure 42 - Leading countries with BIM Adoption. Source: (United-BIM)*

BIM is defined by Khajavi, Motlagh, Jaribion, Werner, and Holmstrom (2019) as a shared resource of information about a facility that can manage the building's evolution during its Lifecycle from conception to demolition. The attributes of sharing lifecycle information about buildings become a very reliable starting point for implementing Circular Economy Principles in several ways.

## 5.2 Uses and capabilities

BIM applications are in architecture, construction, engineering, facility management, design visualization, clash detection, consistency, lean construction cost, and time estimation to facilitate enhanced stakeholders interoperability(Khajavi et al., 2019). Therefore the stakeholders who can use BIM are architects, engineers, and contractors during the design and construction phase (Sacks, Eastman, Lee, & Teicholz, 2018), facility managers during the use phase(Salman, Khalfan, & Tayyab, 2012), and for demolishers during the End of life phase(Ghaffarianhoseini et al., 2017). Due to the possibility of accumulating life cycle information, BIM can be hugely influential in managing data and material flows, making it suitable for a circular Economy (Akanbi et al., 2018).

The capabilities of BIM have been marked as "BIM DIMENSIONS" where 2D and 3D BIM are capabilities sought out by designers and engineers as it includes building information with geometric representations, 4D BIM, includes the component of time useful for scheduling by contractors, 5D Bim which links BIM to cost estimation and 6D with capabilities useful for facility managers. The recent development of

VDC(Virtual Design and construction) can also be attributed to the BIm industry, where BIM models can be viewed using V. (Virtual reality) or AR (Augmented reality) devices, giving constructors more control over site processes and avoiding paper-based drawings(CABR Technology Co.). Scan to BIM Methodology, which uses detailed site imagery and in combination with laser scans, can also be used to generate high fidelity BIM models of buildings constructed without the implementation of the BIM. However, this can often result in a large amount of visual data processing(Boje, Guerriero, Kubicki, & Rezgui, 2020).

## 5.3 Components

### *5.3.1 BIM model types*

Digital Models or BIM models are differentiated as follows(Hoeber & Alsem, 2016):

1. Design model
2. Construction model
3. Commissioning model that corresponds to the as-built
4. The structure as-built
5. Model of use of the structure

BIM, nearly a Digital Model, mainly contains two essential elements: A data core and A graphical representation of the structure. The graphical representation can be a 2D or 3D representation. The Data Core is characterized by a structure defined as an IFC (Industry Foundation Classes), and the graphical representation is characterized by various Levels of Detail (LOD's) and Model View Definitions (MVD's).

### *5.3.2 Industry Foundation Classes (IFC):*

IFC (Industry Foundation Classes) represents the data core of BIM. It represents an open and standardized data model to ensure interoperability between BIM software in the Building Industry (Laakso & Kiviniemi, 2012). As data building elements in a BIM model are structured as an IFC data model, and most current material passport platforms use this data structure for accessing information about specific elements, it becomes crucial to understand its architecture. An IFC data model comprises layers with a controlled referencing hierarchy, as shown in Figure X. The Domain Layer contains models for processes specific to different AEC industry domains, such as structural engineering, HVAC, architecture, etc. The interoperability is more common and generic and can be distributed across the different domains, for example, the IFC wall, Beam-Column stair, etc. IFC Kernel represents some of the most abstract entities, such as groups, processes, products, and specifics relationships between entities. The central aspect about it is that between the layers can only happen downwards, which implies that the lowest layer(i.e., resource layer) is independent and cannot reference any layer above it, as shown in Figure 43.

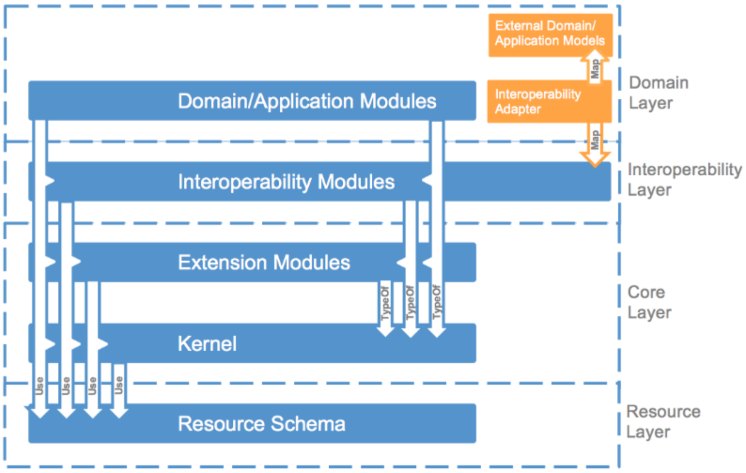


*Figure 43 - Structure of an IFC data Model. Source: (Laakso & Kiviniemi, 2012)*

Essentially an IFC file would be comprised of IFC Entities, which have the project's information and are referenced from a combination of the Different layers, which give each entity several objects and properties. A spatial tree as indicated in Figure 44, indicates this relationship and organizational structure for a typical wall and column represented in a building.

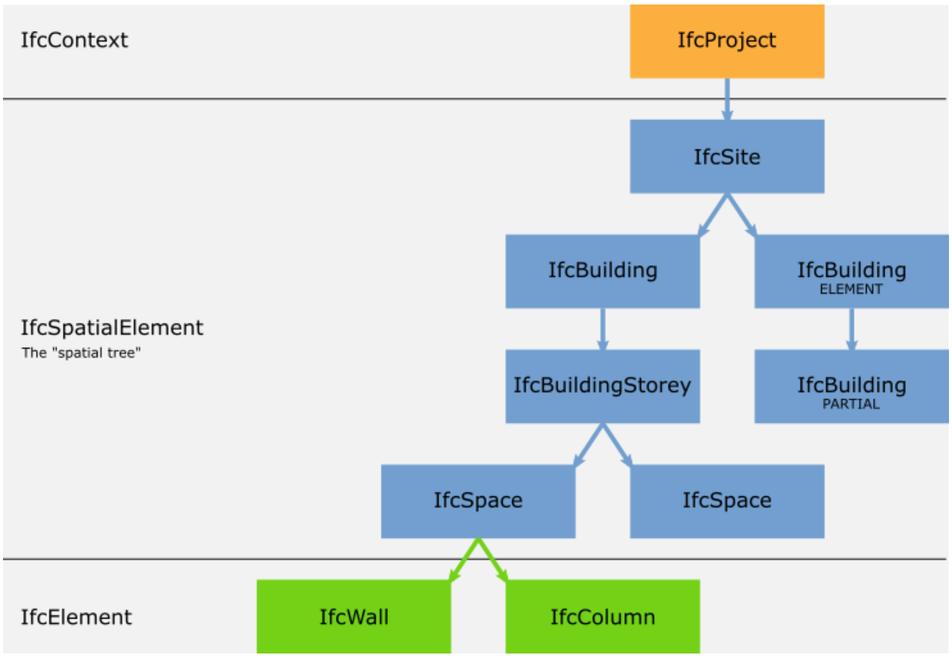


*Figure 44 - The spatial tree of the IFC file. Source : Wiki.OsArch.*

### 5.3.3 Level of Details (LOD's)

Based on the application and scale of the BIM Model, 3d Geometry can be represented in different levels of detail or (LOD's).

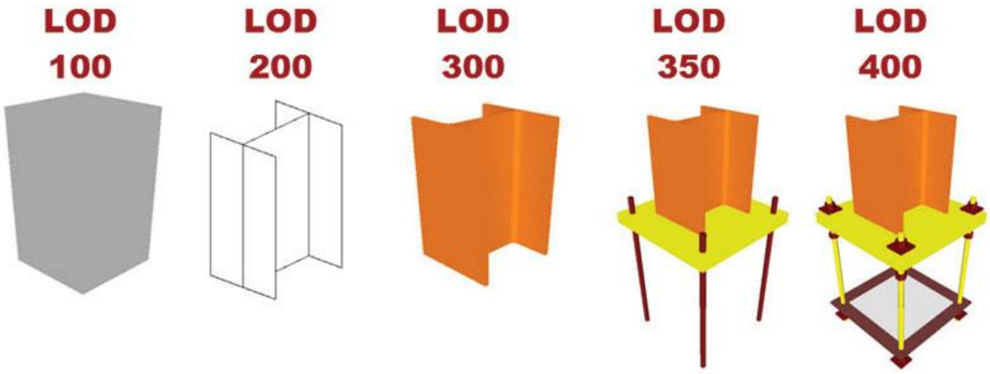


*Figure 45 - Visual representation of the various Levels of Detail(LOD) in BIM. Source: Structuremag*

A breakdown of the different LOD's are as follows:

1. LOD100—Conceptual
2. LOD 200—Approximate Geometry
3. LOD 300—Precise Geometry
4. LOD400—Fabrication
5. LOD 500—As-built verification of a LOD400 model.

For a building's regular architecture design, the model accuracy is somewhere between LOD and LOD 300, but for building facades, the LOD400 level is required to ensure the model can be used for manufacturing and fabrication(CABR Technology Co.). There has been a proposal by Bertin, Mesnil, Jaeger, Feraille, and Le Roy (2020) for developing higher LOD's for periodic updating of the model during the use and therefore quantifying changes of the as-built information to information such as maintenance schedules, performance histories at the End of life for demolition as shown in Figure 46. The project aimed at using these higher levels of details, more representative of mature information of a project rather than modifying the geometric definition, to facilitate reuse of components at the End of life. While this presents an exciting use-case, there are several limitations to this approach detailed later.

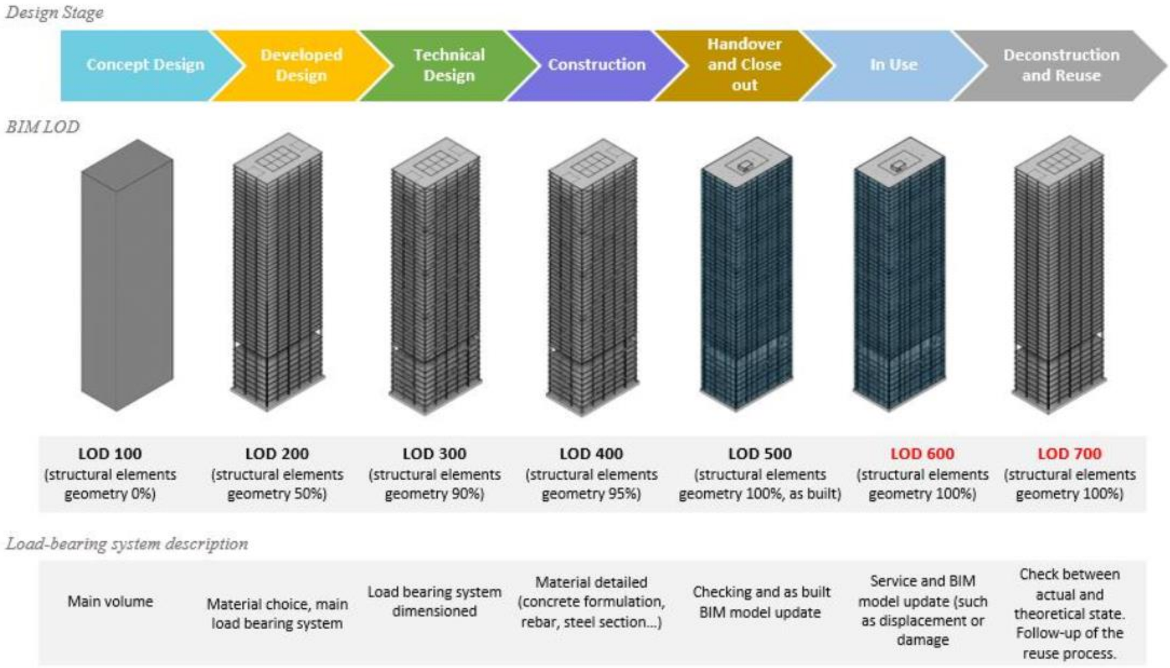


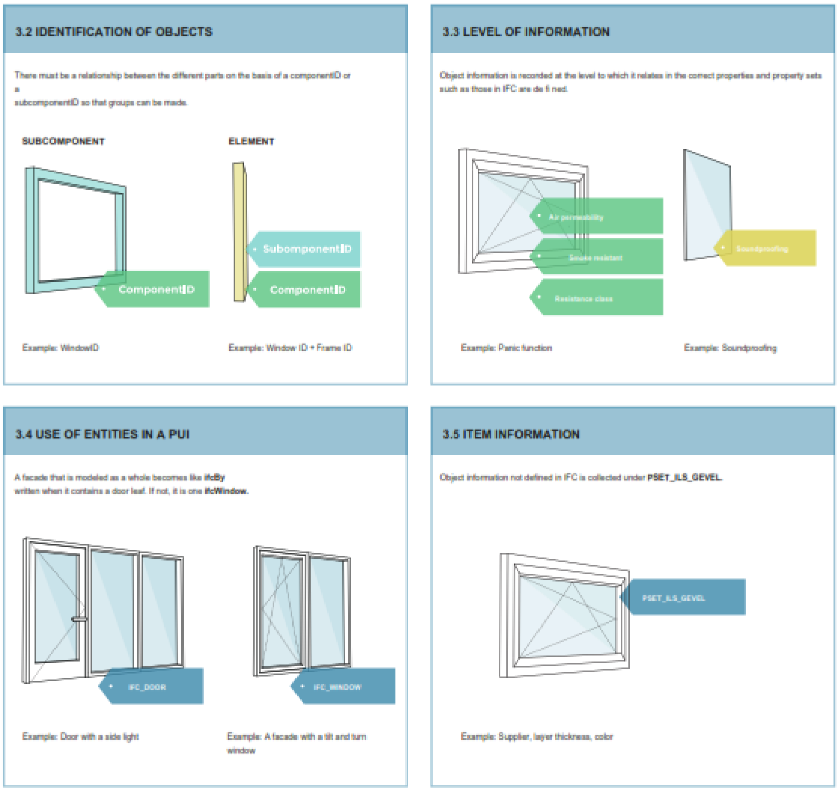
*Figure 46 - Proposal for LOD 600 and LOD 700, for updating live information. Source: {Bertin, 2020 #162}*

## 5.4 BIM Standards

Standards are essential to ensure data can be accessed and linked together among various stakeholders in the entire value chain. One of the major drawbacks identified by Honic, Kovacic, Sibenik, et al. (2019) in their BIM-based Material Passport workflow was the general lack of standard between eco databases, BIM specification terminology, and the National specification standards.

But as IFC was intended to be mostly used as a high-level data model, like STEP, which exists above software implementations, it only provides a standardized data structure but does not enforce a specific way of implementing it into the software (Laakso & Kiviniemi, 2012). Therefore, standards can be specified in the way models can be organized in consideration with the IFC data structure, such as the NBS National BIM Library in the U.K. or the N.L./Sfb in the Netherlands. The NBS has defined BIM Object standards to enable collaboration and efficient information language by giving every object a core property set to adopt a consistent classification approach (NBS, 2018). They contain a repository of BIM objects to be used in models that employ this standard. At a global level, the ISO 29481-1:2010 is developed by buildingSMART to document information flow in a lifecycle of a building.

But there are still issues implementing these standards for building facades, especially when considering the use of the Data for Circularity. For example, while these standards specify nomenclature methods and how objects can be stored in layers, it doesn't give a holistic perspective on how the façade itself is constructed, for example, taking into account the product levels, etc. For this, VMRG has developed the Information Delivery Specification (IdS), which defines how objects, classifications, properties need to be delivered to ensure efficient sharing of information. Figure 47 and 48 are excerpts from the IDS document, indicating how the model needs to be organized, and Figure Y indicates the naming standards for IFC objects. These standards will ensure that every stakeholder accessing the model can understand the building's organizational structure or product and derive its associations, thereby improving the readability of the model and subsequent information access.



3.2 IDENTIFICATION OF OBJECTS

There must be a relationship between the different parts on the basis of a componentID or a subcomponentID so that groups can be made.

3.3 LEVEL OF INFORMATION

Object information is recorded at the level to which it relates in the correct properties and property sets such as those in IFC are de fi ned.

3.4 USE OF ENTITIES IN A PUI

A facade that is modeled as a whole becomes like **ifcBy** written when it contains a door leaf. If not, it is one **ifcWindow**.

3.5 ITEM INFORMATION

Object information not defined in IFC is collected under **PSET_ILS_GEVEL**.

*Figure 47 - Standards defined by the VMRG BIM group for identification of Facade Elements. Source: VMRG*

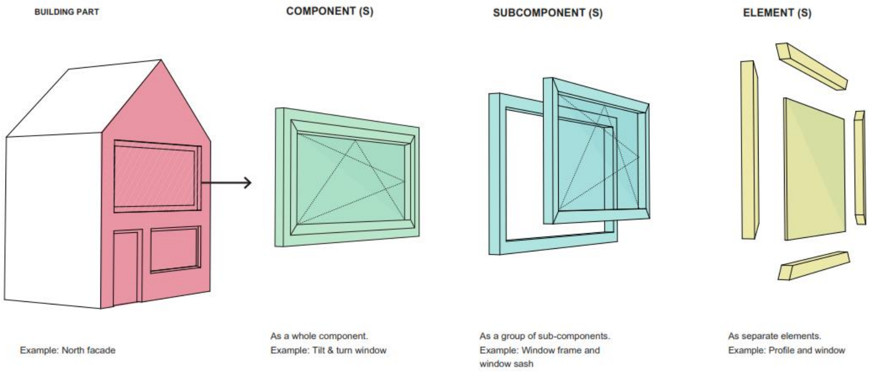


*Figure 48 - Figure 47 – Modelling of façade elements grouped as per product levels. Source: VMRG*

While VMRG association companies mostly use these specifications, it still does not facilitate a national/global information exchange level and cannot be traced in material databases or eco inventories. Also, there exists no relation between the IFC data tree and the product architecture of the façade. Therefore, naming standards for façade components can be developed, which considers the product architecture, the product level, its relation within a building or a façade. This will ensure categorization and referencing for use in linking objects to material passports or displaying clustered information in a standardized way, irrespective of how the object is modeled.

## 5.5 Limitations

Even though BIM is a well-recognized method of documenting building elements, there are still several limitations that need to be filled in with additional platforms. The following are some of the key limitations of BIM found in existing literature for complete integration into use for the Circular Economy.

### *5.5.1 Lack of Existing BIM Documentation:*

. First, in most existing buildings with extensive BIM documentation, there are huge obstacles to producing it (Khajavi et al., 2019). While Scan to BIM methods, photogrammetry, and other methods are useful for generating BIM models, the associated cost, time, and data processing capabilities to produce it quickly and consistently is still beyond current technological capabilities. There are additional challenges associated with data uncertainty when employing these methods and establishing the relationships between entities in the BIM model (Volk, Stengel, & Schultmann, 2014).

### *5.5.2 Lack of integration with real-time data:*

Another issue is that BIM was not intended to work with real-time data as the current usage is majorly for design, construction, maintenance, and stakeholder collaboration, which do not require real-time capability (Bruno, De Fino, & Fatiguso, 2018). For this reason, new methods are being tested out, such as the proposal for higher LOD's by Bertin et al. (2020) discussed in chapter 5.3.3. Even from their perspective, there is a lack of integration of sensor-related data in their methodology, as they state linking data from data acquisition systems such as sensors, laser scans, drones during monitoring of buildings as a challenge(Bertin et al., 2020).

### *5.5.3 Interoperable yet fragmented datasets:*

Processes in the various engineering models and BIM uses in 3,4 and 5D are fragmented, generating an incomplete 3d model, which gives rise to a requirement of connecting the different data sources, information, and knowledge across different domains to take full advantage of BIM (Boje et al., 2020). With the recent advancement of IoT and A.I., which are geared towards automation with a wide range of environmental contexts, the BIM interpretability such as IFC or IFCOwl cannot move from a static to a more dynamic web-based platform(Boje et al., 2020).

### *5.5.4 Lack of stakeholder customization possibilities:*

While BIM is a visual-oriented modeling-based information structuring tool, several stakeholders involved in the Lifecycle of a building or a façade do not necessarily need the visual information in the same way. The MVD(Model View Definitions) aims to cater to this by generating different visual information methods, but this again is geared towards stakeholders involved in the design, engineering, and construction spectrum. There needs to be a customization of BIM capabilities to suit different stakeholders' requirements and capabilities, yet stored centrally and linked to the primary building information model.

### *5.5.5 A requirement of Global standards, designed according to product architecture:*

While many modeling standards such as the N.L./sfb, NBS, or the IDS from buildingSmart have been developed, they mainly pertain to structuring information at the building level. A more robust and understandable standard needs to be specified for facades' documentation globally, with data organization structures closely relating to the product architecture. A possibility for this new integrated approach could pave the way for incorporating digital twins in the workflows of the AEC industry, as detailed in the next chapter.

# 6 Conclusions

Despite the limitations mentioned, BIM is an indispensable tool for building documentation and project coordination due to its wide acceptance and development of National level standards. The possibilities of AR and BIM for site coordination holds many potentials. Nevertheless, at the same time, the limitations make it less applicable for specific goals of the circular economy, especially when it comes to linking live data. Nonetheless, BIM is limited to modeling and documenting information related to building components and their construction. However, as the Circular Economy encompasses all the processes such as manufacturing, transportation, logistics, and reverse logistics processes, additional developments need to be made. Therefore, BIM cannot serve as a common ground to link all of these different processes. There would be a transition period where some of these challenges are solved using used defined workflows or the development of add-ons or plugins, but this would only increase the fragmentation of methods, rendering stakeholder collaboration less streamlined. The recent development of Digital Twins holds potential in solving these issues, as mentioned earlier, enabling seamless linking of the virtual and physical environments and connecting all the different data sources and analysis methods. In this context, BIM would be used as a starting point for visual referencing and collecting construction-related information. Additional layers of information need to be integrated using a semantic web-based platform, as detailed in the next chapter.

# 7 Digital Twins (DT)

## 7.1 Context

Boje et al. (2020) state that the dynamics of human interaction with built assets increase, there is often a limitation of existing Building management systems based on BIM, which need to respond and adapt better to the user's needs. A Digital Twin(DT) could be a possible solution towards ensuring these needs are met. BIM can be viewed as a starting point for developing a DT, which acts as a 3D reference model, and the DT can be used for various applications (Boje et al., 2020). Industry 4.0 implies establishing direct communication and coordination links between several automated production operations along the value stream, resulting in very autonomous production processes (Sacks, Brilakis, Pikas, Xie, & Girolami, 2020). A DT is an evolutionary step in manufacturing capable of bridging manufacturing to Industry 4.0 Principles (Rosen, von Wichert, Lo, & Bettenhausen, 2015). A similar integration can happen with building construction, termed Construction 4.0, which extensively uses BIM for design and construction, industrial production of prefabricated parts and modules, use of cyber-physical systems where possible, digital monitoring of the supply chain and work on construction sites, and integrated with data analytics (Sacks et al., 2020). These methods can give more control over lean construction principles, prioritize efficient production processes with minimal variations, and use resources.

## 7.2 Definition

There are several definitions of a Digital Twin as it is not a domain-specific technology, unlike BIM. In the context of the Building Industry, the definition given by Qi and Tao (2018) states, "Digital twin works especially with real-time data fed by the sensor systems to record and analyze the real-time structural and environmental parameters of a physical asset to perform highly accurate digital twin simulation and data analytics."

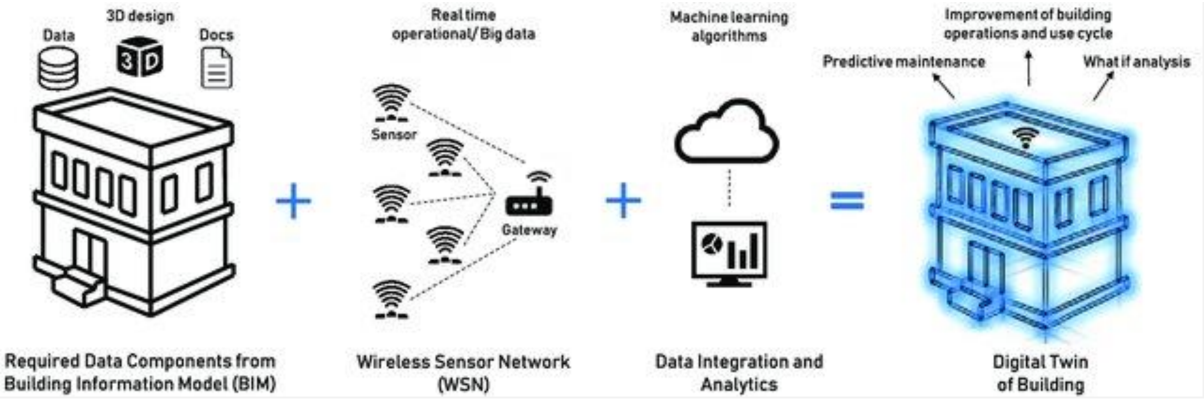


*Figure 49 - Digital Twin, perceived as an extended smart version of a BIM Model. Source: (Khajavi et al., 2019)*

While Digital twin refers to simulating a product, detecting its performance, and mapping out its real-world interactions, they can be also be used as a functional description of a component, product, or system with the relevant operational data(Boschert & Rosen, 2016). Digital Twins are also considered a 'System of Systems; which can help communicate data in a scalable, effective, and intelligent manner(Boje et al., 2020). A distinction needs to be made between a Digital Model, Digital Shadow, and Digital Twin. Figure 49 shows the three stages in the evolution of a Digital Model towards developing a DT(Tchana et al., 2019).

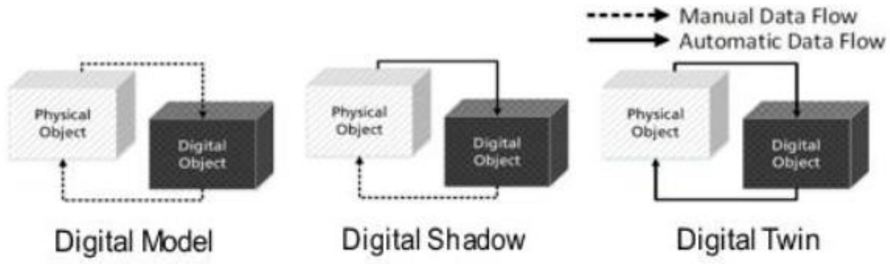


*Figure 50 - Digital Twin as an evolutionary system derived from a Digital Model. Source: Tchana et al. (2019)*

The digital model does not have any form of data exchange between the physical object. The Digital shadow records data from the physical object in an automated manner, using various devices, and sends the data back to be written in the database. In the Digital twin, data flows between the physical object and the digital object seamlessly. In this case, modifications in a digital object can modify attributes of a physical object, while the twin parallelly tries to simulate the physical object in real-time. Moreover, Digital twins need not be realistic representations of the physical object but can instead, abstractions that are more suited for the use case(Arup, 2019).

## 7.3 Components

For implementing a DT, an integration of a wireless sensor network (WSN) integration and data analytics are required (Tao et al., 2018). The digital twin can therefore be a common platform that can be used by different stakeholders and can be looked at as a result of an integration of 3d simulations, IoT devices, 4g and 5g networks, Blockchain, Cloud Computing, and A.I (Arup, 2019). Boje et al. (2020) break down the main DTsou components into three simple parts, as indicated in Figure 51. The "physical part" collects real data and is sent for processing; the "virtual part" can help in discovering this information and manage the "physical" (Boje et al., 2020).

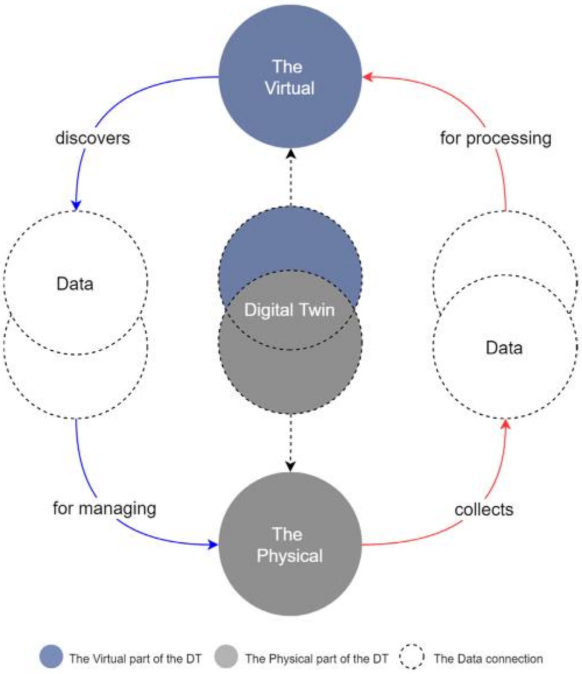


*Figure 51 - Components of a Digital Twin. Source: (Boje et al., 2020).*

The exact subcomponents of the physical, virtual, and the data can be particular to the intended use case as DT is far-reaching. The data connection is referred to as exchanging information between the physical and virtual, enabled by advanced sensing, the Internet of Things(IoT), high-speed networking, and advanced analytics (Sacks et al., 2020). The data used in the communication between the physical and digital in manufacturing and construction can account for what is termed, Big data(Qi & Tao, 2018).

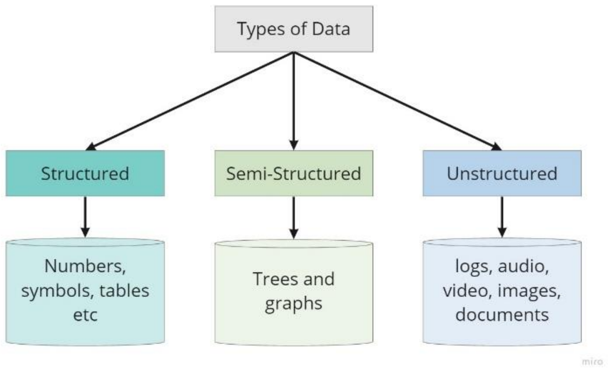


*Figure 52 - Types of data as defined by (Qi & Tao, 2018). Source: Own*

Visualization also plays a crucial role in digital twins, which can be more three-dimensional and dynamic such as images, video, virtual reality(VR), and augmented reality(AR), while raw data in other sources are mostly limited to tables, charts, graphs, and files (Qi & Tao, 2018). Like the physical object, the data linked to a digital twin can evolve and mature over its lifecycle. A scheme of this is indicated in Figure 53. It indicates the digital twin's birth much before the physical twin, starting at the conceptual design stage. The difference between Digital Twin used for design stages, as opposed to a BIM model is that with a Digital Twin there is a possibility of modeling in a dynamic virtual environment which is replicating physical reality fed through with real environmental data fed by sensors, with methods to predict the behavior of the designed component, as opposed to modeling in a static virtual environment.

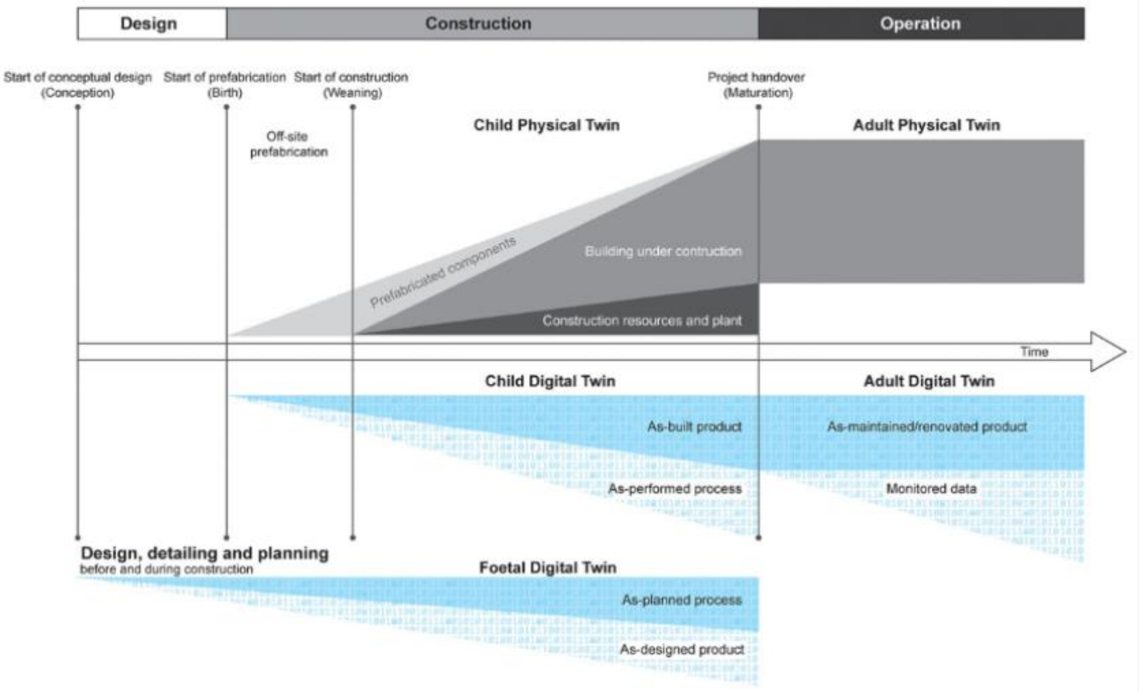


*Figure 53: Lifecycle of a Digital Twin compared to a typical Building Lifecycle(Sacks et al., 2020).*

## 7.4 Advantages of Digital Twins

Building upon a report from (Oracle, 2017), digital twins can add value to the following processes.

1. **Realtime Monitoring and control:** Due to independent location accessibility via wireless network integration, digital and physical information can be monitored and controlled anywhere in real-time.

2. **Greater efficiency and safety:** More autonomy can be ensured where redundant jobs can be offloaded to robots, with humans more focused on control and application in creative work and innovation

3. **Predictive maintenance and scheduling:** By integrating wireless sensors, digital twinning can generate Big Data in real-time, facilitating intelligent analysis of data (Using machine learning and A.I.), and failures can be detected in advance. Therefore, maintenance schedules can be automatically generated.

4. **Scenario and risk assessment:** What-if analysis in the digital twin can help in better risk assessment, to study the response of the product or system during unexpected scenarios, and determine mitigation strategies.

5. **Better Intra and inter-team synergy and collaboration:** With information available in real-time with location-independent possibilities, it would help in teams collaborating better, thereby improving productivity

6. **More efficient and informed decision support systems:** With the availability of quantitative data and advanced analytics in real-time, with assist more informed and faster decision-making processes.

7. **Personalization of products and services:** With detailed historical requirements, preferences of different stakeholders, and continuously evolving market trends, the demand for customized products will increase. Therefore, a digital twin in the manufacturing processes can enable faster customization in real-time to account for changing needs.

8. **Better documentation and communication:** Real-time availability of information with automated reporting in a centralized platform will ensure maximum transparency among the various stakeholders.

9. **Real-time multi-layered data visualization:** As the digital twins can result in a tremendous amount of proven data, visualization techniques for project management can be incorporated for better accessibility while benefitting from real-time data(Judith, Jan, & Zohra, 2012).

## 7.5 Use of Digital Twins in a Lifecycle of a Building

While DT implementation is only beginning to open to the building industry, there is a lack of relevant literature, mainly when focusing on the façade industry. Therefore literature studies were carried out on Digital twins used in manufacturing for key examples to equate it to the façade industry. This argument holds good considering the extensive nature of prefabrication expected in a circular building, with a more production-line approach.

1. Design Stage

   During the design phase, the digital twin, in this case, placed in a virtual environment, can enable iterative optimization of the design enabling real-time adjustments and improvements to achieve a personalized product design(Qi & Tao, 2018). Simulations can be augmented with real data using sensors, therefore improving accuracy Data from sensors can be fed into this virtual world for augmented simulation environments for improving accuracy and fidelity (Boschert & Rosen, 2016). This will help verify the functionality of the product, its behavior, determining the manufacturability reducing the amount of testing and verification required (Qi & Tao, 2018)

2. Manufacturing Stage

   In the manufacturing stage, the design can be fed into a smart workshop, where the entire process can be optimized using a DT(Rosen et al., 2015). Here, a virtual factory model will have all the geometric and logistical information of the different equipment, materials, tools, and a production plan (Tao et al., 2017). DT, combined with BIG data using a hyper network, can enable supply-demand matching and scheduling (Tao, Cheng, Cheng, Gu, et al., 2017), helping find the required resources and integrated analysis planning(Alonso et al., 2019). This is the most effective use of a digital twin, in the context of circular building methods, which can help in moving towards a supply-driven demand, where a constant check of available resources is made, and optimized pathways for production processes are created, rather than a demand-driven supply which can give rise to exploitation of resources.

### 3. Construction Stage

During the construction stage, digital twins can help monitor activities, such as adherence to the master plan or time-based activities such as material supply, location of works, and equipment (Sacks et al., 2020). Simulations can be used to achieve optimized planning or various other construction management objectives (Boje et al., 2020). Real-time tracking of the supply chain and data collection methods can be hugely beneficial in improving stakeholder interactions during a project's construction. They can also perform risk assessment analysis and optimize pathways in the supply chain, and automatically schedule the pickup and drop off actions till the end destination.

### 4. Use and operation phases

During the use stage, the Digital Twin is connected to the physical twin through a network of sensors(Qi & Tao, 2018), which can help perform various performance monitoring or create automated maintenance schedules of spaces, components, or equipment. Real-time reflection can be achieved through learning and optimization by facility managers in the use phase of the building life cycle (Khajavi et al., 2019).

### 5. End of life

Based on the uses mentioned in the above stages, it can be presumed that the digital twin would have an aggregated data log of the different activities in the Lifecycle, which can help make judgments or decisions about the correct End of life. This would highly depend on the nature and quality of the data available. Therefore, there are considerable advantages in BIM slowly transitioning towards Digital Twin while retaining its knowledge domain and technology to integrate A.I. and IoT. This would facilitate the change from more static, closed data with multiple interoperability issues towards more linked data (Boje et al., 2020).

An overview of the various uses and features of the Digital Twin in the Circular Lifecycle of a façade is given in Figure 54

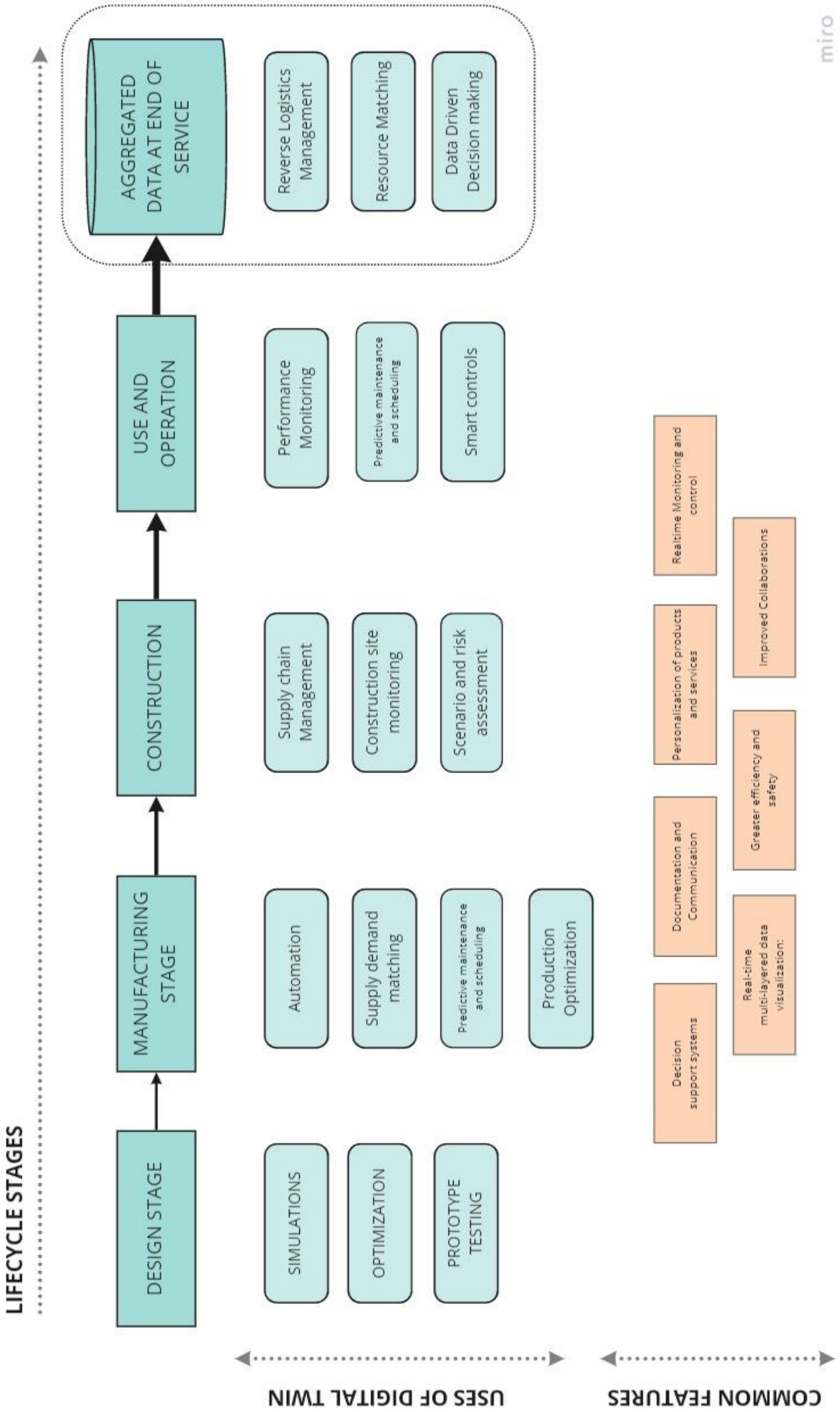


*Figure 54 - Overview of uses and features of a Digital Twin. Source: Author*

## 7.6 Evolution of Digital Twins

Like most technologies, Digital Twins are still at early stages and are expected to evolve. Boje et al. (2020) predict that the eventual merge between virtual models and sensing would converge on a common semantic web platform, where interportability or differences in standards among various stakeholders becomes no longer an issue. Therefore, this would reduce the reliance of IFC data structures and DT's would progresstowards implementing a more flexible frameworks such as Linked Data(LD) and Web Ontology Language(OWL).

Boje et al. (2020) propose the evolution of a Construction Digital Twin in three stages, as illustrated in Figure 53

1. First-generation can be considered an enhanced version of BIM on construction sites, with a live data monitoring capability.

2. The second generation includes enhanced monitoring platforms with limited intelligence and a standard web language integrated into IoT devices.

3. The third generation could be a self-reliant, self-updatable, and self-learning Digital Twin with data acquired by AI agents such as machine learning, deep learning, data mining, and analysis (Boje et al., 2020).

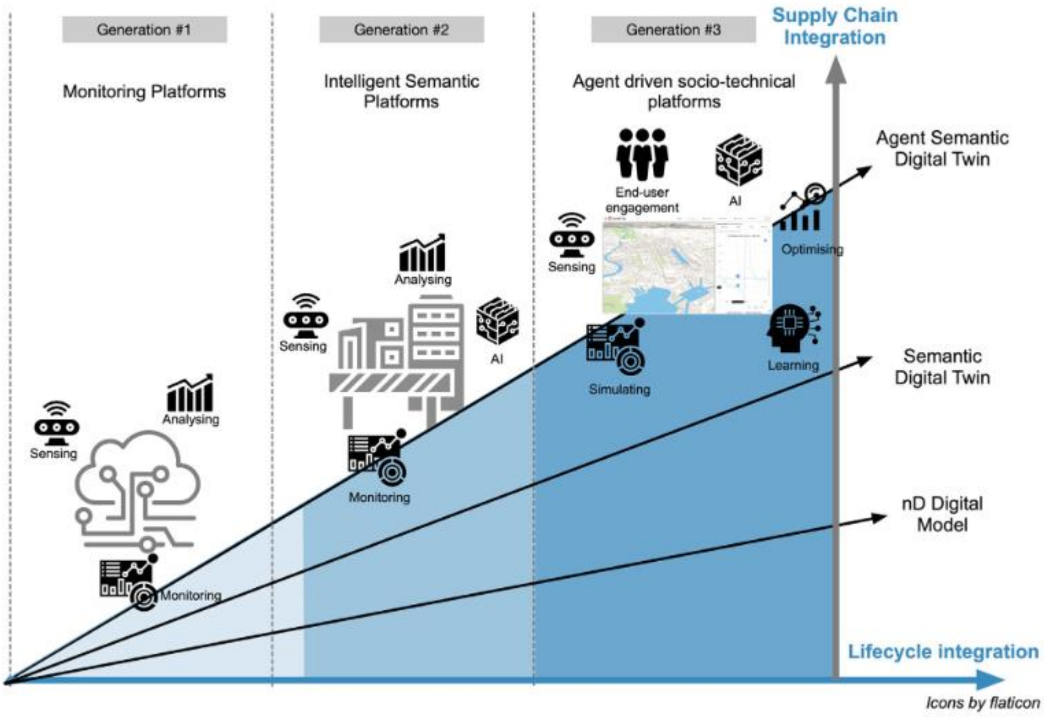


*Figure 55 - 3 Tier evolution of the Construction Digital Twin. Source: (Boje et al., 2020).*

Similar evolutionary characteristics can be considered for Digital Twins applicable for other uses, starting with just monitoring platforms or mere Digital Shadows and evolving towards an Agent Driven Socio-technical platform.

## 7.7 Limitations

Although the numerous potentials Digital Twins can offer to the building industry, especially in facilitating circular economy goals, implementing digital twins would require overcoming technical, social, organizational, and commercial barriers.

1. The use of digital twins can lead to a large amount of data. While the Data itself may have little value, it needs to be interpreted, processed, and compared with other data to extract useful information from it (Floridi, 2013).
2. Implementation of such systems is difficult in the conservative construction industry, as there are already difficulties in integrating BIM workflows seamlessly for construction projects (Sacks et al., 2020).
3. In general, big data describes a large amount of structured, semi-structured, and unstructured data created by data sources, which would need too much time and money to be stored and analyzed to obtain value (Qi & Tao, 2018).

## 7.8 Conclusions

Based on the above review, it is evident that moving towards Digital Twins' development can prove to be very useful for streamlining all processes in a project's lifecycle. Aspects such as real-time data monitoring and recording are already being tested in buildings and RFID tracking in logistics companies to monitor packages' locations. Researchers have confirmed the merger of these varied different applications into a common semantic platform where all systems are interconnected, and data can be exchanged in all nodes of a supply chain. Therefore, it is inevitable that these Industry 4.0 concepts would go a long way in improving the circularity of buildings or facades.

With this context, we must also recognize that most of the construction industry is still lagging in implementing BIM in a holistic platform, and the concept of material passports is barely being considered due to the lack of value addition to the way our economies are structured. While this is expected to change with the implementation of CO2 tax and other new business models, a specific transition needs to take place for which frameworks need to be developed. The frameworks need to kept conceptual considering the context, to ensure it is adaptable for drastic technological developments over the years. While Digital Twins, combined with Agent-driven AI systems, is a potential future for the interconnected nature of products, processes, and systems. A conceptual framework can be interpreted in both directions serving as a transitory tool rather than defining the end goal. Therefore, systems can be implemented to the present market using the framework while allowing it to transition with technology development.

# 8 Integrations

# 9 Bibliography

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