Barriers and Recommendations for Integrating Circularity in Construction Projects

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ABSTRACT

The building and construction industry is notorious for consuming large amounts of natural resources where these resources are disposed after their use. This unsustainable business model is expected to change toward a circular version, which promotes the use of materials at their highest possible utility in order to decrease waste and to preserve natural resources. However, it is proven to be difficult to integrate circularity in the industry for numerous reasons. Dutch construction company Dura Vermeer also experiences these difficulties. This research aims to integrate circularity in the standard way of working at Dura Vermeer, which is called *FLOW* based on the standard description of project phases in the Dutch construction industry. The focus of this research is on the design phase as the decisions on circular principles such as construction methods and materialization are taken in this phase. This phase thus heavily influences the eventual circularity in the project.

To this end, a list of 53 barriers to implementing circularity in the design process was compiled and categorized into five dimensions: technical, social, organizational, economical, and regulatory. The presence of these barriers was evaluated in practice through a multiple case study of four projects with a circular focus at Dura Vermeer. The data from the case studies were collected through semi-structured interviews and complemented with a document analysis.

Of these 53 barriers, 24 barriers surfaced notably more in practice compared to literature. Furthermore, ten other barriers surfaced in practice that were not found in literature. Ultimately, the findings highlighted five insightful lessons learned, subsequently transformed into recommendations for Dura Vermeer. These recommendations are 1) to early formulate feasible and detailed circularity ambitions; 2) to ensure a warm handover of project phases; 3) to materialize the design early in the project; 4) to make use of standard solutions and designs; and 5) to involve partners early in the project. The application of these recommendations has been validated by conducting two focus group sessions of in total seven participants. These sessions confirmed that these five recommendations were relevant as they address barriers that are continuously experienced in projects at Dura Vermeer. Furthermore, these sessions confirm that the ambition statement in the initiative phase is leading for the course of the project as incorporating salvaged materials requires a different strategy than novel circular materials. Lastly, the focus group session helped in highlighting the project phases and responsible team members whose responsibility it is to carry these recommendations.

Keywords: *Circularity; Construction; Design phase; Barriers; Recommendations*

1. Introduction

The building and construction industry is a large consumer of resources as it employs a strong linear business model that handles resources according to the take-make-dispose rationale. The circular economy is expected to replace this unsustainable linear business model in the industry within the next few decades. The circular economy promises to decouple economic growth from material use and waste production (EMF, 2015). However, transitioning from a linear economy to a circular alternative has proven to be difficult as design professionals lack systematic methodologies that help implement the circularity principles into their projects (Van den Berg, et al., 2019). Dutch construction company Dura Vermeer (DV) also faces these difficulties in their transition towards circular construction. Effective implementation of circularity in the construction industry is still in its infancy stage as the concept only gained widespread attention in various business sectors since the Ellen MacArthur Foundation (2012) published its seminal report in February 2012 (Geissdoerfer, et al., 2017; Benachio, et al., 2020). The research into various challenges to the integration has also gotten more diverse (Hossain et al., 2020). Therefore, definitions of the concept of circularity have also diversified (Kirchher, et al., 2017). The most important aspects and assumptions of circularity and its application on the industry are presented next.

The Ellen MacArthur Foundation defined the circular economy as follows: "A circular economy 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." (EMF, 2015, p. 2). Three principles of a circular economy can be applied to this definition, applicable to all industries: (1) preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows, (2) optimize resource yields by circulating products, components, and materials in use at the highest utility at all times in both technical and biological cycles, (3) foster system effectiveness by revealing and designing out negative externalities (EMF, 2015, p. 6). These principles highlight the importance of a project's design phase as it can significantly impact the project's overall environmental, social, and economic factors (Winkler, 2011).

Therefore, a specific focus on a project's design and development phase is important (Van den Berg, et al., 2019).

The industry is known for having a project-based character where projects are temporary collaborations to create a unique product with a definite beginning and end, following a predefined set of phases (Fewings & Henjewele, 2019). Construction projects at DV are follow the same phases. DV is one of the largest contractors in the Netherlands, specialized in infrastructure and construction. Project teams at DV use a working method called *FLOW*, which follows a uniform process of eight phases visualized in Figure 1. This method covers the initiative phase to handover to the client and subsequent end-user usage after final delivery. The distinct *FLOW* phases derive from a Dutch industry-wide used separation of project phases as outlined in DNR STB 2014. These project phases ensure a design process that develops the design from coarse to fine over time (BNA & NLingenieurs, 2014). There are three different versions of this working method tailored to the specializations of DV. These are: residential construction, non-residential construction, and renovation and maintenance. This research does not focus on renovation and maintenance projects as existing buildings are at the core of those projects. The design phase of these projects are therefore different. Schematic diagrams of the residential and non-residential *FLOWs* display the products to be delivered and responsibilities of team members per phase and are added to appendices A, B, C, and D. As stated, the design phase is most important for the eventual design decisions. In *FLOW* these are phases 1 *(SD)* through phase 4 *(TD)*, as visualized in Figure 1 at the bottom of this page.

The objective of this research is to integrate circularity in the design phase of the *FLOW* methodology. To achieve this objective, first, actions are presented for those involved at DV in the form of recommendations. Subsequently the phases when the actions of the involved team members should take place determined and validated by a focus group. These actions and moments arise from this study in the form of lessons learned from four construction projects at DV in a multiple case study.

Hossain, et al. (2020) outlined numerous barriers to the implementation of circularity and noted that little research has been conducted on the impact of a combination of multiple barriers. Chapter 2 outlines how these barriers can be organized into multiple dimensions. These barriers can all exert influence on each other and on the eventual circularity of the project. Therefore, Hossain, et al. (2020) urge researchers to conduct interdisciplinary research involving circularity, buildings, and policy measures for the sustainable transition to a circular built environment. Similarly, Pomponi & Moncaster (2017) argue that interdisciplinary research with a selection of dimensions is needed to properly implement circularity in the built environment. Thus, this research's scientific relevance is found in filling the gap of interdimensional barrier research. The interconnectedness of these barriers will be taken into account by incorporating multiple barriers into different lessons learned and recommendations. Another scientific relevance is checking the presence of a list of internationally compiled barriers to circularity integration in the Dutch context. This way, a better understanding of the Dutch context is established.

The practical relevance of this research is that it addresses the lack of systematic methodologies for implementing circularity of design professionals as explained by Van den Berg, et al. (2019). This is done by providing recommendations for the integration of circularity in the design phase based on an analysis of four construction projects of DV. Subsequently, the outcome of the analysis will be we applied on the standard way of work at DV Bouw & Vastgoed, called *FLOW*.

This report proceeds with an overview of all relevant barriers to implementing circularity in construction projects as extracted from the literature. Known barriers are a suitable research frame for a case study to find lessons learned in practice. They encompass the most often mentioned problems project teams face when implementing circularity in their projects. Afterwards, the research methodology is covered. Then, the results of the multiple case study are presented. These results include the lessons learned from the four cases, an explanation of the impact of the barriers through the dimensions, and their application on *FLOW*. Finally, the discussion and conclusion are provided.

2. Theoretical background

This chapter presents an overview of the differences between a linear and a circular construction project. These differences are illustrated by known practical barriers that arise during this transformation.

Scholars often identify five dimensions of barriers to integrating circularity: technical, social, organizational, economical, and regulatory (Charef, et al., 2021; Hossain, et al., 2020; Kok, et al., 2013; Masi, et al., 2018; Tura, et al., 2019; Wuni, 2022; Zimmann, et al., 2016). This classification makes it easier to comprehend the complex dynamics behind fundamental changes in business operations. Also, each dimension, or combinations thereof, and their associated barriers require targeted solutions and mitigation strategies to improve the adoption of circularity in the industry (Wuni, 2022). The dimensions that serve as a framework for researching the implementation of circularity in the construction industry are outlined in Section 2.1.. Section 2.2. introduces a list of 53 barriers based on 19 papers used as input for the case study.

Currently, the exhaustiveness of the list of barriers presented in the next section is unsure, as documented reflections on the recent implementation of circularity in construction projects are scarce (Van den Berg, et al., 2019). However, fundamental literature has been reviewed and incorporated in this list. Therefore, dealing with this list adequately could significantly impact the implementation of circularity in the industry.

2.1. Dimensions of the implementation of circularity

2.1.1. Technical

The technical dimension refers to all physical construction design aspects such as quality and availability of construction materials, construction methods, and technical skill of employees as it eventually must be physically built through manual work.

Rahla, et al. (2021) outline how circularity principles essentially comes down to the use of materials through, for example, the hierarchical importance of a 3R-model of "Reduce",

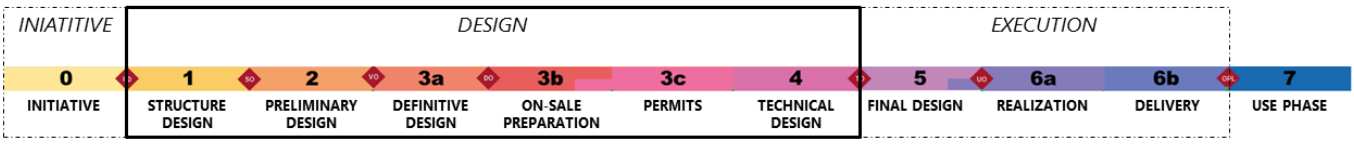

Figure 1: Overview of FLOW phases for residential construction

"Reuse", and "Recycle". Benachio, et al. (2020) amplify this importance of selecting circular materials, and keeping them in a closed loop for as long as possible. Circular materials can be put into two categories non-renewable sources used for recycling or upcycling for long as possible (Rahla, Mateus, & Bragança, 2021), and novel biobased materials (Cheshire, 2017; Platform CB'23, 2021a). The selection of materials influences reusability and recyclability at end-of-life, environmental and life cycle impact, feasibility, construction speed, and expected maintenance (Platform CB'23, 2021a; Cheshire, 2017; Rahla, et al., 2021; BAMB, 2016; Hossain, et al., 2020; Geldermans, 2016; Malmqvist, et al., 2018), and is often based on organizational goals, ambitions and subsequent strategies that are pronounced before the start of the development and design phase (Platform CB'23, 2021a). These indicate a strong link with social and organizational aspects as explained in later sections.

Rahla, et al. (2021) compiled a list of technical criteria that determine their origin, use performance and end-of-life handling. In practice, these criteria are difficult to evaluate as the material quality and the performance in the use phase is uncertain (Adams, et al., 2017; Eberhardt, et al., 2019; Iacovidou & Purnell, 2016). Underlying this barrier is the poor information provision of new and reclaimed materials. The reused materials' history use is often unknown and insights on current performance of both reused and biobased materials deviate over time (Govindan & Hasanagic, 2018; Masi, et al., 2018; Rose & Stegemann, 2018). This complicates measuring the rate of circularity. Several measuring techniques are currently in use. However, these are not widely adopted (Platform CB'23, 2021a).

Besides uncertain material quality, there is a lack of standards and specifications which circular construction materials and design must adhere to (Giorgi, et al., 2022; Iacovidou & Purnell, 2016; Wuni, 2022). Lastly, this transition period without proper standards leads to a clash of materials and buildings that historically are not built in accordance with circular building standards. Therefore, harvesting these materials, as well as implementing them in new circular designs is inherently complex (Adams, et al., 2017; Rahla, et al., 2021).

2.1.2. Social

The social dimension includes the personal views and opinions of individuals or groups of individuals on the integration. These can encompass their knowledge, awareness, and expectations of circularity, but also their willingness to adapt and the presence of leadership.

Ever since EMF started to publish on circularity in 2012, the concept gained more traction at academia, industry, and policymakers (Charef, et al., 2021; Geissdoerfer, et al., 2017). However, knowledge on and awareness of the concept has historically still been low (Adams, et al., 2017; Govindan & Hasanagic, 2018; Guerra & Leite, 2021; Van den Berg, et al., 2019). A lack of knowledge is a barrier as it leads to wrong preconceptions of all stakeholders and users of the building methods and materials (Cruz Rios, et al., 2015; Govindan & Hasanagic, 2018). Also, the absence of one accepted definition of circularity adds to developing wrong preconceptions and expectations of all stakeholders (Eberhardt, et al., 2019; Iacovidou & Purnell, 2016; Kanters, 2020). Oftentimes in such a definition, means for a practical implementation is lacking (Kirchher, et al., 2017).

Historically, the industry is known for being resistant to change. A possible reason for this is the large financial risks of these changes as profit margins are relatively low (Kanters, 2020). Finally, because of the project-based character of the industry and the slightly differing goals of all actors in a project, all actors aim to achieve the highest possible profit margins. This leads to insufficient collaboration and mistrust (Eberhardt, et al., 2019).

2.1.3. Organizational

The organizational dimension encompasses all aspects that deal with the internal company structure and collaboration, supply chain collaboration, and project goal setting.

Adopting circularity principles into a construction project starts with agreeing on a definition of circularity and pronouncing circular ambitions among project actors and setting measurable goals. However, due to the inherent project-based character of the industry, there is often a misalignment between short-term goals and long-term benefits (Adams, et al., 2017; Hossain, et al., 2020; Mackenbach, et al., 2020). The long-term benefits do not financially pay off in one single project in this stage of the transition (Eberhardt, et al., 2019). Building long-term collaborative relationships enables manufacturers and suppliers to invest in product development instead of having to focus on the next sale (Cheshire, 2017; Mackenbach, et al., 2020; Wuni, 2022).

The traditional supply chain in a construction project is known to be complex, fragmented, and temporary (Guerra & Leite, 2021; Iacovidou & Purnell, 2016; Rose & Stegemann, 2018). Ghisellini, et al. (2018), Govindan & Hasanagic (2018), and Leising, et al. (2017) mention that the traditional supply chain requires a transformation towards a more integrated version with extended responsibilities for all actors involved. BAMB (2016) and Platform CB'23 (2021a) presented collaboration designs with all required actors and emphasize increased collaboration links between them. A lack of collaboration is a barrier for the application of circularity (Adams, et al., 2017; Eberhardt, et al., 2019; Hossain, et al., 2020; Mackenbach, et al., 2020). Both BAMB (2016) and Kanters (2020) argue for different roles of different partners such as a more central role of the architect in the design phase. The architect is in the position of raising the ambition level and can act as the link between product suppliers, the client and main contractor. Furthermore, project success is traditionally measured in time, budget, and quality. However, tight project budgets are known to be a significant barrier in implementing circularity principles in project design (Ghaffar, et al., 2020; Iacovidou & Purnell, 2016).

Also, new business models and forms of ownership are required in order to develop and design circular buildings as current ownership models incorporate outdated concepts from the linear economy such as one-time-use and single purchase (Giorgi, et al., 2022).

2.1.4. Economical

The economical dimension comprises the financial costs of building in accordance with circular principles such as, business cases, maturity of the material markets, and external costs.

As the inherent nature of companies is to gain profit from providing their supplies or services, the transformation towards a circular industry must be financially attractive as well. This requires a different business case for involved parties (Giorgi, et al., 2022). As mentioned, designers can either plan for reuse of non-renewable materials or use novel biobased materials in their designs. However, the current challenge of the adoption of these materials is the infancy of market of circular components which leads to a temporal and spatial mismatch in supply and demand (Kanters, 2020). Storage of salvaged materials would benefit the market but is known to be inefficient and expensive through renting storage space and extra streams of logistics (Cruz Rios, et al., 2015). Also, the market of traditional building materials is better developed which means that there is more supply, and virgin non-circular materials are cheaper (Giorgi, et al., 2022; Kanters, 2020; Masi, et al., 2018). The supply chain experiences difficulties in establishing the correct price of novel bio-based or recovered products (Ghaffar, et al., 2020; Iacovidou & Purnell, 2016). In combination with, for example, the application of new collaboration modes, this requires high upfront costs (Allwood, et al., 2011; Cruz Rios, et al., 2015; Ghaffar, et al., 2020). These higher costs due to a novel working method can be seen in many barriers. It requires more time in the design phase and design fees are higher when incorporating existing components and remanufacturing is time-consuming and labor-intensive (Govindan & Hasanagic, 2018; Iacovidou & Purnell, 2016; Kanters, 2020). The biobased material market should also focus on rapid certification as this can take away a key barrier in applying novel biobased material.

Moreover, the costs of labor for recycling are oftentimes not lower than the costs of newly produced similar material. The incentive for innovation in materials or careful component harvesting is therefore lacking (Kanters, 2020). Next, the absence of a clear business case for actors in the supply chain impacts the adoption of circularity (Adams, et al., 2017; Ghaffar, et al., 2020; Guerra & Leite, 2021; Hossain, et al., 2020). This absence is in line with the organizational barrier of misalignment of short-term goals and long-term benefits. Multiple new business models for actors in a construction supply chain are proposed (Cheshire, 2017; Lacy, et al., 2014; Mackenbach, et al., 2020). However, adoption by a resistant supply chain is difficult.

2.1.5. Regulatory

The regulatory dimension entails all rules and regulations, governmental policies, and juridical aspects of the transition to circular construction.

Building projects in the Netherlands are bound to strict rules and regulations to ensure quality and safety of structures. In the industry there is a need for reducing waste in accordance with the 3 or 10R-ladder (Potting, et al., 2017). Stricter rules can force companies reduce waste through innovation (Kanters, 2020). However, Kanters (2020) also ambiguously argues for more flexible regulations as reused and salvaged materials are difficult to incorporate.

Furthermore, governments can take action to promote circularity. It can act as a launching customer by requiring circularity in their own tenders, it can act as policy developers for minimum requirements of circularity in new building and renovation, or it can make subsidies available for circular investments, (Arcadis, 2022; Govindan & Hasanagic, 2018). The Dutch government already pronounced their goal to have a circular economy by the year 2050 (Rijksoverheid, 2021).

Also, circularity can be fostered in construction projects by proposing indicators by which to assess the implementation and performance of circularity throughout the supply chain. Subsequently, unambiguous policy standards for building according to circularity principles can be developed to ensure a straightforward implementation. However, this requires definition of circularity in the industry which is not available right now. Currently, the governmental financial incentives still support the traditional linear economy (Ghaffar, et al., 2020; Govindan & Hasanagic, 2018; Guerra & Leite, 2021; Masi, et al., 2018). In general, it is understood that policy and laws for circularity have been insufficiently implemented on all governmental levels (Govindan & Hasanagic, 2018; Giorgi, et al., 2022; Iacovidou & Purnell, 2016; Kanters, 2020; Wuni, 2022). Besides that, the current rules and regulations are not fit for employing novel biobased materials (Arcadis, 2022; Hossain, et al., 2020; Giorgi, et al., 2022).

Lastly, the legal nature of the contract forms currently employed can act as a barrier. The short-term goals of the supply chain members and the envisioned long-term benefits are not aligned in traditional contracts that foster the take-make-dispose rationale. The business model and contract duration should align with parts of the lifecycle of the designed building. Also, competition legislation inhibits collaboration between companies (Masi, et al., 2018). Procuring organizations should steer away from competitive tendering on price as this has a negative effect on circular ambitions.

2.2. Summary

Nineteen papers and reports on barriers to the integration of circularity on the industry have led to the list of 53 different barriers presented in Table 1 which are categorized into each of the five dimensions. This categorization serves as a research framework for the analysis of the projects subject to this research. The scientific methodology behind the use of this framework is explained in chapter 3.

Table 1: Overview of barriers mentioned in literature

Dimension	#	Barrier	Frequency	Eberhardt, et al. (2019)	Adams, et al. (2020)	Huang, et al. (2018)	Ghaffar, et al. (2020)	Giorgi, et al. (2022)	Guerra & Leite (2021)	Govindan & Hasanagic (2018)	Masi, et al. (2018)	Kanters (2020)	Cruz Rios, et al. (2021)	Arcadis (2022)	Allwood, et al. (2011)	Rose & Stegemann (2018)	Mackenbach, et al. (2020)	Hossain, et al. (2020)	Gálvez-Martos, et al. (2018)	Iacovidou & Purnell (2016)	Rahla, et al. (2021)	Wuni (2022)
Technical	1	Uncertain material quality	14	x	x		x	x		x	x	x	x	x	x	x		x		x		x
Technical	12	Accurate information of materials is not available	8							x	x		x	x		x		x		x		x
Technical	14	Existing building stock are complex and do not have circularity principles	7		x			x					x			x				x	x	x
Technical	24	Reused materials increase the complexity in design	5		x										x		x				x	x
Technical	37	Lack of sufficient list of material standards	3					x												x		x
Technical	38	Lack of skill by employees in the industry	3							x										x		x
Technical	41	New circular materials are not available	3									x								x		x
Technical	51	No year round supply of biobased resources in NL	1											x								
Technical	52	Transition materials not applied	1											x								
Social	4	Lack of knowledge of circularity in the industry	10	x	x			x	x	x		x	x	x				x				x
Social	8	Lack of awareness of circularity in the industry	8	x	x			x	x	x	x							x				x
Social	15	Higher perceived risks	6					x					x	x		x		x				x
Social	16	Resistance to change	6						x		x	x	x				x					x
Social	18	Consumer perception of reused/bio based material is flawed	6							x			x	x				x		x		x
Social	23	Poor leadership and management	5							x	x						x	x				x
Social	25	No commonly accepted definition of circularity	5	x				x				x						x				x
Social	29	Mistrust between stakeholders	4	x							x				x							x
Social	32	No established best practices	4										x			x				x		x
Social	53	Aesthetics and commercial desirability	1																	x		
Organizational	7	Misalignment between short-term goals and long-term benefits	9	x	x				x	x	x			x			x	x				x
Organizational	9	Lack of collaboration between stakeholders	8	x	x						x		x		x		x	x				x
Organizational	11	Time constraints	8				x		x	x			x		x	x				x		x
Organizational	17	Lack of supply chain infrastructure for recovery, refurbishment, and storage	6		x								x		x	x				x		x
Organizational	19	Insufficient proven circular business models and difficult to apply	6					x	x	x	x							x				x
Organizational	20	Complex a fragmented supply chain	5	x	x											x	x			x		
Organizational	22	Project-based practice	5	x	x			x									x					x
Organizational	27	Ownership issues	4							x	x						x	x				
Organizational	28	Time constraints for deconstruction	4										x		x	x				x		
Organizational	43	Construction process does not allow for interdisciplinary interactions	2					x														x
Organizational	45	Organizational structure makes it difficult to apply circularity in firm	2							x												x
Organizational	47	Lack of information exchange system between different stakeholders	2								x											x
Organizational	50	Current roles in project development unfit	1									x										
Economical	3	Market of virgin materials is better developed	12					x		x	x	x	x	x	x	x		x	x	x		x
Economical	5	High upfront costs	10				x	x	x	x	x		x		x	x				x		x
Economical	6	Absence of a clear business case	9	x	x		x	x	x	x			x					x				x
Economical	21	Higher streams of logistics expected	5				x	x					x				x			x		
Economical	26	Difficulties in establishing correct price of products in supply chain	5							x							x	x		x		x
Economical	30	Remanufacturing is time-consuming and labor-intensive	4							x		x								x		x
Economical	31	Low value of many construction products at end-of-life	4		x													x		x		x
Economical	34	Banks and investors regard circular business models as riskier	3					x				x										x
Economical	36	Design fees are higher when design is built around existing components	3						x						x							x
Economical	39	Recertification reclaimed components is expensive and time-consuming	3												x					x		x
Economical	42	Insufficient internalization of external costs	2							x	x											
Economical	44	Owner or client has tight budget constraints	2					x														x
Economical	48	Mismatch between costs labor and materials	2									x										x
Regulatory	2	Unfit policy, rules, and regulations	13				x	x	x	x	x	x	x	x	x		x	x		x		x
Regulatory	10	Lack of standards for circularity principles	8			**x**	x			x	x	x	x					x				x
Regulatory	13	Lack of (governmental) financial incentives to design for circularity	7		x					x	x						x	x		x		x
Regulatory	33	H&S Regulations (favor demolition over deconstruction)	3				x								x							x
Regulatory	35	Lack of flexibility in building codes and regulations	3									x		x								x
Regulatory	40	Unfit contract forms for circularity	3	x									x									x
Regulatory	46	Competition legislation inhibits collaboration between companies	2								x											x
Regulatory	49	Circularity is not effectively incorporated in innovation policies	1								x											

3. Methodology

The objective of this research was to integrate circularity in the design phase of the *FLOW* methodology by presenting recommendations based on lessons learned from a multiple case study on construction projects with a circular focus. This chapter presents the research methodology used in this research to reach this objective.

3.1 Research design

In this research a multiple case study was conducted where the design phases of four different construction projects were analyzed. A multiple case study design allowed for providing rich evidence-based descriptions of barriers to create a more holistic understanding of these barriers for the implementation of circularity in broader and more generalizable real-life contexts (Corbin & Strauss, 2015; Yin, 2003). A multiple case study allows for cross-case validation of results.

This research used a case study methodology in which three separate phases are demarcated based on Yin (2003). These three phases are presented in Figure 3 at the bottom of this page and are presented next.

3.1.1. Define & design

In this phase, the theory that serves as input for case study interviews was reviewed and summarized into a research framework along the lines of 53 barriers divided in five dimensions. Subsequently, a data collection strategy was developed. Four projects were selected for the multiple case study of which two were residential projects, and two were non-residential to draw lessons learned from both construction types and subsequently apply these on both *FLOW*s.

The projects and the interviewees for these cases were selected using a mix of multiple sampling strategies. First, the projects for the multiple case study were selected using theoretical sampling. Using this sampling technique the projects were selected based on the presence of the concept of circularity. The projects were required to have a pronounced circularity ambition. Next, the projects were further selected using selective sampling for two preconditions. First, individual project team members or clients were not involved in more than one of the cases. This ensures a good understanding of solutions to barriers independent from personal views of project team members. Second, DV as main contractor had to have been involved in *FLOW* phase 4 *(TD)* or earlier as this is considered the design phase. Also, the project had to have been executed as only design stages that led to an executed project were considered. Lastly, throughout the selection of the projects, convenience sampling was used as all projects were executed by DV. DV is also the company this research was performed at.

A mix of sampling strategies was also used for selecting the nine interviewees. Selective sampling was used as there was a requirement for the involvement of team members in the project. According to the *FLOW* methodology the project developer and project manager were continuously involved and responsible for the development and design of the project. It was assumed that these team roles would thus carry the most knowledge about decisions on design and circularity. Convenience sampling was used as well, as enough team members with an overview of the project were present besides project managers. BIM-engineers were therefore involved as well. These subsequently brought forward different insightful aspects of the design phase.

Detailed descriptions of projects for the case study with selected interviewees are presented in Table 2 at the top of the next page.

The first case was the non-residential Alliander Westpoort project. The office building incorporates several circular design aspects as it is design uses CLT, and it can be disassembled after its end-of-life. DV joined the project after the Preliminary Design was already developed by the client, its architect, and its engineers. Alliander had pronounced ambitious circularity goals and subsequently allocated funds for these goals.

The second case was the residential Hortus Ludi project. The rights for the design and construction were procured from the municipality of Nijmegen. The municipality had extensive ambitions for sustainability as it demanded energy neutral and climate adaptive houses. On top of this, DV pronounced their own circularity ambitions. The buildings were designed for a higher price range which allowed for more room for application and exploration of its circularity and sustainability measures such as the incorporation of CLT.

The third case was the residential De Zangvogel project. For stage two and three the project team pronounced some circularity ambitions which it explored and researched throughout the development of the project. In stage two of De Zangvogel eight of the 35 houses was built with a wooden frame construction. In stage three, 12 of the 72 houses were built with a timber frame and wooden cladding.

The fourth case was the non-residential Weener XL. The client and architects already made a design for this project. DV Bouw Zuid won the procurement and was subsequently asked to join in an advisory role on suggested design solutions upon which they got granted the execution. The goal of this project was to produce no waste and to use as much circular material as possible. The core structure is entirely of wood.

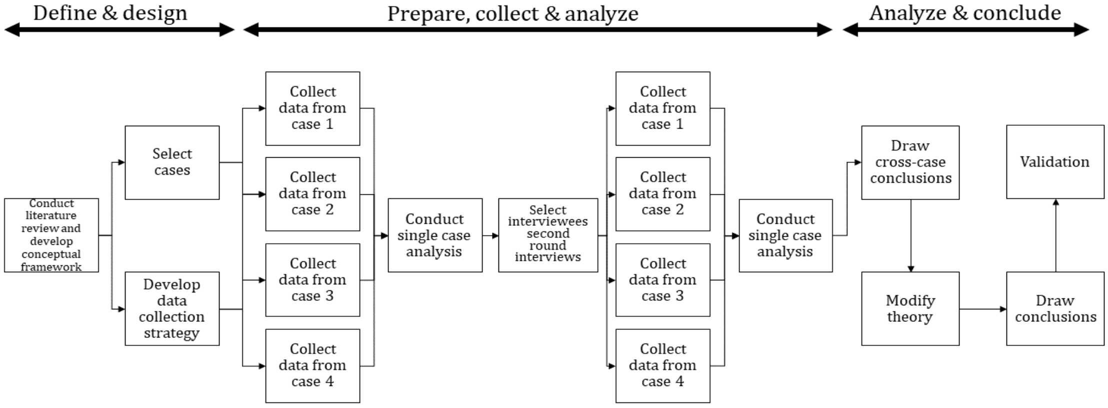

Figure 2: Case study procedure (Adjusted from Yin (2003))

Table 2: Overview of projects for case study

Project name	Client	Contract type	Project description	Office DV	Period	Project phases involved	Roles interviewees
Alliander Westpoort, Amsterdam	Alliander	Early contractor involvement	Non-residential construction of a production area, storage area, and an office area of in total 25.000 m2	DV Bouw Midden-West	March 2021 - February 2023	Phase 3 (DD) - phase 7 (Use phase)	1 - Project manager (PM) 2 - BIM engineer (SBE) & Project coordinator
Hortus Ludi, Nijmegen	Own development and design	Own development	Residential construction of 11 high-end houses	DV Bouw Zuid	April 2020 - December 2022	Phase 0 (Initiative) - phase 7 (Use phase)	1 - Project developer (PD) 2 - BIM engineer (SBE)
De Zangvogel, Vlaardingen	Own development and design	Own development	Residential construction 172 houses part of a larger area development project called De Nieuwe Vogelbuurt of 418 houses. Stage 2 and 3: 20 of 107 houses built with circular aspects.	DV Bouw Zuid-West	Summer 2020 - Summer 2022	Phase 0 (Initiative) - phase 7 (Use phase)	1 - Project manager (PM) 2 - BIM Engineer (SBE) 3 - Project developer (PD)
Weener XL, Den Bosch	Weener XL	Early contractor involvement	Non-residential construction of a production area, office area, and other supportive facilities	DV Bouw Zuid	April 2020 - Ongoing	Phase 3 (DD) - phase 6 (Realization)	1 - BIM Engineer (SBE)

The used data collection strategies were questionnaires, a semi-structured interviews and document analysis. In these questionnaires, the interviewees where asked to mark each of the 53 barriers compiled in the literature review on whether the were encountered in the project or not. Each marked barrier was subsequently presented to the interviewees after which they could elaborate on the presence of and dynamics behind these barriers.

Semi-structured interviews were selected as this allowed interviewees to deviate from the main questions into aspects they wanted to emphasize (Wilson, 2014). This allowed for a more detailed description of the most important processes and reasoning behind certain design decisions . On top of that, other barriers besides these 53 compiled barriers could be explored. These insights were used for the development of the recommendations for *FLOW* later on.

3.1.2. Prepare, collect & analyze

The data collection phase entailed conducting semi-structured, in-depth interviews with a document analysis afterwards. These case findings were first individually analyzed after which they were accumulated to draw cross-case conclusions in a later phase.

In Figure 2, the selection of the second round of interviewees takes place after the collection and analysis of the data from the first round of interviews. Yin (2003) explained that a possible redesign of the study's case study protocol can be based on the preliminary findings in the first gathering of data. Without such a redesign the researcher might get accused of distorting or ignoring the discovery simply to accommodate the original design (Yin, 2003). In this research, this occurred when the findings of the first round of interviews presented different and more technical aspects in the project development and design provided by the BIM-engineer of Weener XL. Subsequently, team members that were involved in the execution such as an BIM-engineering were approached for the second round of interviews.

3.1.3. Analyze & conclude

The data analysis of single cases was accumulated to draw cross-case conclusions. A cross-case analysis is conducted to prevent premature and false conclusions drawn from single cases. Humans are notoriously poor processers of data (Eisenhardt, 1989). A cross-case analysis counteracts this characteristic by looking at topics and data from many different angles. Eisenhardt (1989) suggests selecting categories or dimensions, and then looking for within-group similarities coupled with intergroup differences. This research adopted this strategy. Using coding software, codes were applied on excerpts from the interviews in the following manner. First, a quote was labeled with a barrier in the form of *[n] BARRIER NAME*. This quote was subsequently specified with either a *B* indicating the presence of the barrier, *O* indicating a used solution (Dutch: Oplossing), and *HO* indicating a hypothetical solution (Dutch: Hypothetische Oplossing). Some quotes received labels of multiple barriers as they touched upon multiple barriers due to the interconnectedness of the barriers. A more extensive description of this coding strategy and what this meant for the analysis is found in Appendix E.

This coding strategy allowed for quick comparisons between data on all levels and cross-case comparison could quickly be made. Hypothetical solutions to a certain barrier coined by an interviewee of one project could be validated by similar solutions used by interviewees of other projects.

The results of the analysis are presented in Section 4.1 as standalone lessons learned with an explanation of barriers. Afterwards, these lessons learned are applied on the *FLOW* methodology where several operational suggestions are provided.

To validate the efficiency, accuracy, and proper placement per phase and per responsible project team role of the suggestions in *FLOW*, a focus group session was organized with five different participants at DVBH. These participant all had knowledge of circularity, innovation, project management, and *FLOW* from their own job experience and can therefore be considered as experts for this validation session. None of the participants were involved with the four projects in the case study to ensure external validation. A focus group was used as this allowed all participants to demonstrate and share their knowledge and opinions more actively and in more detail (Jung & Ro, 2019). Also, when a discussion is evoked, the participants are activated to think about the suggestions from others. The list of participants in the focus group is presented in Table 3.

Table 3: Overview over participants of focus group

#	Job title	Project team role
1	Senior Project manager	Yes
2	Senior BIM engineer	Yes
3	Development manager	Yes
4	Manager Digital construction	No
5	Manager Innovation and product development	No
6	Tender manager	Yes
7	Tender manager	Yes

During the first focus group session it became apparent that the frame of reference of the group was mainly on residential construction due to the nature of the projects they were involved in. To prevent the validation of the results to be skewed towards the residential *FLOW* process, another validation meeting was arranged with two tender managers where the focus was on non-residential construction. These tender managers also fulfil the roles of design leaders, and project managers and are thus considered experts in the field of non-residential construction design.

Participants 1, 2, 3, 6, and 7 have practical knowledge of *FLOW* through their continuous involvement in projects. Participant 4 is one of the developers of *FLOW* and he knows the methodology by heart. Lastly, participant 5 is actively working on innovation and circularity at DV and is thus knowledgeable of circularity and innovation.

4. Results

In line with the sub questions of this research, Section 4.1. first presents an overview of the lessons learned followed by a reflection of the barriers involved. The table at the start of each section presents the impacted dimensions and barriers and an indication of application of lesson learned in project phases. Then, Section 4.2. presents an application of these lessons learned in the form of recommendations for *FLOW*.

4.1. Barriers found in project cases

An overview of all barriers experienced in either of the four projects subject to this case study is presented in Appendix F. This overview contains remarks on the notability of these barriers. Notable barriers are used in this result section to draw lessons learned. A barrier is considered notable when there is a large mismatch of 50 percentage points between occurrence in practice and literature. These are calculated by subtracting the percentage of the 19 papers mentioning a certain barrier, from the percentage of projects this barrier occurred in practice.

This returns 24 barriers that were found in literature beforehand, and ten new barriers were found. These new barriers are indicated by [x…]. In the case study, solutions to overcome these barriers were presented for 14 out of the 24 barriers found in literature, and seven out of ten newly found barriers. These solutions were eventually addressed in five recommendations. Table 11 in Appendix G presents an overview of the five recommendations, the barriers they impact, and their occurrence in literature and practice.

4.1.1. Accurately formulate feasible and detailed circularity ambitions

The first recommendation is to accurately formulate feasible and detailed circularity ambitions at the start of the project. This recommendation impacts the organizational, social and technical dimensions as presented in Table 4.

Table 4: Overview of impacted barriers and application on FLOW through responsible team members and FLOW phases of Recommendation 1

Barriers impacted	Organizational	[7]; [22] ; [x1]; [x3]; [x8]
	Social	[4]; [16]; [25]; [53]
	Technical	[x4]

Application on FLOW	Team members \ Phase	Initiation	Conceptual Design	Preliminary Design	Detailed Design	Technical Design	Final Design	Execution
	Development Manager	▨						
	Project Developer	▨						
	Project Manager							
	Construction Project Manager							
	BIM-Engineer							
	Site Manager							

The social dimension of this recommendation is found in overcoming four barriers. Designing and building in compliance with principles of circularity starts by defining the concept of circularity and the subsequent measures. This requires a certain level of knowledge. A lack of knowledge of circularity, barrier [4], emerged in every project and turned out to be a defective starting point for stakeholders to integrate circularity. Similarly, barrier [25], no commonly accepted definition of circularity, arose in 26% of the literature while it surfaced as a barrier in all projects in practice. Interviewee 1 of Weener XL experienced this and stated: "There are extremists, and some people tend to have a rather simplistic view of it. Everyone has their own perspective on it". Furthermore, he stated that the aesthetical desires of the client, architect, and architectural review board impacted the eventual circularity of the building, which is barrier [53]. These three barriers culminated in the unnecessary use of materials, such as the façade, which could have been avoided if one clear definition of circularity was pronounced. The lack of knowledge was present in governmental organizations as well. This led to difficult collaboration with government, which is newly found organizational barrier [x8] and is found in three out of four projects. Interviewee 1 of Hortus Ludi explained that issuers of permits are generally critical and skeptical of using timber in the design as they are unexperienced and risk-averse.

Project Alliander Westpoort, pronounced the ambition for circularity and based it on ambition documents of Alliander, the Municipality of Amsterdam, and City District Sloterdijk. It stated in the Sustainable Ambition Document and read as follows: “to use reused materials as much as possible.” The wish was: “to use 100% circular material of which is 50% reused and 50% new but recyclable.” However, it did not provide further explanation of these concepts and percentages. This lack of quantitative and qualitative explanation was critical for the eventual circular aspects in the project. In practice, both client and architect demanded new pavement tiles, a new wooden fence, and a new storage shed for aesthetical, financial, and practical reasons, while reusable circular options were available. Three out of four projects experienced barrier [53], compared to only 5% of the papers reviewed. Only at Hortus Ludi there were no inhibiting aesthetical barriers present. Interviewee 1 of Hortus Ludi explained: “The type of people who were involved all matched well with each other [...] There was also no architect who insisted on getting their way.”

The resistance to change [16], and thus the reluctance to incorporate novel circular or salvaged construction materials, was visible throughout these projects. Interviewee 1 of De Zangvogel suggested accurately defining circularity and ambitions to overcome this barrier: “Make it as specific as possible so that it is also measurable, and you know what needs to be done for it.”. However, this is difficult due to the lack of measurable indicators, a newly found barrier [x4]. This barrier inhibits quantitatively selecting the most effective circular materials for projects. This technical barrier explicitly surfaced in 50% of the projects due to the lack of knowledge and standards in the industry.

Lastly, the organizational dimension of this recommendation is impacted by overcoming the project-based character of the industry, barrier [22]. This barrier was present in all projects compared to only 26% of the reviewed papers. Long-term collaborations must be built upon the industry's common definition and ambition of circularity. If two projects have different definitions of circularity, which require different efforts and investments, there is no incentive to innovate throughout multiple projects. At De Zangvogel, benefits of collaboration with the same partners were experienced where they innovated from no circularity aspects in stage 1, to incrementally more in stages 2 and 3. Stage 1, the project team started to think about what is possible in stage 2. In three out of four projects, newly found barrier [x3], too diverse project ambitions, surfaced. To ensure a manageable set of feasible project ambitions, interviewee 1 from De Zangvogel explained that they split up their ambitions where stage 2 focused on replacing the concrete walls into a timber frame and stage 3 on adding a timber cladding.

At Hortus Ludi, the circularity ambition of DV was high. Buyers had lots of design freedom on top of an already novel construction method for DV. Interviewee 2 admitted that they should have been more discerning in their ambition and design freedom as many of the circular initiatives were complex and unknown.

As summarized from these individual lessons learned outlined above, a three steps for developing circularity ambitions from the start of the project proposed. Table 5 below presents the steps and outlines the barriers of recommendation 1 the steps help to overcome.

Table 5: Three-step approach of developing circularity ambitions at the start of a project

Three-step approach

Step	Barriers
1. Define circularity among stakeholders	[4] Lack of knowledge [22] Project-based industry [25] No commonly accepted definition of CE [x8] Difficult collaboration with stakeholders
2. Make circularity measurable	[16] Resistance to change [x4] Measurability of circularity
3. Develop feasible, manageable, and measurable circularity ambitions and objectives in collaboration with stakeholders	[7] Misalignment between short-term goals and long term benefits [53] Aesthetical and commercial desires [x1] Ambition of client inhibiting [x3] Too diverse project goals

4.1.2. Ensure a warm handover of project phases

The second recommendation is to ensure a warm handover of project phases throughout the project. By a warm handover meant a more integrated handover between team members responsible through and earlier involvement and a more detailed project description. This recommendation impacts the organizational and social dimensions as presented in Table 6.

Table 6: Overview of impacted barriers and application on FLOW through responsible team members and FLOW phases of Recommendation 2

Barriers impacted	Organizational	[11]; [50]; [x2]; [x10]
	Social	[4]; [23]

Application on FLOW

Team members \ Phase	Initiation	Conceptual Design	Preliminary Design	Detailed Design	Technical Design	Final Design	Execution
Development Manager							
Project Developer							
Project Manager							
Construction Project Manager							
BIM-Engineer							
Site Manager							

Ultimately, the ambition must be integrated throughout the project, as highlighted in the proposed approach. This surfaced as a critical aspect as "…such a mindset goes beyond just some words on a piece of paper," as Interviewee 1 of Weener XL put it.

For this, it is crucial to facilitate a warm handover of project phases. These handovers occur between phase 0 (Initiative) and phase 1 (CD), phase 2 (PM) and 3 (DD), and 4 (TD) and 5 (FD). During phase 5 (FD) until phase 6 (Execution), the designed project is completely handed over to the execution team and moves from the office to the construction site. These handovers are influenced by individual opinions team members. This is due to barrier [4] a lack of knowledge of circularity which entails the social dimension of this recommendation. Better integration of team members through a longer overlap of team roles responsible is important as it can bring together differing opinions on circularity. This improves the possibility to share tacit knowledge on circularity, and dynamics behind circular designs. Also, one central leadership is vital as DM of Hortus Ludi and PM of De Zangvogel were vanguards in the project through their continued involvement.

The organizational dimension is found in overcoming barriers [11] time constraints, [50] unfit uncoupled team roles, [x2] different execution on-site than designed at the office, and [x10], hard handover of project phases. These all tie into each other. Of these, the core barrier is [50] and was present in three out of four projects but notably surfaced in 5% of the scientific papers. Barrier [50] is oftentimes influenced by barrier [11], which is common in many projects. Especially during the execution phase of the project, the project follows a tight schedule. Barriers [50] and [11] culminated into barrier [x2] which is observed in all four projects but not in literature beforehand. The dynamics in the execution phase are different from the design phase at the office because the goals of responsible team roles differ, as Interviewee 1 of De Zangvogel explained. Interviewee 2 of Alliander Westpoort agrees and explains that the people involved in the development and design phase are more creative and open-minded. However, in the execution phase, the schedule and agreed-upon budget are leading.

Concludingly, the handover of the project phases should be warmer through longer involvement of project team roles responsible in which there is a longer possibility for the transferring of tacit knowledge on project goals, ambitions, and knowledge of circularity. An early involvement of project team member in the execution phase should is therefore important too.

As a result of recommendation 3, a detailed BIM model helps to ensure a warm handover and takes away these risks in the execution too. The dynamics behind this lessons learned are illustrated by Interviewee 2 of Alliander as he said the following about the handover from the office to the construction site, called *kick-off 4*, and how different team roles view the project differently: "Kick-off 4 is the moment when the entire technical dossier is handed over. […] Kick-off 4 should simply say: 'This project can be done like this, it costs this much, and that's what we've planned.' And then the time pressure begins.".

4.1.3 Recommendation 3

The third recommendation is to materialize early in the project. This recommendation impacts the technical, social, organizational, and economical dimensions as presented in Table 7.

Table 7: Overview of impacted barriers and application on FLOW through responsible team members and FLOW phases of Recommendation 3

Barriers impacted	Technical	[1]; [12]; [24]
	Social	[4]; [15]
	Organizational	[x1]; [x7]; [x8]
	Economical	[5]; [21]; [30]; [39]; [48]

Application on FLOW

Team members \ Phase	Initiation	Conceptual Design	Preliminary Design	Detailed Design	Technical Design	Final Design	Execution
Development Manager							
Project Developer		▨	░				
Project Manager		▨	░				
Construction Project Manager							
BIM-Engineer		▨	░				
Site Manager							

The materialization of the design is crucial in establishing the eventual circularity of a building. In the *FLOW,* materialization starts in phase 3 *(DD)* by developing a bill of materials. The materialization must start as soon as possible. Interviewees 1 of Alliander Westpoort and De Zangvogel both coined the idea to reverse the design order, and to start the design around available materials. DV's circular material storage hub, *Urban Miner*, would benefit from as well. Currently, this hub does not find enough traction in DV's construction projects because it is difficult to incorporate materials with unexpected dimensions, as surfaced in all projects and explained by barrier [24]. The benefits of early materialization are two-fold. First, it allows for extra time in the design phase to find and test proposed circular building materials. Incorporating reused and novel circular materials are known to be difficult and perilous through the lack of material information which are barriers [1] and [12], encompassing the technical dimension of this recommendation. Interviewee 1 at Weener XL stated: "You have to allocate time for it in the design process from a planning perspective and set many milestones.". Interviewee 1 of Alliander Westpoort agreed and stated: "When you start looking at available materials and think about constructability straight after the development of a program of requirements, you can significantly impact the eventual circularity."

The second benefit is in line with recommendation 2 as handing over the project to the execution is conducted more thoroughly using a more detailed project design. At De Zangvogel, a highly detailed materialization ensured a relatively straightforward execution phase with few impactful non-circular design decisions left to be taken. This reduced the time for materialization required toward the execution where a high pressure on schedule is present, as explained in recommendation 2. At Hortus Ludi, the SBE was involved from phase 1 *(SD),* to provide feedback on the design and to get acquainted with the circular ambitions for the project. Involving technical team roles from the execution early is thus beneficial for two reasons.

Overcoming the lack of knowledge at parties involved, and the subsequent higher perceived risks of owners and users, barriers [4] and [15] are the social dimension of this recommendation. These can be overcome in the same manner as barriers [1] and [12], thus creating enough time to gain confidence in the materials through early materialization and developing reports on material performance, as explained by both interviewees of Hortus Ludi. Especially the presence of barrier [15] is notable as it was only mentioned in 32% of the literature while being present in all projects. Risk management is essential to construction activities in minimizing losses and enhancing profitability. Construction risks influence project objectives of cost, time, and quality (Akintoye & MacLeod, 1996). All of these events are highly unsure when incorporating salvaged or novel construction materials which are usually expensive, uncertified, and difficult to obtain.

Newly found barriers [x1], [x7], and [x8] encompass the organizational dimension of this recommendation. Barrier [x1] is the ambition level of the client to which Dura is tied to as explained illustrated by the example of Alliander Westpoort in section 4.1.1. Barrier [x7] the traditional design sequence surfaced in all projects. Recommendation 3 can elicit a fundamental change in the design process by switching the design sequence from 'materialize a construction design' into 'develop a design around a set of materials', as explained by Interviewees 1 of Hortus Ludi and De Zangvogel.

Lastly, five barriers encompass the economical dimension of the recommendation. Of these, three all assume higher costs for circular design and materialization. Barriers [30] remanufacturing is time-consuming and labor-intensive, [39] recertification of reclaimed components for re-use is expensive and time-consuming, and [48] mismatch between costs of labor and new materials all outline the costs of upcycling. These three barriers are all found notably less in literature than all surfaced in three out of four projects. Interviewee 1 of Alliander Westpoort explained how the industry is currently not experienced with upcycling materials and budgeting. This introduces new unwanted risks in the project. Early materialization allows for a longer search for available and (re-)certified materials. Thus the possibility of finding and incorporating accurate circular materials is higher.

4.1.4 Recommendation 4

The fourth recommendation is to make use of standardized solutions and designs. This recommendation impacts the technical, organizational and economical dimensions as presented in Table 8.

Table 8: Overview of impacted barriers and application on FLOW through responsible team members and FLOW phases of Recommendation 4

Barriers impacted	Technical	[12]; [37]
	Organizational	[x8]
	Economical	[26]; [30]

Application on FLOW

Team members \ Phase	Initiation	Conceptual Design	Preliminary Design	Detailed Design	Technical Design	Final Design	Execution
Development Manager							
Project Developer		▨					
Project Manager		▨	▨				
Construction Project Manager							
BIM-Engineer		▨	▨				
Site Manager							

The efficiency of the project increases when being able to fall back on a standard design (Aapaoja & Haapasalo, 2014). This was experienced firsthand in De Zangvogel as this is a further circular development of an already existing standard housing product at DV, called PCS (Pre-Choice System). Interviewee 1 of De Zangvogel stressed the benefits of having the predefined dimensions of this: "When you have to redo things and figure them out again, it is nice to have a little database to fall back on.". Therefore, the circular development of the design was cut up in stages 2 and 3. However, Interviewee 1 of De Zangvogel admitted that he was somewhat disappointed in the partners' ability to innovate between phases but attributed that to a resistance to change [16] and a lack of knowledge of circularity [4].

Interviewee 1 of Hortus Ludi also recognized that their project had to pioneer and start with a timber building from scratch. They solved this by approaching other companies and relying on their expertise. However, this was extremely time-consuming and inefficient, as outlined in section 4.1.3.

Both interviewees of Alliander Westpoort explained how they expect standard designs to contribute to quicker and more accurate budgeting as material volumes and dimensions are indicatively known beforehand.

Barriers [12] unavailable accurate material information, and [37] a lack of material standards, encompass the technical dimension of this recommendation. [37] is the most notable barrier, as it surfaced in three out of four projects, compared to only 16% in literature. Developing standard designs and solutions helps overcome that barrier [37], which is used and improved continuously. It is recommended to develop material standards and design solutions inside DV as this ensures economies of scale which can have a flywheel effect for the entire industry. It is recommended to early involve known partners with detailed technical knowledge to establish these standard designs. Interviewee 1 of De Zangvogel explained how some partners recently admitted they could improve their design from stage 2 to stage 3, as they recently gained more knowledge on circularity.

Barrier [x8] difficult collaboration with governmental organizations, encompasses the organizational dimension of this recommendation, which was not found in the literature beforehand but surfaced in three out of four projects. Since the practical application of circularity is such a novel practice, government-related agencies such as architectural review boards, fire departments, and permit issuers can be risk-averse and demand highly detailed reports of the material to be used, as explained by Interviewee 2 of Hortus Ludi. These should demonstrate comparable performance to traditional construction materials. He explained that first, an early materialization of the design is needed to establish such reports. These detailed reports become unnecessary once these materials and designs become standard practice.

The economical dimension of this recommendation is found in the impacted two connected barriers [26] difficulties in establishing the correct price of products, and [30] remanufacturing is time-consuming and labor-intensive. Barrier [26] was mentioned in 26% of the reviewed literature but surfaced in all projects in practice. Large scale use of both salvaged and novel circular materials is new in construction projects. The prices of these products are unpredictable through fluctuating quality and quantity of supply and costs for upcycling salvaged materials. Interviewee 1 of Alliander Westpoort stated the following about upcycling a light fixture: "Estimating the labor component in upcycling is challenging. We have limited experience in that regard. Those costs can escalate quickly compared to shipping a new light bulb from China. In the Netherlands, an employee [for upcycling] is typically more expensive."

For many products, the economies of scale are not realized in the industry, and thus integration of reused materials is inhibited. Interviewee 1 of Hortus Ludi explained: "The quantities actually limit the possibilities." If novel construction materials and whole building designs are developed according to industrywide standards, this will foster the benefits of economies of scale in demolition and novel construction design.

4.1.5 Recommendation 5

The fifth recommendation is to involve partners early in the project. This recommendation impacts the technical, social, organizational and economical dimensions as presented in Table 9.

Table 9: Overview of impacted barriers and application on FLOW through responsible team members and FLOW phases of Recommendation 5

Barriers impacted	Technical	[1]
	Social	[32]; [53]
	Organizational	[17]; [22]
	Economical	[21]

Application on FLOW: Team members \ Phase	Initiation	Conceptual Design	Preliminary Design	Detailed Design	Technical Design	Final Design	Execution
Development Manager							
Project Developer							
Project Manager							
Construction Project Manager							
BIM-Engineer							
Site Manager							

The required knowledge to develop a feasible circular design is not always present at DV. Similar to traditional construction, many specialized companies on circular components exist throughout the industry. Advisors and suppliers that should be involved are based on the type of project, the ambition, and measures pronounced, in line with recommendation 1.

Impacted barrier [1] unknown technical material quality, entails the technical dimension of this recommendation. The recommendation is the close consultation and collaboration with suppliers and demolition companies to obtain accurate knowledge on materials. These are the parties with in-depth material knowledge. Early involvement ensures enough time for research.

Interviewee 2 of Alliander Westpoort argued for early involvement of a team role with specific technical knowledge in the design phase in line with recommendation 2, such as SBEs, SMs, or CPMs. This ensures both a check on constructability and increases the understanding of the design at the team roles involved later in the design.

Furthermore, the timely involvement of suppliers and architects is recommended. The supplier of novel circular construction materials is the expert of the material. After stage 2 at De Zangvogel, the project team learned to involve the timber frame builder earlier in the PD, and preferably in the SD, in stage 3 for their practical input of other design aspects, such as floor construction, which can influence the eventual building height. Interviewee 1 of De Zangvogel: "It is important to take these aspects into account for your first drawings and designs". Interviewee 1 of Weener XL explained the importance of involving an architect for: "An architect has a broader knowledge of materials than we as contractors do. We only stumble upon things by chance, while manufacturers approach architects more often."

The social dimension of this recommendation is found in two impacted barriers. First, barrier [32] no established best practices, is a notable barrier. The projects in this research were at the forefront of the transition toward circularity. Nowadays, there are more example projects at DV. Barrier [53] aesthetics and commercial desirability inhibit circularity as traditional, 'new' materials are desired in practice. Early involvement of the architect or client to form the circularity ambition also ensures one definition of circularity as explained recommendation 1.

The organizational dimension of this recommendation is found in the impacted two barriers [17] lack of supply chain infrastructure, and, as such, a supply chain is relatively new. For new actions, it is safer to collaborate with known parties as explained by both interviewees of Hortus Ludi as they approached Belgian CLT supplier LTS which were also involved at Alliander Westpoort and Weener XL. This also helps overcome barrier [22], project-based practice. Continuously working with known partners contributes to overcoming the project-based character of the industry. The partners can help to co-create solutions and innovate as there is an incentive through continuous collaboration.

The economical dimension of this recommendation is found in the impacted barrier [21], higher streams of logistics expected. An unknown and underdeveloped supply chain requires storage since demolition and construction schedules are not aligned. All projects experienced this barrier where salvaged materials were attempted to be incorporated. Therefore, this barrier only applies to projects where salvaged materials play a role.

4.2. Application on FLOW

The following section presents an explanation and substantiation of the placement of the lessons learned in the *FLOW* methodology based on the held validation sessions. Appendix F presents a visual representation of this application. An integration of these recommendations in *FLOW* ensures circularity by establishing one measurable, feasible, and manageable definition of circularity in collaboration with the supply chain and along all project team member involved in the project. Later, the development of the design is improved through early materialization of the design which allows for a better integration of salvaged and novel materials. Similar to establishing one central circular definition, the early involvement of partners is important for an early materialization of the design. Lastly, standardization of the design and process increases feasibility and efficiency.

4.2.1 Accurately formulate feasible and detailed circularity ambitions at the start of the project

Inside the industry, one industry-wide definition for circularity must be adopted. However, until this definition is adopted by the entire industry, one shared definition of circularity must be defined in individual projects. In line with recommendation 4, this must occur in close collaboration with all relevant stakeholders. Phase 0 *(Initiative)* consists of three stages being *Ready, Set,* and *Go.* Defining the shared circularity ambition for the project must occur in the *Ready* step of phase 0 *(Initiative)* in collaboration with the municipality, client, and other stakeholders. Subsequently, the ambition on circularity should be defined in the *Set* step, prior to making an investment request as circularity is known to be more expensive. Focus group participant 3 noted, however, that the *Ready* step of project development can take years, depending on stakeholder collaboration and market dynamics. Therefore, a continuous update on the definition of circularity should take place on which the ambition is based. This because insights on circularity might deviate over time in the next few year. The development manager or tender manager is responsible to carry this recommendation, as defining the core ambitions for the plan is already their task.

4.2.2. Ensure a warm handover of project phases

Next, the handover of the project phases among team roles should be fostered. These handovers from responsible team roles occur four times. These moments, together with these team roles, require attention in their handover. The handovers should be improved through more prolonged involvement of all responsible team roles around their handovers. A detailed description of the project and its design decisions in a detailed BIM model.

The last handover from office to construction site should be addressed in the initiative phase by involving team roles such as the site manager in developing the project ambition. This adds to the feeling of "we came up with this in the office" rather than "they came up with this in the office", as mentioned by focus group participant 6. This is called sharing tacit knowledge. Tacit knowledge is all experience-based knowledge that is not codified or expressed in words and figures and is housed in the human brain. The construction industry largely dependent on tacit knowledge (Zhang & He, 2016).

4.2.3. Materialize the design early in the project

It is critical to divide a construction design into separate work packages. Focus group participant 7 suggested dividing the design into the: structural, façade, installations, finishing, and infrastructure. For novel construction materials, these work packages, and moments of materializing them are not much different from those used in traditional construction projects, as explained by focus participant 1. However, if the ambition is pronounced to incorporate salvaged materials, the materialization should occur earlier in the design process because of the differing dimensions of these materials. Starting in phase 1 *(CD)* and finishing early in phase 2 *(PD)*, as mentioned by Focus group participant 4. Focus group participant 2 agrees, as it must be budgeted for in the design phase.

Early materialization is the responsibility of the PD, PM, and SBE, as they have the technical knowledge of constructability and are aware of budgets.

4.2.4. Make use of standardized solutions and designs

Every project is essentially unique which means that standard solutions can not be applied identically everywhere. Focus group participant 2 emphasizes that parties in the supply chain can employ standard solutions and designs as long as the right preconditions and fundamental assumptions are described. As standard solutions and designs become standard practice, some steps in FLOW can be left out as a design standard can be used for these previously unique design sprints.

This recommendation is difficult to grasp in a single phase and a single project responsible. Over time, throughout phase 1 *(CD)* and phase 2 *(PD)* more standardized design solutions must be used. These must be suggested and incorporated by PD, PM, and SBE.

4.2.5. Involve partners early in the design

Clients, architects, and advisors must be involved during phase 0 *(Initiative)* to define circularity and a shared ambition. A shared ambition forms the basis of the project and acts as the starting point for determining the measures. Furthermore, in the design from phase 1 *(CD)* to phase 2 *(DD)*, partners should be involved based on the ambition stated for their technical and practical knowledge of constructability and feasibility. Also, this activates them to think about circular design solutions. The architect should be closely involved for its knowledge of circular materials and to ensure a circular aesthetic design. Early involvement of different partners, such as demolition companies and technical advisors, is essential when salvaged materials are to be used.

5. Discussion

The objective of this research is to integrate circularity in the design phase of the *FLOW* methodology. Ultimately present actions for those involved at DV through recommendations. These moments and actions arose from finding lessons learned from a multiple case study of four construction projects with a circular focus at DV.

This chapter first presents a reflection on the scientific and practical contribution of this research in section 5.1. Afterwards, the main findings of this research are assessed and discussed in section 5.2. Then, the limitations of this research are explained after which recommendations for further research are presented.

5.1. Scientific and practical contribution

The scientific contribution of this research is the presentation of five lessons learned of dealing with barriers to integrating circularity in the design phase that can be incorporated in design processes at construction companies.

This was done through checking 53 unique barriers that were found in international scientific literature in two residential and two non-residential construction projects. This led to an emphasis on certain barriers in the Dutch context at projects of DV such as the uncertain material quality, lack of knowledge and awareness of circularity, higher perceived risks, and difficulties in budgeting for circularity in the design phase. Besides finding the emphasis of these 53 barriers in a Dutch context, ten newly found barriers were found throughout the case study such as the leading ambition of the client, difficult handover of project phases between the office and the construction site, and too diverse project goals. These barriers are further evaluated in section 5.2.. These barriers can serve as input for future scientific research. Ultimately, the presence of these barriers and how is dealt with them culminated into lessons learned and recommendations for DV. This addresses the lack of systematic methodologies for implementing circularity in construction projects as explained by Van den Berg, et al. (2019).

The practical contribution of this research for DV is an outline of five recommendations on which they should focus when aiming to integrate circularity in their construction projects from an organizational viewpoint.

5.2. Discussion of recommendations

This research stresses the importance of accurately formulating feasible and detailed circularity ambitions in the initiative phase of projects. Other literature also emphasizes this starting activity of defining circularity among supply chain members and other stakeholders. This is an important aspect in the collaboration tool by Leising, et al. (2017), and the project management framework for integrating circularity by Többen & Opdenakker (2022). Also Kooter, et al. (2021) outline shared circular goals as a prerequisite for setting and realizing circular ambitions. This recommendation also addresses newly found barrier [x4] measurability of circularity, which is also found in other literature as Geisendorf & Pietrulla (2018), and Platform CB'23 (2021a) argue for measurability tools and SMART definitions of project goals.

The second finding of this research is the importance of ensuring a warm handover of project phases throughout the project. The knowledge and reasoning behind the circular ambitions and project goals can be shared implicitly as tacit knowledge. Zhang & He (2016) confirm that tacit knowledge is especially present in the construction industry and agree with this recommendation that a longer possibilities of social interactions increases the chance of handing over this knowledge. Other literature agrees with the findings that project goals can shift in the execution phase (Krane, et al., 2012). For example, site managers can have differing personal, often more traditional, goals (Tengblad, 2012; Zavari & Afshar, 2021). Wuni & Shen (2019) agreed with the need for collaboration between execution team and design team to prevent the execution team will be involved in the assembly of circular construction materials to which they were not acquainted with in the design decision-making. Nevertheless, besides this literature, little research has been conducted on barrier [x2] and the differing dynamics of between people involved in the design and execution phase, and the involvement of the execution phase in the design phase. Furthermore, barrier [x10], the hard handover of project phases was not found in literature either but played an important role in this research. These barriers are therefore interesting for future research.

The third main finding of this research is that it is important to materialize the design early to ensure the circularity outcome of the project. Wuni & Shen (2019) present a similar recommendation of an early design freeze as finalizing the major design decisions early allows for many benefits in the design phase. It should be noted, however, that an early design freeze requires a lot of work early in the design through an early involvement of all relevant project participants as highlighted by Wuni & Shen (2019). This is covered in recommendation 5.

Using standardized solutions and designs throughout projects is the fourth main finding in this research. This finding is widely supported in literature. Anastasiades, et al. (2023) and Dams, et al. (2021) argue for standardization in production to increase application of circularity. Aapaoja & Haapasalo (2014) explain how morphological standardized products and standardized processes go hand in hand and combining them is expected to yield the best results. The aim of this research was to incorporate circularity into the standard way of work, *FLOW*. Therefore, this is in line with the recommendation of Aapaoja & Haapasalo (2014). As all projects are still inherently unique, further research is required on the applicability of the exact amount of standardization in projects.

Lastly, this research advocates for an early involvement of partners in the initiative and design phase. This is in line with various earlier research findings (Briscoe & Dainty, 2005; Vrijhoef, 2011). They stress the benefits of the exchange of knowledge among all parties involved. Various other research agrees with this as well. Anastasiades, et al. (2023) explain how the early involvement of partners such as architects, engineers, and contractors in the conceptual design phase results in a more efficient and circular construction. Al-Werikat (2017) confirms that the early involvement of partners in the initiative phase adds to achieving congruence in ambitions and goals a mutual understanding.

The benefits of early involvement of partners are clear. However, not all partners can be involved at all times as this would make communication lines too complex, and it this has financial implications for partners involved. Therefore, further research on when to involve which contractor is required.

5.3. Limitations of this research

The largest limitation of this research is found in the development of the recommendations. The research framework encompassed 53 barriers which were presented to the interviewees. Of these 53 barriers, 24 were considered notable according to a chosen difference of 50 percentage points between presence in literature and occurrence in practice. To this, a list of ten newly found barriers was added. Finally, of these combined 34 barriers similar patterns in responses and solutions returned for 28 barriers. Subsequently these could be addressed in five lessons learned. This strategy intentionally leaves out possible valuable information twice when reducing the number of barriers from 53 to 24 and then again from 34 to 28. It should be noted that the information on the left out barriers could contain insights that is now disregarded. Also, the impact on the barriers was not quantified by the interviewees. Ultimately, only the occurrence of a barrier in a project added to the perceived importance in the analysis together with personal emphasis of interviewees expressed in the interviews. In retrospect, a weighting of these barriers by using, for example a 5-point Likert scale, would have been more beneficial in order to make the importance of these perceived barriers more quantifiable. A quantified set of barriers helps crafting and substantiating the policy measures proposed (Oluleye, Chan, Olawumi, & Saka, 2023).

Secondly, because of the wide variety of definitions of circularity in the industry, a broad research scope was intentionally crafted at the start of the research. This, in an attempt to form well-rounded arguments on the complex dynamics behind the integration of circularity in the industry. Eventually, this scope turned out to be so broad that it was at the expense of the depth of the research. This issue continued in the depth and specificity of the answers, lessons learned, and ultimately in the recommendations developed.

Thirdly, some of the 53 unique barriers that were identified for this research are in essence somewhat similar. Reflecting upon this list, some barriers could have been merged or simply left out of this research to prevent an unnecessary and unjustified focus on these issues. On top of that, not all barriers are on the same level of detail as some barriers can be considered specified explanations of other barriers such as [2] unfit policy, rules and regulations, and [49] circularity is not effectively incorporated in innovation policies.

Lastly, it is assumed that the phases separated in the *FLOW* methodology are followed sequentially where one phase must be finished before assuming the next phase. Many employees of DV Bouw Hengelo explained that in practice these phases are not as distinctively separated as the *FLOW*-diagram suggests on paper, as the design phase is a much more iterative process.

5.4. Suggestions for future research

One objective of this research was to find the moments and team roles actions in the *FLOW* that have impact on integrating circularity in the design of a construction project, and dynamics behind them. This research culminated into five recommendations for the application of circularity in the standard way of work of DV. Each of these five recommendations requires detailed research to gain a specific understanding of the application in daily practice.

This research is conducted from a contractor's perspective. The interviewees in the case study all emphasized that the governmental policy and regulations such as the subsidies or building codes are important aspects in integrating circularity. However, they noted that these were out of there direct sphere of influence, and they were waiting for the government to steer the market through legislation as mentioned in section 5.3. Future research should look specifically at the regulatory dimension and the interplay between private companies and legislation. From this research, barriers [13] the lack of governmental financial incentives for circularity, [10] development of circularity principles, [49] circularity innovation policies, should for example be researched.

Furthermore, solutions to barriers in the regulatory dimension of the implementation of circularity in the construction design process were barely mentioned in interviews. Many interviewees acknowledged certain barriers to be a problem but did not have adequate solutions for them as they considered them to be outside their direct sphere of influence. They noted that this is the responsibility of governments to develop. As a result of this dynamic, the regulatory dimension did not resurface as lessons learned based on the found barriers. However, this dimension is expected to have a large influence on the direction of the construction industry and the felt need to innovate. Further research must be conducted on the impact of governmental policy on the innovation of the industry and transition towards circular construction.

Lastly, ten barriers were found in practice that were not found in the literature beforehand. These each demand detailed research as these can be specific to the Dutch context since the project phases and its dynamics might be specific for the Dutch industry.

6. Conclusion

The integration of circularity in construction design phases is not easy and straightforward transition due to a plethora of different barriers. The aim of this study was to integrate circularity in the design phase of construction projects at a Dutch construction company by drawing lessons learned from a multiple case study of four construction projects with a circular focus. This done by compiling a list of 53 barriers that were divided into either a technical, social, organizational, economical, or regulatory dimension. These barriers and dimensions were used as a research framework to establish their relevance at construction projects.

The multiple case study entailed a questionnaire about these barriers, a series of semi-structured interviews together and a document analysis. The presence and solution to the barriers that surfaced in this case study were clustered and led to five lessons learned and recommendation on how to deal with these barriers in the future. These lessons learned were subsequently tailored to the standard way of work of the same Dutch construction company.

Also, the difference between frequency of occurrence in literature compared to practice is evaluated which pointed out 24 barriers that occurred notably more in practice compared to their presence in literature. Some barriers that occurred notably more than assumed from literature are the unfit separated project roles in project development, barriers that revolve around the higher costs of reusing salvaged material, lacking governmental incentives and policies, and a lack of knowledge. Beyond the 53 barriers found in the literature, ten other barrier were found in practice. Of these, the most notable were the different execution of the project on site compared to the design in office, too diverse project goals, unfit design sequence for reused materials, hard handover of project phases, and difficult collaboration with governmental organizations.

The following five lessons learned emerged from these findings: 1) To accurately formulate feasible and detailed circularity ambitions at the start of the project; 2) To ensure a warm handover between project phases; 3) To materialize in the design early in the project; 4) To make use of standardized solutions and designs; 5) To involve partners early in the project. Lessons 1 and 4 are widely understood to be of great benefit for circularity by other scholars. Other literature also highlight the importance of lessons 3 and 5, however this requires a significant shift in the emphasis in project phases as the early design phases require more input of partners. Lastly, lesson 2 is new finding as it is not yet widely covered in literature. Not much research on the handovers between phases and from office to execution phase is currently present. However, this did play a significant role in practice and thus requires future research.

Due to the broad scope of this research, the recommendations are not yet easily to be implemented and require a deeper understanding of the ongoing dynamics. The implication of these recommendations on a day-to-day basis must be researched individually. This paper serves as a background to the interconnectedness and presence of barriers and solutions to these barriers in practice.

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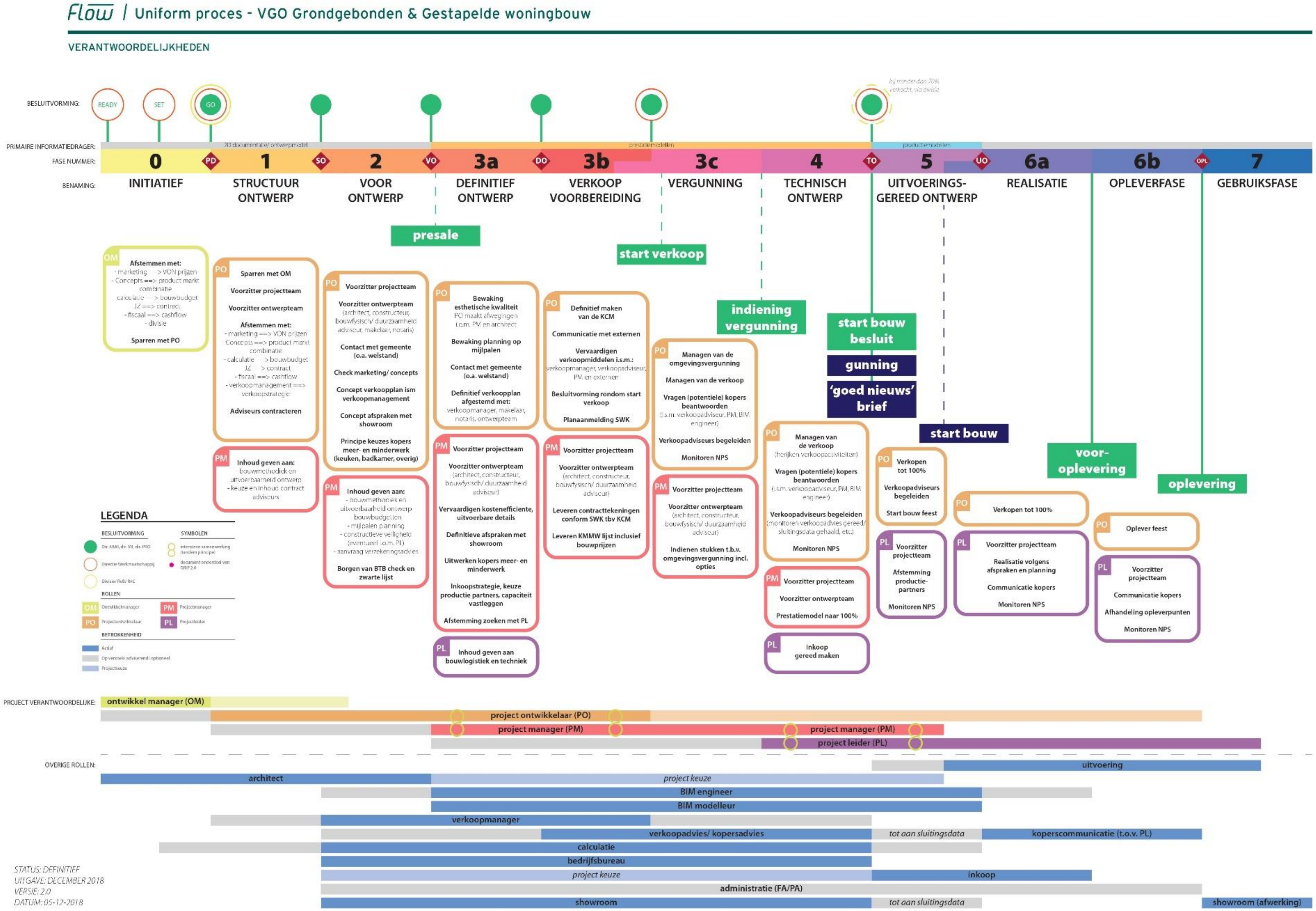
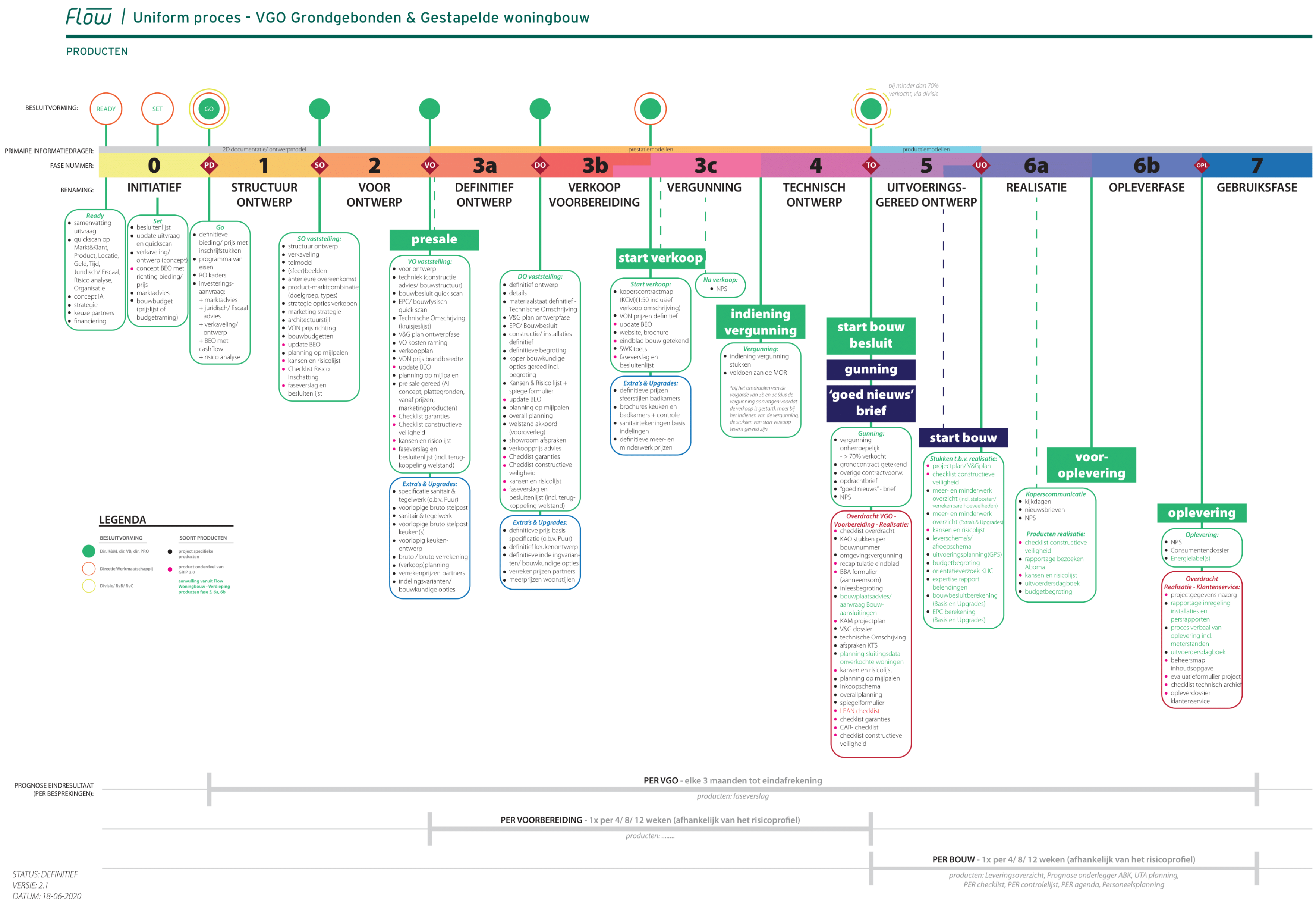
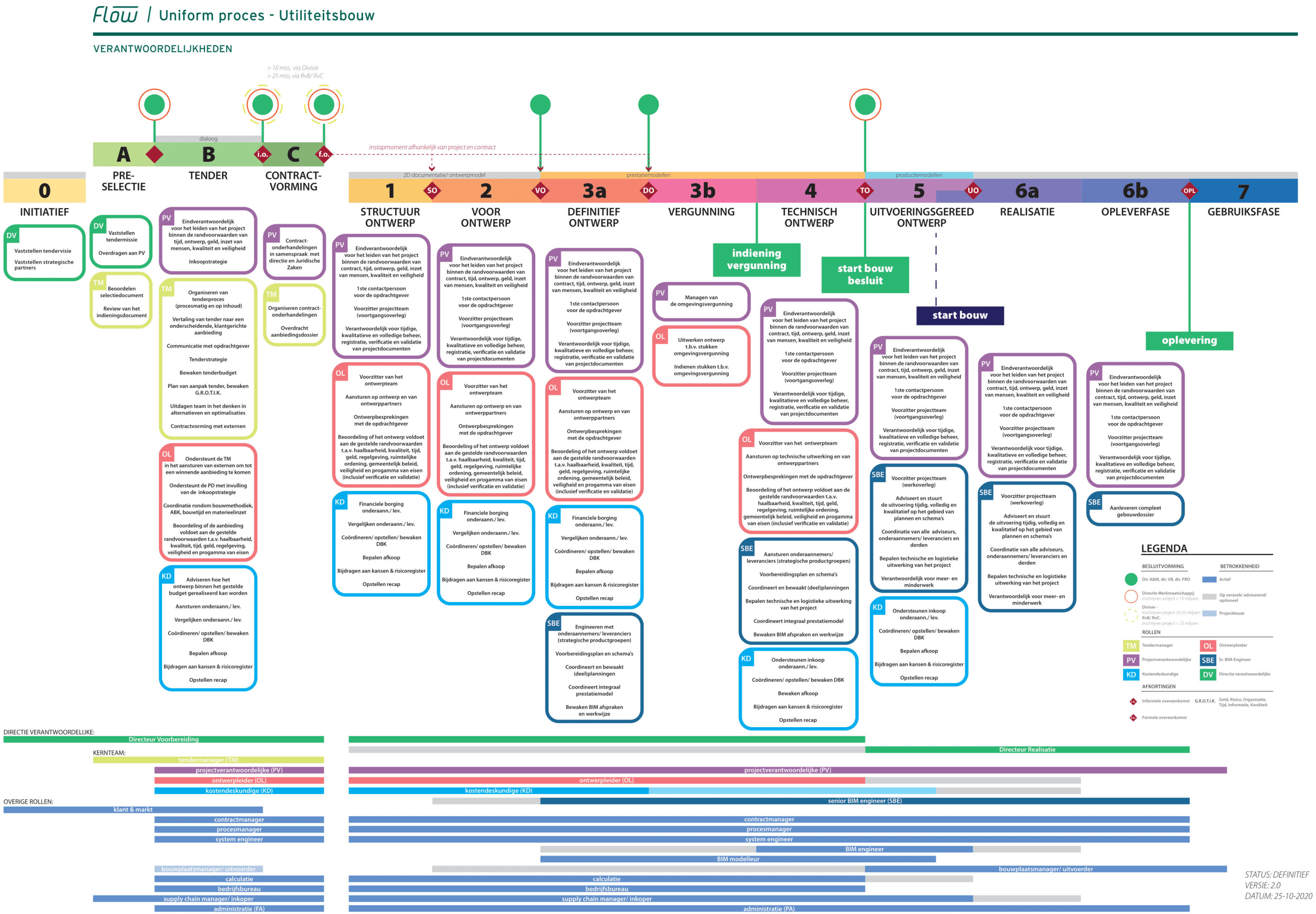
Appendices

Appendix A – FLOW diagram residential construction - Responsibilities

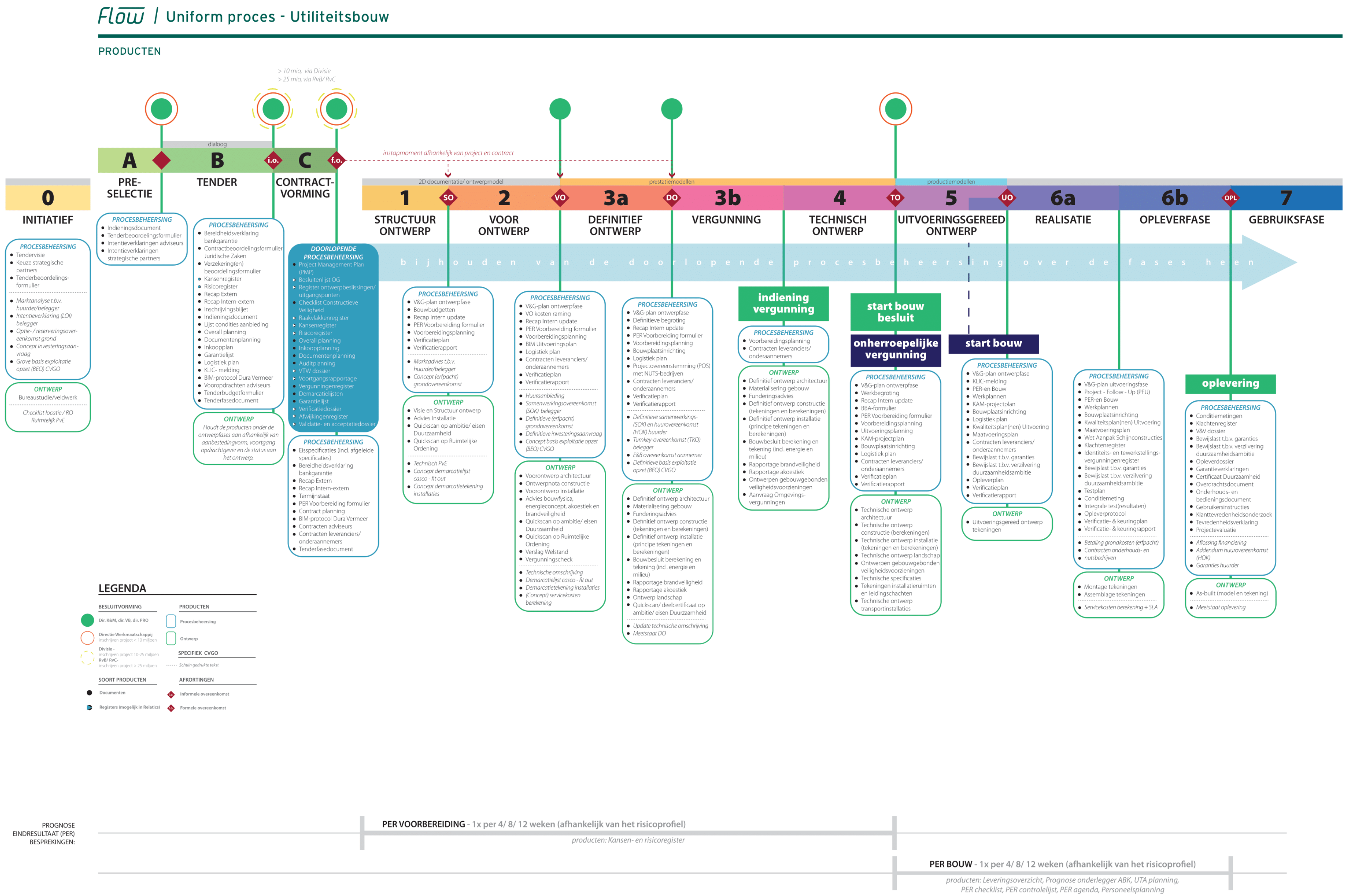




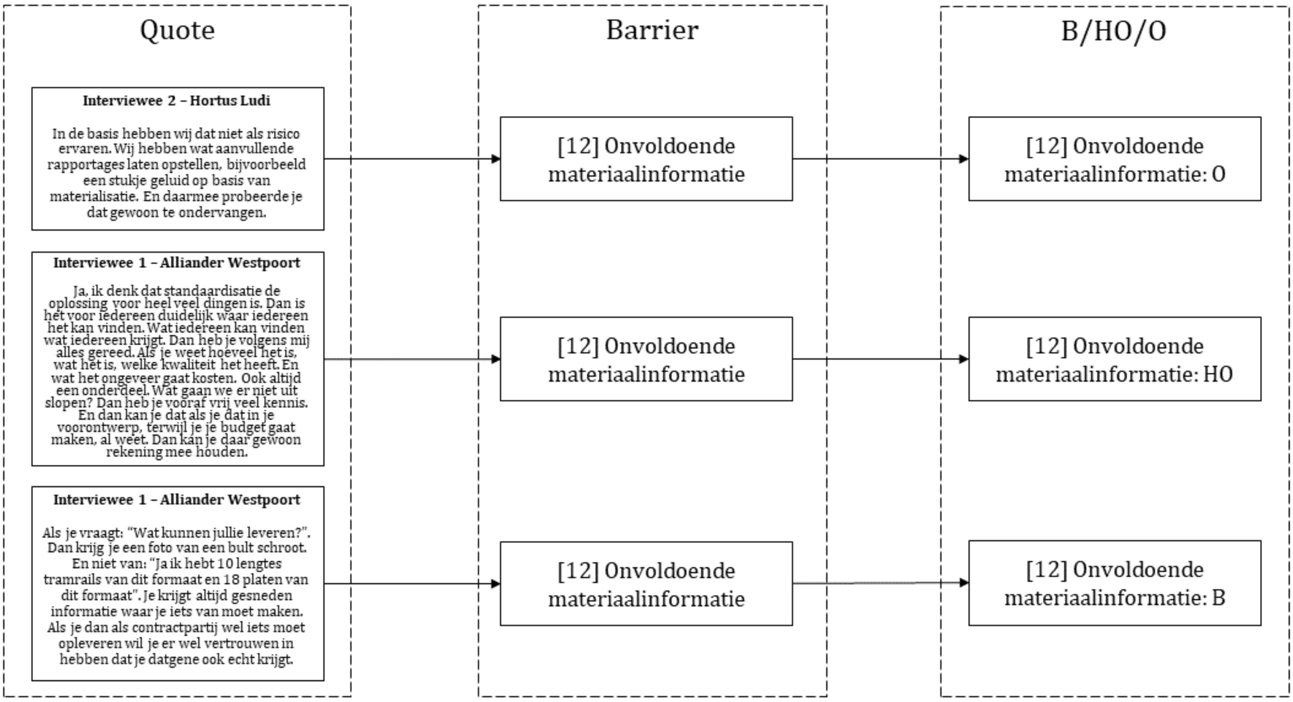
Flow | Uniform proces - VGO Grondgebonden & Gestapelde woningbouw
PRODUCTEN
BESLUITVORMING:
READY
SET
GO
bij minder dan 70% verkocht, via divisie
PRIMAIRE INFORMATIEDRAGER:
2D documentatie/ ontwerpmodel
prestatiemodellen
productiemodellen
FASE NUMMER:
0
PD
1
SO
2
VO
3a
DO
3b
3c
4
TO
5
UO
6a
6b
OPL
7
BENAMING:
INITIATIEF
STRUCTUUR ONTWERP
VOOR ONTWERP
DEFINITIEF ONTWERP
VERKOOP VOORBEREIDING
VERGUNNING
TECHNISCH ONTWERP
UITVOERINGS-GEREED ONTWERP
REALISATIE
OPLEVERFASE
GEBRUIKSFASE
presale
start verkoop
indiening vergunning
start bouw besluit
gunning
'goed nieuws' brief
start bouw
voor-oplevering
oplevering
LEGENDA
BESLUITVORMING
SOORT PRODUCTEN
PROGNOSE EINDRESULTAAT (PER BESPREKINGEN):
PER VGO - elke 3 maanden tot eindafrekening
producten: faseverslag
PER VOORBEREIDING - 1x per 4/ 8/ 12 weken (afhankelijk van het risicoprofiel)
producten: ....
PER BOUW - 1x per 4/ 8/ 12 weken (afhankelijk van het risicoprofiel)
producten: Leveringsoverzicht, Prognose onderlegger ABK, UTA planning, PER checklist, PER controlelijst, PER agenda, Personeelsplanning
STATUS: DEFINITIEF
VERSIE: 2.1
DATUM: 18-06-2020



Flow | Uniform proces - Utiliteitsbouw
VERANTWOORDELIJKHEDEN
0 INITIATIEF
A PRE-SELECTIE
B TENDER
C CONTRACTVORMING
1 STRUCTUUR ONTWERP
2 VOOR ONTWERP
3a DEFINITIEF ONTWERP
3b VERGUNNING
4 TECHNISCH ONTWERP
5 UITVOERINGSGEREED ONTWERP
6a REALISATIE
6b OPLEVERFASE
7 GEBRUIKSFASE
indiening vergunning
start bouw besluit
start bouw
oplevering
LEGENDA
STATUS: DEFINITIEF
VERSIE: 2.0
DATUM: 25-10-2020



STATUS: DEFINITIEF
VERSIE: 2.0
DATUM: 25-10-2020



Using Atlas.ti, the coding strategy indicated above is further categorized into folders, so-called Code Groups. All mentioned barriers in the interviews are categorized into their dimension as indicated in the research framework of Table 1.

Using the coding strategy from Figure 3 above in Atlas.ti returns an overview of quotes that can be revisited from multiple levels. Atlas.ti allows for finding quotes from both the barrier as well as the nature of the quote as barrier (B), Hypothetical Solution (HO), or Solution (O). Retrieving quotes from the barrier number allows for quick matching of similar barrier encounters, solutions, and hypothetical solutions throughout multiple cases.

Appendix F – Presence of barriers in literature and cases

Barriers is experienced when discussed in the interviews or marked in the questionnaire beforehand.

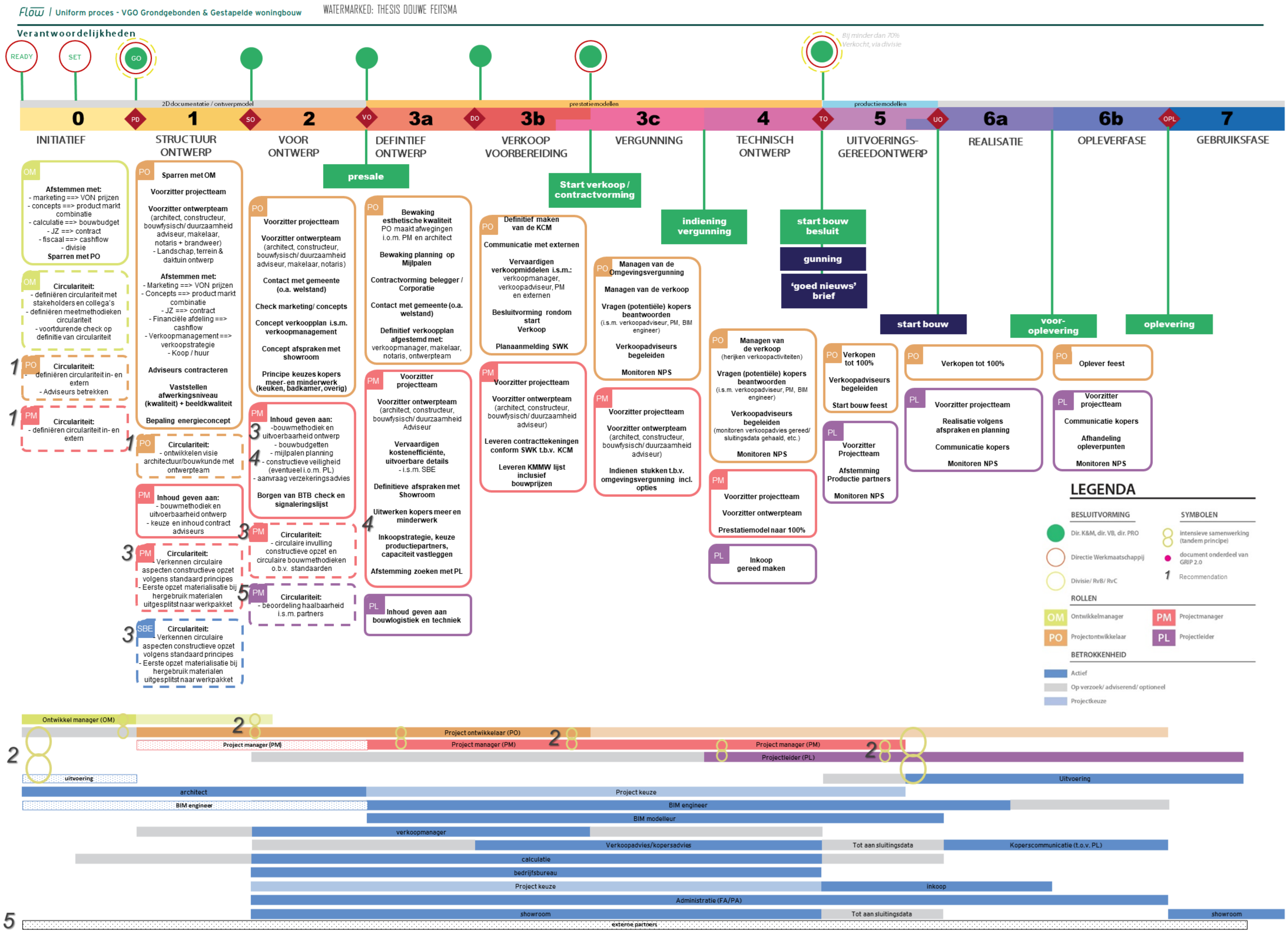
Dimension	#	Barrier	Literature		Cases		0.5																					Case study Interviews				Analysis	Case study Survey				Analysis	Total			
			Frequency	Percentage	Frequency	Percentage	Notable	More present in	Eberhardt, et al. (2019)	Adams, et al. (2020)	Huang, et al. (2018)	Ghaffar, et al. (2020)	Giorgi, et al. (2022)	Guerra & Leite (2021)	Govindan & Hasanagic (2018)	Masi, et al. (2018)	Kanters (2020)	Cruz Rios, et al. (2021)	Arcadis (2022)	Allwood, et al. (2011)	Rose & Stegemann (2018)	Mackenbach, et al. (2020)	Hossain, et al. (2020)	Gálvez-Martos, et al. (2018)	Iacovidou & Purnell (2016)	Rahla, et al. (2021)	Wuni (2022)	Alliander Westpoort	Hortus Ludi	De Zangvogel	Weener XL	Frequency	Alliander Westpoort	Hortus Ludi	De Zangvogel	Weener XL	Frequency	Alliander Westpoort	Hortus Ludi	De Zangvogel	Weener XL
Technical	1	Uncertain material quality	14	74%	4	100%	No		x	x		x	x		x	x	x	x	x	x	x		x		x		x	x	x	x	x	4	x	x	x	x	4	x	x	x	x
Technical	12	Accurate information of materials is not available	8	42%	3	75%	No								x	x		x	x		x		x		x		x	x		x	x	3	x		x	x	3	x		x	x
Technical	14	Existing building stock are complex and do not have circularity principles	7	37%	1	25%	No			x			x					x			x				x	x	x					0	x				1	x			
Technical	24	Reused materials increase the complexity in design	5	26%	3	75%	No			x										x		x				x	x	x				1	x	x		x	3	x	x		x
Technical	37	Lack of sufficient list of material standards	3	16%	3	75%	Yes	Practice					x												x		x	x	x	x		3	x	x	x		3	x	x	x	
Technical	38	Lack of skill by employees in the industry	3	16%	3	75%	Yes	Practice							x										x		x		x	x		2			x	x	2		x	x	x
Technical	41	New circular materials are not available	3	16%	3	75%	Yes	Practice									x								x		x			x		1	x			x	2	x		x	x
Technical	51	No year round supply of biobased resources	1	5%	2	50%	No												x													0			x	x	2			x	x
Technical	52	Transition materials not applied	1	5%	0	0%	No												x													0					0				
Social	4	Lack of knowledge of circularity in the industry	10	53%	4	100%	No		x	x			x	x	x		x	x	x				x				x	x	x	x	x	4	x	x	x	x	4	x	x	x	x
Social	8	Lack of awareness of circularity in the industry	8	42%	3	75%	No		x	x			x	x	x	x							x				x		x		x	2	x				1	x	x		x
Social	15	Higher perceived risks	6	32%	4	100%	Yes	Practice					x					x	x		x		x				x	x	x	x	x	4	x	x		x	3	x	x	x	x
Social	16	Resistance to change	6	32%	3	75%	No							x		x	x	x				x					x	x		x	x	3	x		x		2	x		x	x
Social	18	Consumer perception of reused and bio based material is flawed	6	32%	2	50%	No								x			x	x				x		x		x			x	x	2			x	x	2			x	x
Social	23	Poor leadership and management	5	26%	2	50%	No								x	x						x	x				x			x		1			x	x	2			x	x
Social	25	No commonly accepted definition of circularity	5	26%	3	75%	No		x				x				x						x				x		x	x	x	3			x	x	2		x	x	x
Social	29	Mistrust between stakeholders	4	21%	2	50%	No		x							x				x							x	x			x	2	x			x	2	x			x
Social	32	No established best practices	4	21%	3	75%	Yes	Practice										x			x				x		x		x	x		2		x	x	x	3		x	x	x
Social	53	Aesthetics and commercial desirability	1	5%	3	75%	Yes	Practice																	x			x	x		x	3	x			x	2	x	x		x
Organizational	7	Misalignment between short-term goals and long-term benefits	9	47%	3	75%	No		x	x				x	x	x			x			x	x				x	x		x		2	x		x	x	3	x		x	x
Organizational	9	Lack of collaboration between stakeholders	8	42%	2	50%	No		x	x						x		x		x		x	x				x			x	x	2					0			x	x
Organizational	11	Time constraints	8	42%	2	50%	No					x		x	x			x		x	x				x		x	x				1	x			x	2	x			x
Organizational	17	Lack of supply chain infrastructure for recovery, refurbishment, and storage	6	32%	3	75%	No			x								x		x	x				x		x	x		x		2	x		x	x	3	x		x	x
Organizational	19	Insufficient proven circular business models and difficult to apply	6	32%	4	100%	Yes	Practice					x	x	x	x							x				x	x	x	x		3	x	x		x	3	x	x	x	x
Organizational	20	Complex a fragmented supply chain	5	26%	2	50%	No		x	x											x	x			x							0	x			x	2	x			x
Organizational	22	Project-based practice	5	26%	4	100%	Yes	Practice	x	x			x									x					x	x	x	x		3	x			x	2	x	x	x	x
Organizational	27	Ownership issues	4	21%	1	25%	No								x	x						x	x									0				x	1				x
Organizational	28	Time constraints for deconstruction	4	21%	2	50%	No											x		x	x				x				x		x	2				x	1		x		x
Organizational	43	Construction process does not allow for interdisciplinary interactions	2	11%	1	25%	No						x														x					0				x	1				x
Organizational	45	Organizational structure makes it difficult to apply circularity in firm	2	11%	2	50%	No								x												x	x				1	x	x			2	x	x		
Organizational	47	Lack of information exchange system between different stakeholders	2	11%	3	75%	Yes	Practice								x											x	x	x			2				x	1	x	x		x
Organizational	50	Current roles in project development unfit	1	5%	4	100%	Yes	Practice									x											x		x		2	x	x		x	3	x	x	x	x
Economical	3	Market of virgin materials is better developed	12	63%	3	75%	No						x		x	x	x	x	x	x	x		x	x	x		x	x		x	x	3	x		x	x	3	x		x	x
Economical	5	High upfront costs	10	53%	4	100%	No					x	x	x	x	x		x		x	x				x		x	x	x	x	x	4	x	x	x	x	4	x	x	x	x
Economical	6	Absence of a clear business case	9	47%	3	75%	No		x	x		x	x	x	x			x					x				x		x			1	x			x	2	x	x		x
Economical	21	Higher streams of logistics expected	5	26%	3	75%	No					x	x					x				x			x			x	x		x	3	x	x		x	3	x	x		x
Economical	26	Difficulties in establishing correct price of products in supply chain	5	26%	4	100%	Yes	Practice							x							x	x		x		x	x	x	x		3	x	x		x	3	x	x	x	x
Economical	30	Remanufacturing is time-consuming and labor-intensive	4	21%	3	75%	Yes	Practice							x		x								x		x	x		x	x	3	x			x	2	x		x	x
Economical	31	Low value of many construction products at end-of-life	4	21%	2	50%	No			x													x		x		x			x		1				x	1			x	x
Economical	34	Banks and investors regard circular business models as riskier	3	16%	1	25%	No						x				x										x					0				x	1				x
Economical	36	Design fees are higher when design is built around existing components	3	16%	3	75%	Yes	Practice						x						x							x					0	x		x	x	3	x		x	x
Economical	39	Recertification reclaimed components for re-use is expensive and time-consuming	3	16%	3	75%	Yes	Practice												x					x		x	x		x		2	x		x	x	3	x		x	x
Economical	42	Insufficient internalization of external costs	2	11%	3	75%	Yes	Practice							x	x												x	x			2	x			x	2	x	x		x
Economical	44	Owner or client has tight budget constraints	2	11%	4	100%	Yes	Practice					x														x	x		x	x	3	x	x	x		3	x	x	x	x
Economical	48	Mismatch between costs labor and materials	2	11%	3	75%	Yes	Practice									x										x	x			x	2	x	x		x	3	x	x		x
Regulatory	2	Unfit policy, rules, and regulations	13	68%	3	75%	No					x	x	x	x	x	x	x	x	x		x	x		x		x	x		x		2		x	x		2	x	x	x	
Regulatory	10	Lack of standards for circularity principles	8	42%	3	75%	No				x	x			x	x	x	x					x				x	x	x	x		3		x	x		2	x	x	x	
Regulatory	13	Lack of (governmental) financial incentives to design for circularity	7	37%	4	100%	Yes	Practice		x					x	x						x	x		x		x	x		x	x	3	x	x	x	x	4	x	x	x	x
Regulatory	33	Health & Safety regulations	3	16%	0	0%	No					x								x							x					0					0				
Regulatory	35	Lack of flexibility in building codes and regulations	3	16%	2	50%	No										x		x								x					0	x	x		0	2	x	x		
Regulatory	40	Unfit contract forms for circularity	3	16%	2	50%	No		x									x									x	x		x		2	x				1	x		x	
Regulatory	46	Competition legislation inhibits collaboration between companies	2	11%	2	50%	No									x											x	x				1	x			x	2	x			x
Regulatory	49	Circularity is not effectively incorporated in innovation policies	1	5%	3	75%	Yes	Practice								x																0		x	x	x	3		x	x	x
Organizational	x1	Ambition client	0	0%	4	100%	Yes	Practice																				x	x	x	x	4					0	x	x	x	x
Organizational	x2	Different execution on site compared to designed in office	0	0%	4	100%	Yes	Practice																				x	x	x	x	4					0	x	x	x	x
Organizational	x3	Project goals too diverse	0	0%	3	75%	Yes	Practice																					x	x	x	3					0		x	x	x
Technical	x4	Measurability of circularity	0	0%	2	50%	No																						x	x		2					0		x	x	
Organizational	x5	Different moments of entering the design phase	0	0%	1	25%	No																								x	1					0				x
Social	x6	Unrealistic expectations of performance	0	0%	2	50%	No																						x	x		2					0		x	x	
Organizational	x7	Traditional design order	0	0%	4	100%	Yes	Practice																				x	x	x	x	4					0	x	x	x	x
Organizational	x8	Difficult collaboration with governmental organizations	0	0%	3	75%	Yes	Practice																				x	x		x	3					0	x	x		x
Organizational	x9	Difficult to live up to ambition	0	0%	1	25%	No																					x				1					0	x			
Organizational	x10	Hard handover between project phases	0	0%	2	50%	No																					x		x		2					0	x		x	

Appendix G – Recommendations with relevance of impacted barriers

Table 10: Overview of recommendations with impacted barriers

Recommendation	Dimension	#	Barrier	Presence in literature	Presence in practice
1. To early formulate feasible and detailed circularity ambitions	Technical	x4	Measurability of circularity	0%	50%
	Social	4	Lack of knowledge of circularity in the industry	53%	100%
		16	Resistance to change	32%	75%
		25	No commonly accepted definition of circularity	26%	75%
		53	Aesthetics and commercial desirability	5%	75%
	Organizational	7	Misalignment between short-term goals and long-term benefits	47%	75%
		22	Project-based practice	26%	100%
		x1	Ambition client	0%	100%
		x3	Project goals too diverse	0%	75%
		x8	Difficult collaboration with governmental organizations	0%	75%
2. To ensure a warm handover of project phases	Social	4	Lack of knowledge of circularity in the industry	53%	100%
		23	Poor leadership and management	26%	50%
	Organizational	11	Time constraints/tights schedules	42%	50%
		50	Current roles in project development unfit	5%	100%
		x2	Different execution on site then designed in office	0%	100%
		x10	Hard handover between project phases	0%	50%
3. To materialize the design in the project	Technical	1	Uncertain material quality	74%	100%
		12	Accurate information of materials is not available	42%	75%
		24	Reused materials increase the complexity in design	26%	75%
	Social	4	Lack of knowledge of circularity in the industry	53%	100%
		15	Higher perceived risks	32%	100%
	Organizational	x1	Ambition client	0%	100%
		x7	Traditional design order	0%	100%
		x8	Difficult collaboration with governmental organizations	0%	75%
	Economical	5	High upfront costs	53%	100%
		21	Higher streams of logistics expected	26%	75%
		30	Remanufacturing is time-consuming and labor intensive	21%	75%
		39	Recertification reclaimed components for re-use is expensive and time-consuming	16%	75%
4. To make use of standardized solutions and designs	Technical	12	Accurate information of materials is not available	42%	75%
		37	Lack of sufficient list of material standards	16%	75%
	Organizational	x1	Ambition client	0%	100%
		x8	Difficult collaboration with governmental organizations	0%	75%
	Economical	26	Difficulties in establishing correct price of products in supply chain	26%	100%
		30	Remanufacturing is time-consuming and labor-intensive	21%	75%
5. To involve partners early in the project	Technical	1	Uncertain material quality	74%	100%
	Social	32	No established best practices	21%	75%
		53	Aesthetics and commercial desirability	5%	75%
	Organizational	17	Lack of SC infrastructure for recovery, refurbishment, and storage	32%	75%
		22	Project-based practice	26%	100%
	Economical	21	Higher streams of logistics expected	26%	75%

Appendix H – Visual representation of applied circularity recommendations on FLOW



Appendix I – Glossary of Terms

Table 11: Glossary of Terms

Dutch	English
Ontwikkelmanager (OM)	Development manager (DM)
Projectontwikkelaar (PO)	Project developer (PD)
Projectmanager (PM)	Project manager (PM)
Projectleider (PL)	Construction project manager (CPM)
Werkvoorbereider/Senior BIM Engineer (SBE)	Senior BIM-engineer (SBE)
Bouwplaatsmanager/Uitvoerder	Site manager (SM)
Iniatief	Initiation
Schetsontwerp (SO)	Conceptual design (CD)
Voorontwerp (VO)	Preliminary design (PD)
Definitief ontwerp (DO)	Detailed design (DD)
Technisch ontwerp (TO)	Technical design (TD)
Uitvoeringsgereed ontwerp (UO)	Final design (FD)
Realisatie	Execution
Woningbouw	Residential construction
Utiliteitsbouw	Non-residential construction
Kruislaaghout	Cross Laminated Timber (CLT)
Bouwsector	Building Construction Industry (INDUSTRY)
Welstandscommissie	Architectural review board