Digital Twins as Enabler in Circular Construction Management

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I Preface

This master's thesis presents a one-year research project that is part of the Design and Construction Management graduation lab of the MSc programme Management in the built environment, at Delft University of Technology. I chose this graduation lab as an extension of my previous study and work in the field of architecture design, and aim to contribute to a more circular built environment under the trend of digitalization.

Throughout the research process, a lot of people contributed to the research in different ways. I firstly want to thank my two mentors, Catherine and Tuuli, thanks for inspiring and guiding me every time I got lost in the research. And thanks for all the feedback, questions, and talking in all the meetings and presentations. I learned a lot from you, both in the content of this thesis, but also the ways of doing research.

I also want to thank the interviewees and focus group participants who were involved in this thesis. It was always hard to reach stakeholders, but luckily you replied me and gave very helpful information. The thesis couldn't be done without your kind help.

Doing a master's thesis during the COVID-19 period is definitely not an easy task, especially at the same time I was also busy finding my first job after graduation. The research tasks and job interviews always made me exhausted. Luckily I always have my friends, Yadan Luo, Lingkong Yin, Ziqi Zhang, Jinjie Mao, Yun Sun, Yujie Liu, Ning Cai, and others by my side, by talking, traveling, studying together, and meeting on zoom at midnight to accompany each other, etc. I also want to thank two other guys, Putthipong Assaratanakul and Krit Amnuaydechkorn, your work encouraged me a lot and made my days.

Especially, I want to thank my parents, although they don't speak English so they probably can't read this report and this preface. But they are the ones who always support my decisions unconditionally and finance my study and life in the Netherlands. I haven't met you for two years due to the pandemic, but I believe we will meet soon.

My student life is reaching the end. I believe the two-years study at TU Delft is a treasured time in my life. I stepped out of my comfort zone and learned a lot of new things. I'm happy to explore my views and believe they are helpful in my future life.

II Glossary

Digital Twins (DT): DT is the virtual representation of a physical product. This concept consists of four parts: physical product, virtual product, connected data that ties the physical and virtual product, and the simulation capacity. In practice, the most common working flow is starting with building a digital model in BIM at the beginning of the design stage, which will be complete at the end of construction. Later, sensors and data points would be added to the building and connected with the model to form a DT model of the building to optimize maintenance and operation (Tao et al., 2017).

Circular economy (CE): Circular economy is an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes (Kirchherr et al., 2017). The circular economy model tries to keep the products and materials ‘in flow’ by means of effective and smart re-use strategies, therefore, reducing the use of virgin materials and negative environmental impacts (Mirata, 2004).

Circular construction (CC): Circular construction is defined as the development, use and reuse of buildings, areas and infrastructure without unnecessarily exhausting natural resources, polluting the living environment, and affecting ecosystems. Construction in a way that is economically sound and contributes to the well-being of humans and animals. Here and there, now and later (Circular construction economy, 2018).

III Abstract

With the increasing attention on circularity and digitalization in the built environment, Digital Twins (DT), as a means of linking the digital world and real-world data, is considered as an enabler of circular construction (CC) and dealing with the related societal challenges, such as slowing the material loop, optimizing the decision-making, reducing waste, and lowering the overall cost. Despite these benefits, the application of DT-based CC is still at the very beginning stage resulting in some gaps to be addressed, such as the lack of discussion on the whole process of building the DT model, the fragmented application of the DT concept across the project life cycle, and the lack of a framework in implementing DT in assisting CC.

Therefore, this thesis aims to analyze the role of DT and CC in the project life cycle and to develop a framework for implementing DT technologies in realizing CC. A qualitative methodology is applied and divides the research into three phases: theoretical research, empirical research, and synthesis. A systematic literature review is conducted to develop the knowledge framework of applying DT in CC. Focus group and case study are used in adapting the knowledge framework into implementation by integrating stakeholder perspectives. In the end, a DT-based CC management framework is proposed for benefiting circular project management.

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Executive Summary

1. Introduction

Context

The attention on circularity in the built environment has increased in the last two decades due to the huge environmental impact and ineffective consumption from the construction industry(UNEP, 2016). According to Solís-Guzman et al. (2009), 35% of the waste to landfill across the world is generated by the construction sector. In the Netherlands, many people hold the impression that it has an almost circular construction sector because the recycling rate of the construction and demolition waste (C&DW) is 95%. However, it's not the case, only 3% of them are upcycled and returned to building construction, while the rest went to civil engineering, functioning as road base and filter materials. Therefore, the construction industry can hardly be called circular with the use of secondary materials only consisting of 3% to 4% of the total consumption (Schut et al., 2016). On the other hand, the increasing population and their demands also lead to the scarcity of resources and a lot of them can be lost for future use (Benton & Hazell, 2013).

The increasing demand and decreasing supply lead to the recognition that it is urgent to pursue slowed and even closed resource flow, which is the concept of CE (European Commission, 2016; Ludeke-Freund et al., 2018). CE in the construction industry Is further called CC and consists of three basic ideas: reduce, reuse, and recycle. This means it is crucial to managing C&DW to avoid downcycling (e.g. crushing concrete for road foundation), landfill, or incineration (Ghaffar et al.,2020; Ghisellini et al., 2018). At the same time, it is also important to increase the productivity and value of materials, environmentally and economically (Adams et al., 2017). In this sense, the existing linear economic model of "take, make and dispose of resources" is not applicable anymore in CC because it works based on a huge raw material input (Mangialardo & Micelli, 2018; EMF, 2015). It also increases the companies' exposure to risks and decreases the competitive edge (McKinsey, 2013).

Digitalization has been seen as a crucial enabler of CC under the context of Industry 4.0 due to its strengths in data visualization and intelligence (Antikainen et al., 2018). Among the diverse digital technologies, Digital Twin (DT), a mean of linking the digital world and real-world data, is considered helpful in dealing with the societal challenges related to CC, such as slowing the material loop, optimizing the decision-making, improving the building performance, reducing waste, lowering the overall cost, and supporting the sustainable business model (Rocca et al.,2020; Khajavi et al., 2019; Kyrö et al., 2019; Boje et al., 2020; Mellado & Lou., 2020).

The notion of DT firstly came from the manufacturing industry where it is quite developed, it consists of four parts: physical product, virtual product, connected data that tie the physical and virtual products, and simulation capacity to make the model active (Tao et al, 2017; Focus group, 2021). There is no single software called DT, it consists of a set of technologies, including cloud computing, building information models (BIM), simulation, Internet of Things (IoT), 3D scanning, and material passport□Tobias, 2019; Tobias, 2020).

In the construction industry, the DT concept exists at three levels: building, city, and material. Building a DT model typically begins with BIM, which is the digital representation of the building. While the two concepts of BIM and DT are often confused. There are more elements in DT, such as simulation capacity, sensor networks, social systems, and urban artifacts beyond the scope of buildings, thus requiring a holistic approach that takes factors in dynamic data at different levels into account (Boje et al., 2020). At the building level, the most common working flow in practice is starting with building a digital model in BIM at the beginning of the design stage, which will be complete at the end of construction. Later, sensors and data points would be added to the building and connected with the model to form an active DT model of the building to optimize maintenance and operation. At the urban level, city scale information can also be gathered by IoT sensors to build a DT model of the city, which is the basis of ‘smart city’ (ARUP, 2019). The information all the way down to the components and materials can be used in the material passport to match the resources at a macro level. It partially overlaps with building DT but the scope goes beyond the latter (Benachio et al., 2019).

Using DT technology in assisting circular construction management, which is the DT-based CC, is expected to facilitate circularity through intelligent construction processes and smart life cycle management. To be more specific, cloud computing technology allows the creation of integrated platforms within projects and across projects to increase the accessibility of data at the city level and optimizes collaboration within the projects (Rocca et al., 2020; ARUP, 2019; Eadie et al., 2013). BIM, construction simulation, 3D scanning, and IoT sensor networks provide tools in supporting the circular design and its realization (Mellado & Lou., 2020; Adams et al., 2017; Pagoropoulos et al., 2017). Material passport balances the supply and demand and thus maximizes reuse and minimizes waste (Patterson & Ruh, 2019; Ghaffar et al., 2020). These technologies’ benefits are interrelated and can enhance each other. The implementation of DT-based CC consequently further benefits the built environment through improved life cycle cost, higher built asset resilience, reduced environmental impact, optimized communication of stakeholders (Boje et al., 2020). Some efforts have already been made in practice, for instance, BIM has been widely used in design and construction in the past decades. IoT has been used in maintenance and operation in the past years (ARUP, 2019). While material passports also started to be applied in some representative projects (CE100, 2016).

Problem statement

Despite the benefits and efforts of applying DT-based CC, only limited research has been done so far concerning the value of DT in circularity ((ARUP, 2019; Eadie et al., 2013). As the trends of digitalization and circularity continue to grow in the market, there are some gaps needing to be filled.

Firstly, in the current construction industry, the concept of ‘DT’ is restricted to the traditional meaning, which is the building-level DT. This limits the application of DT to the usage stage. However, the embedded technologies in the DT concept all positively affect CC and, therefore, worth being discussed together. Secondly, insufficient awareness and capital lead to the limited and fragmented application of the DT concept across the project life cycle. Thirdly, in order to maximize DT’s benefits, a framework in implementing it in CC is required.

Research objective

To sum up, this research aims to analyze the role of DT and CC in the project life cycle and to develop a framework for implementing DT-based CC.

Research question

Main research question

“How can Digital Twins technologies be used in improving circular construction management?”

Sub questions

SQ1: What is the role of circularity in the built environment?
SQ2: What DT technologies are able to assist CC and why?
SQ3: How to implement DT technologies in realizing CC?

Conceptual framework

Following the research questions, the research is further divided into three steps. As shown in Figure I. The three different colors in the diagram represent the three SQs. SQ1 aimed to understand the role of CC in the built environment, including its meaning and assessment criteria. SQ2 illustrated the role of DT in the project life cycle on the one hand and explained why DT can be used in benefiting CC. SQ3 was answered by an implementation framework, which worked as a catalyst in the process of using DT in achieving CC. The implementation framework was proposed by synthesizing the theoretical and empirical contributions.

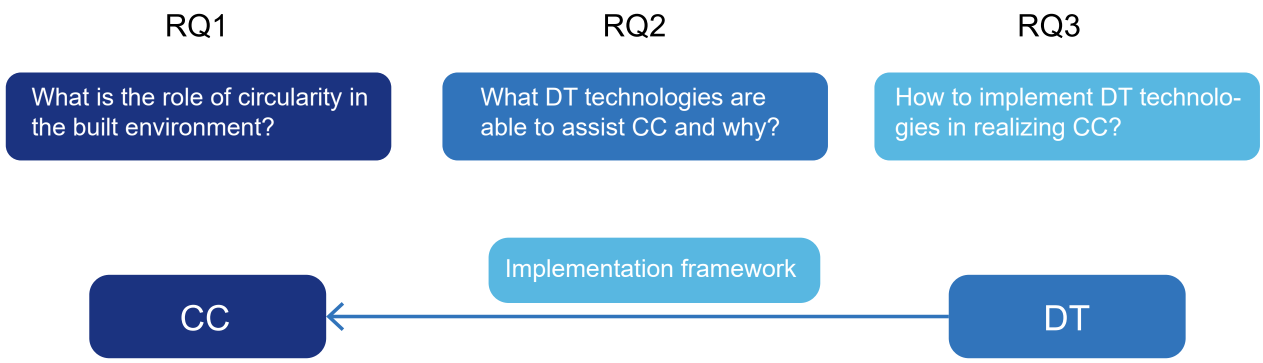


Figure I: Conceptual framework (own illustration)

2. Methodology

This study is based on a qualitative research method, which emphasizes an inductive approach to the relationship between theory and research and aims to gain an understanding of the social world through an examination of the interpretation from its participants (Bryman, 2016). Two stages of research, followed by a synthesis section, are designed to answer the research questions step by step. The methods applied are shown in Figure II, in which blue texts represent data collection approaches.

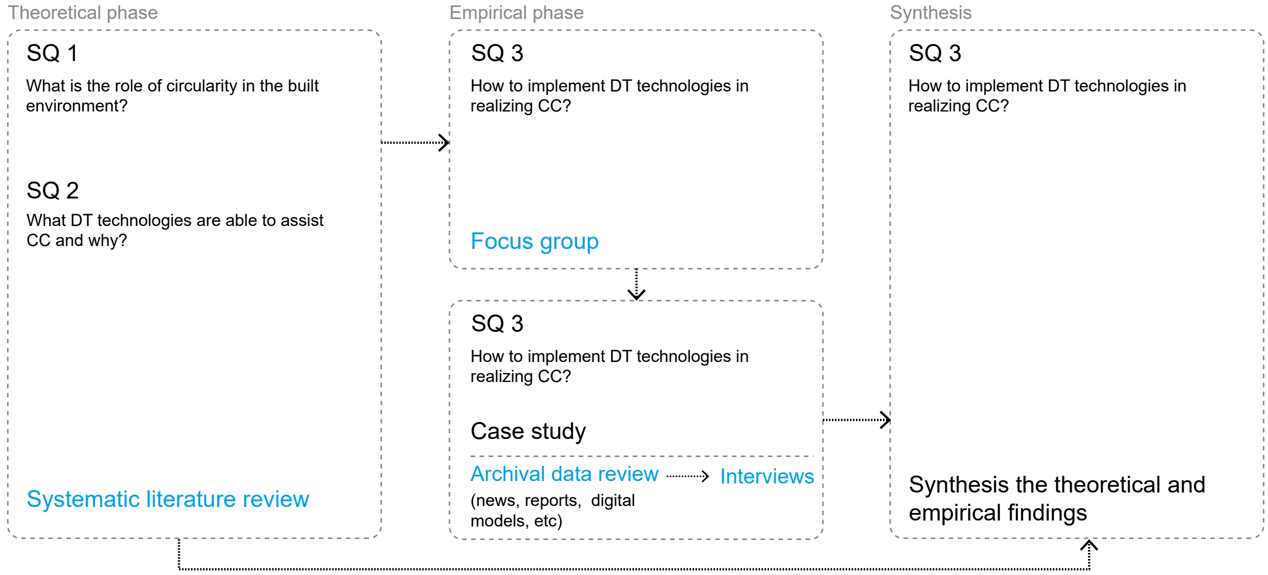


Figure II: Methodology (own illustration)

Theoretical research

The theoretical method involves the creation of a theoretical system of analysis based on published sources for how groups of concepts evolve over time and relate to each other (Esterson, 2003). The objective of theoretical research is to address research SQ1 and SQ2. In order to do this, firstly, a systematic literature review, which is usually used to generate unbiased and comprehensive accounts of the literature, of journals, books, and reports, was conducted for the following concepts: 1) CC's role across the project life cycle, 2) assessment criteria of circularity, 3) DT technologies' roles across the project life cycle, 4) assessment criteria of DT and 5) the reason why DT technologies can assist CC. The structure of the literature review is shown in Figure III. The secondary data gathered from the literature are essential to building a comprehensive understanding of the existing theoretical knowledge, which acts as a preparation for empirical research (Bryman, 2016). As a result, a knowledge framework of DT-based CC applications was proposed.

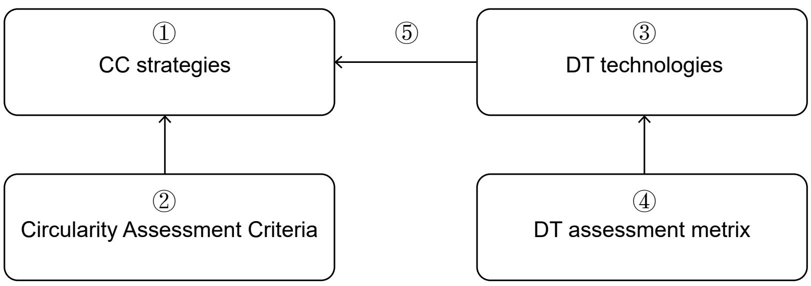


Figure III: Structure of the systematic literature review (own illustration)

Empirical research

The empirical method aims to understand and produce knowledge and focuses on formulating explanations of past conditions (Barendse et al., 2012). The empirical research in this thesis aims to answer SQ3 and includes two steps. The first step is to discuss the theoretical finding, which is the knowledge framework, with relevant experts for their practical inputs in refining and implementing it. The second step is to further develop the implementation framework by conducting a case study.

Focus group

The knowledge framework was put in a focus group workshop, where four experts in the field of DT and CC commented on the structure and content of it and suggested how it could be adjusted in implementation. Suggestions were used in reflecting and improving the knowledge framework, as well as inspiring the implementation framework development. As a result, a management framework canvas was delivered.

Case study

After the focus group, a case study was conducted. There are two objectives of the case study, the first one is to examine the application of the DT-based CC in the real case by reflecting on the knowledge framework from the theoretical research. The second objective is to learn from the case and inspire the implementation framework.

The selection of the case is based on criteria that both DT technologies and CC principles should be applied. Several possible cases are pre-selected, after a preliminary data collection of the cases, Leishenshan hospital (Figure IV) was selected for further research.

Figure IV: Leishenshan Hospital (Provided by CASDI)

Project name: Leishenshan Hospital
Location: Wuhan, China
Client: Wuhan municipality
Architect: CSADI
Contractor: China Construction Third Engineering Bureau Co. Ltd
Year of construction: 2020
Area: 75000 m²
Development type: New built
Main function: Hospital

Data were gathered by two methods. Firstly, an archival data review was conducted to get an overview of the case. Archival data in qualitative research includes personal documents, official documents, mass-media outputs, and internet resources. Under the context of this study, news, reports, and drawings of the projects were collected and analyzed. Afterward, the unclear information and knowledge gaps were answered by organizing semi-structured interviews with the relevant stakeholders. The relatively unstructured nature of semi-structured interviews and its capacity to provide insights into how the participants view the world is crucial to the research (Bryman, 2016). The management framework canvas delivered from the focus group was used in analyzing the case. The findings provided practical inputs to answering SQ3 and further developed the implementation framework.

Synthesis

The knowledge framework, together with the practical contribution from the case study were synthesized to the DT-based CC management framework, as figure V shows. Then, the management framework was analyzed from different perspectives to formulate the answer to SQ3, which is how to implement DT technologies in realizing CC?

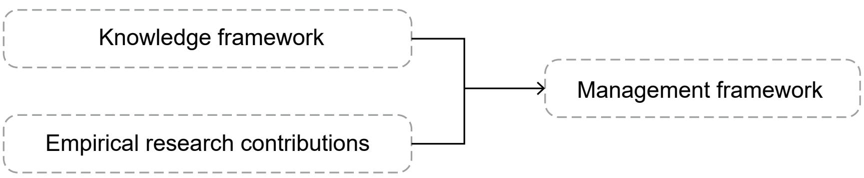


Figure V: Synthesis of the research findings (own illustration)

3. Findings

Theoretical research

After a systematic literature review, the correlation between DT technologies and CC principles is revealed as shown in the knowledge framework (Figure VI).
It gives an overview of which CC principles can be assisted by which DT technologies, as well as the reasons behind that (reference for the reasons see Appendix I). It also works as a knowledge basis for further implementation framework development.

(light cell)	Why this DT technology can assist this CC principle
(grey cell)	Not applicable

	Cloud computing	Material pas
Circular business model	Integrating circular intention across the project life cycle	Supporting circular busi across sectors and proj
Integrate CE regulation and market development	Optimizing decision-making by increasing awareness of circularity	
Integrate circular principle early in the project	Increasing awareness of circularity by providing revevant reference projects	Integrating circular inte the beginning of the pr
Collaboration	Enabling effective and efficient communication within the project organization	Enabling effective and communication cross s projects
Balance supply and demand	Supporting the redistribution of the resources	Matching the resources different sectors and pr
Procure and use secondary materials	Recording and providing materials' information	Recording and providi information
Specify recycled/reclaimed material		
Design for disassembly		
Design for standardisation		
Design for adaptability		
Off-site construction		Providing materials' info assembly and suppliers
Use less materials/Optimize material use		
Evaluate the state and value of the materials		Recording and providin information for evaluatio
Predict the value and reuse potential of materials at the end-of-life stage		
Minimize waste	Minimizing rework by scheduling management	Recording materials' inf design optimization
Increase the lifespan		Recording and providin information
Predictive maintenance		
Selective demolishment		
Reuse of materials and components after end of life	Supporting the redistribution of the resources	
On-site sorting of demolition waste		
Upcycling of materials		
Close-loop recycling		
Adaptive refurbishment		Benefiting reusing mater existing builidngs

Figure VI: DT-

ssport	BIM	Construction Simulation	IoT (Active DT model)	3D scanning
iness model ects	Integrating diverse circular requirements in design			
ntion from ojects				
efficient ectors and	Enabling effective and efficient communication within the project organization	Enabling effective and efficient communi-cation between certain stakeholders (contractor, suppliers,engineer)	Enabling effective and efficient communi-cation betweem certain stakeholders (operators and users)	
s between rojects				
ng materials'				
	Working as supporting platform for storing materials'information			
	Providing technical support for circular design and its realization	Supporting the realization of the design		
rmation of				
	Optimizing design	Simulating the construction process to minimize mistakes and reworks		
g materials' on			Providing active information of materials	
	D-DAS predicts the value of the materials			
ormation for	Optimizing design	Simulating the construction process to minimize mistakes and reworks	Facilitating energy efficiency by moniroting the interior environment	
g materials'	D-DAS predicts the value of the materials		Providing active information of materials	
	Working as supporting platform for storing materials'information			
			Providing active information of materials	
rial from	Supporting design and reuse of materials	Supporting the realization of the design	Providing active information of the building's condition	Duplicating the building's condition precisely

-based CC knowledge framework (own illustration)

Empirical research

In order to adapt the knowledge framework into practice, a focus group workshop was conducted. Based on the ideas generated from the workshop, stakeholder perspective is necessary for implementing the knowledge framework. Therefore, in the implementation framework canvas (Figure VII), the cells that are filled with reasons in Figure VI are left blank for adding relevant stakeholder perspectives in further research.

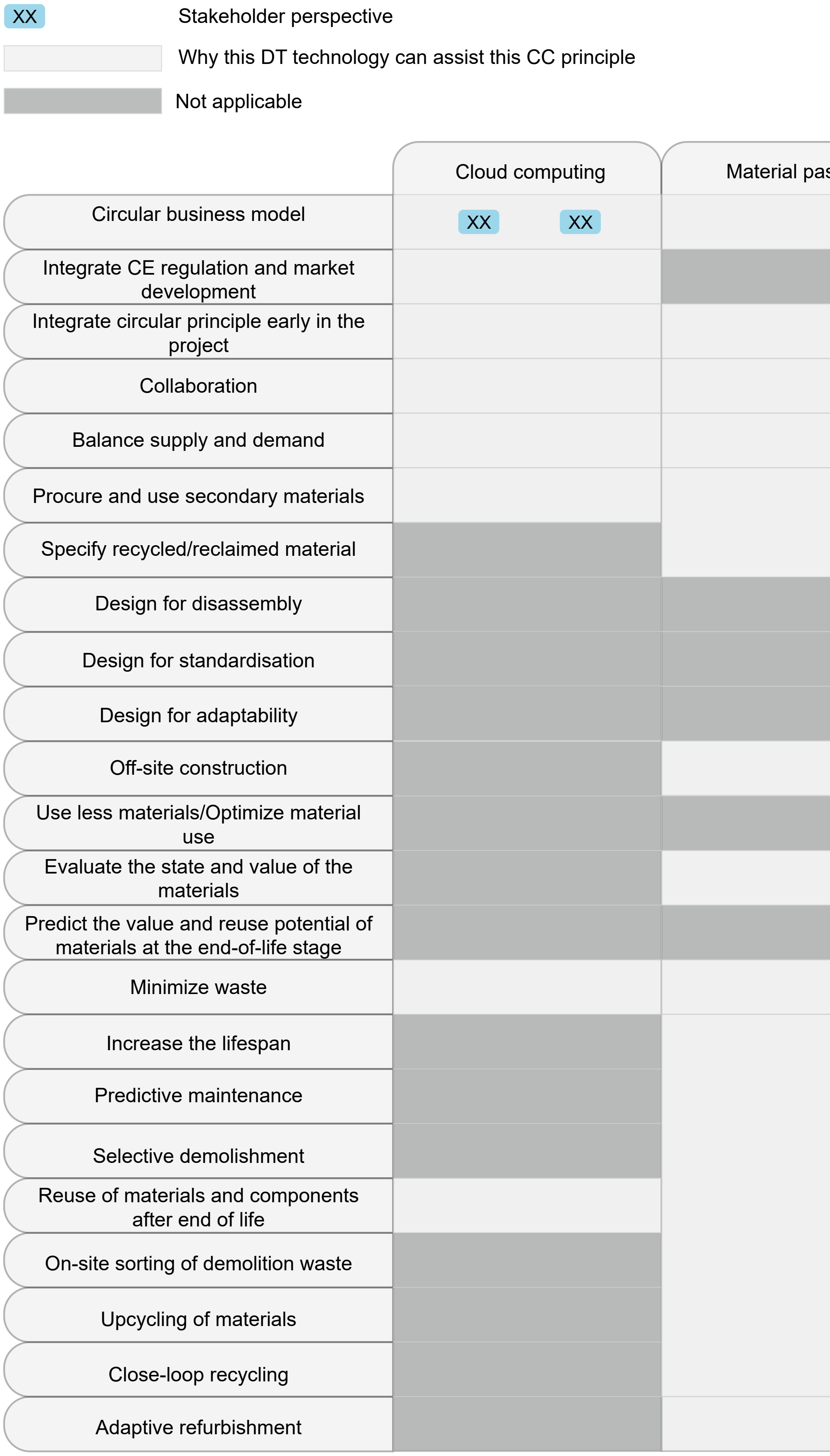
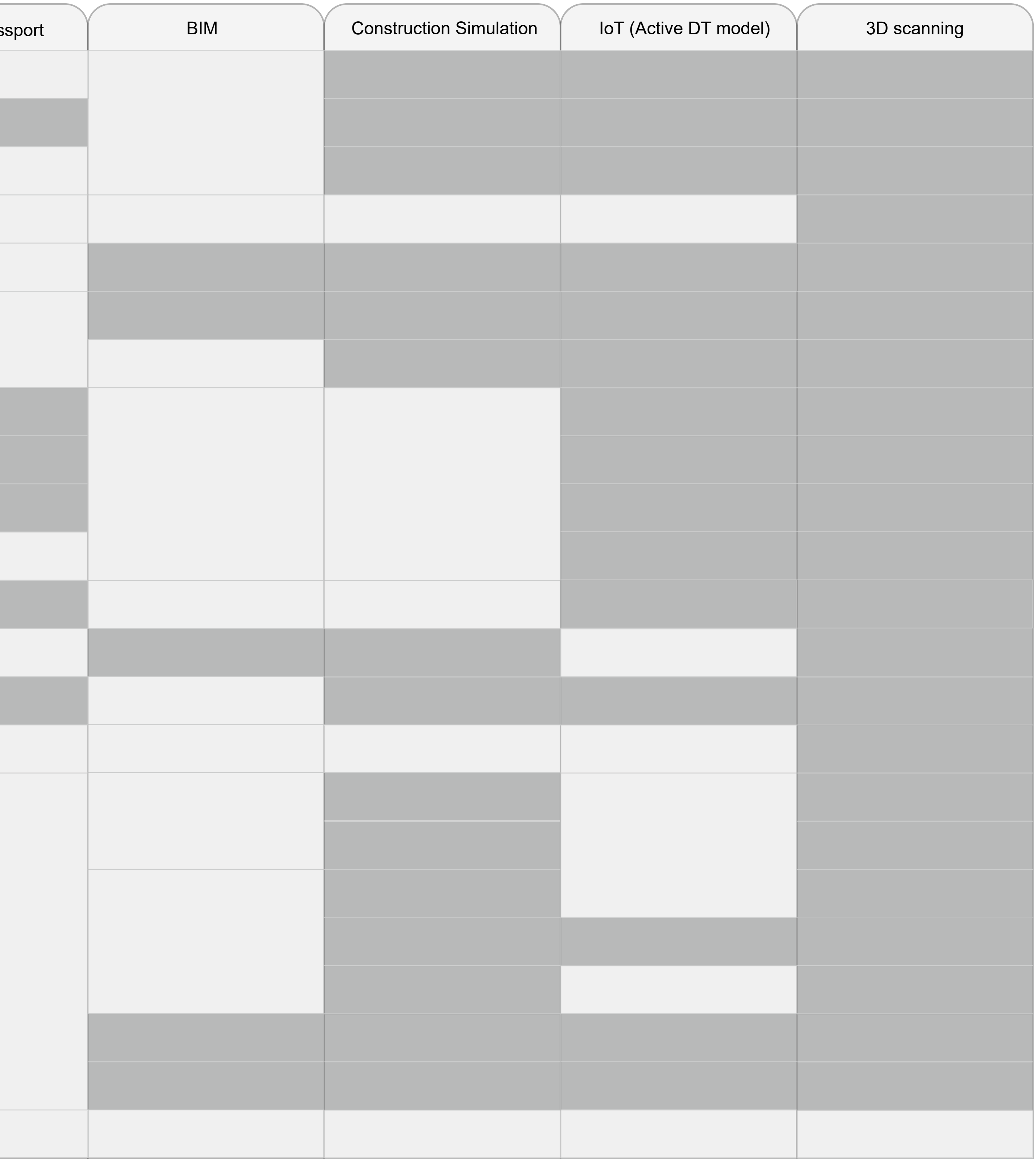


Figure VII: DT-



-based CC implementation canvas (own illustration)

Case Study

The implementation canvas is used in analyzing the case. The CC principles applied and DT technologies that assist the principles are discussed, as well as the stakeholders who used the DT technologies. With the contribution from the case and a supplementary literature study, the primary version of the DT-based CC management framework is developed as shown in Figure VII. Compared to the knowledge framework, the stakeholder dimension is added, which could be useful in implementation. So far, the information of the management framework is almost complete; However, it is yet structured and lacks project management thinking. Therefore, in the synthesis chapter, the primary version of the management framework is restructured to a more practical version.

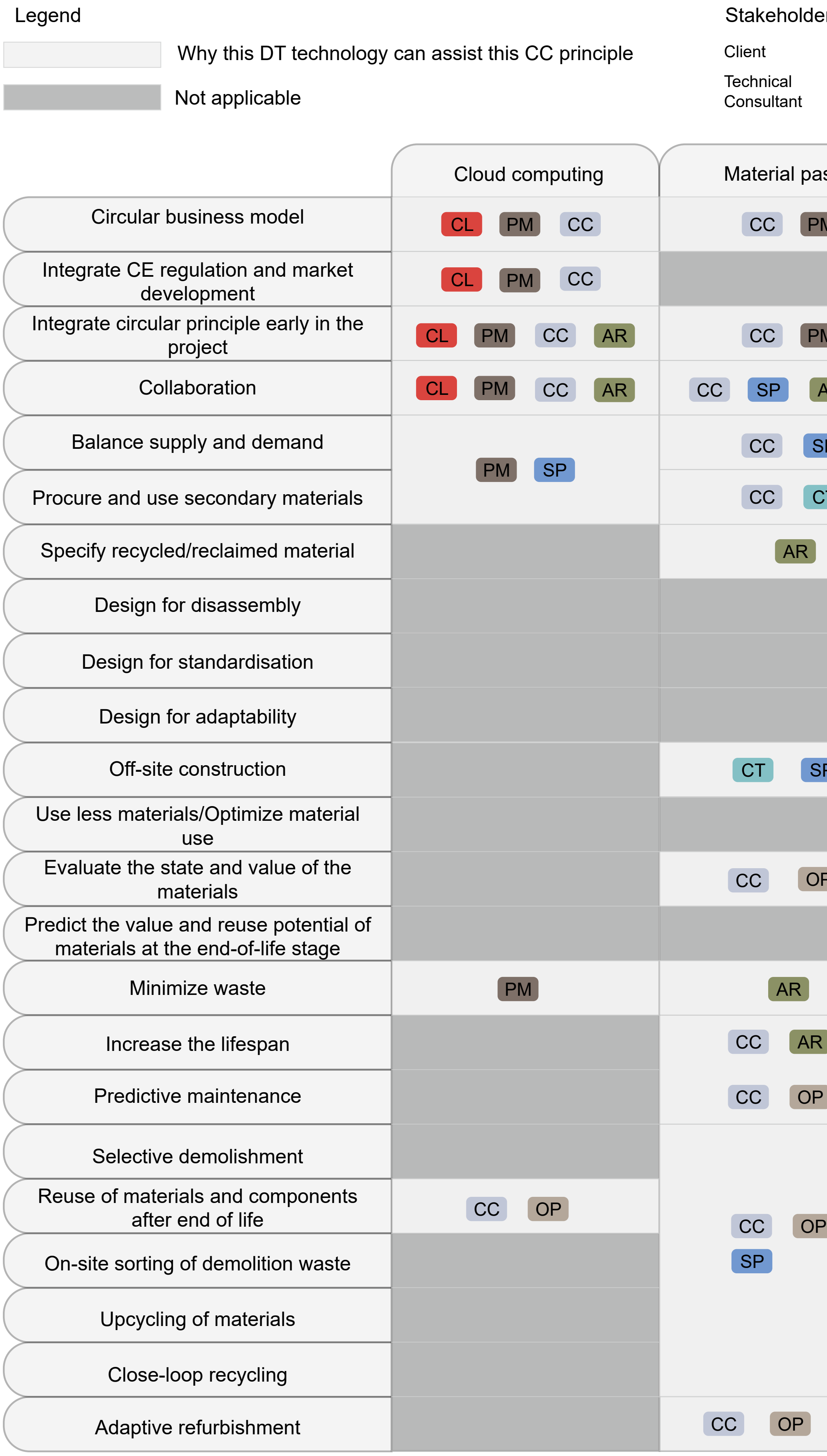
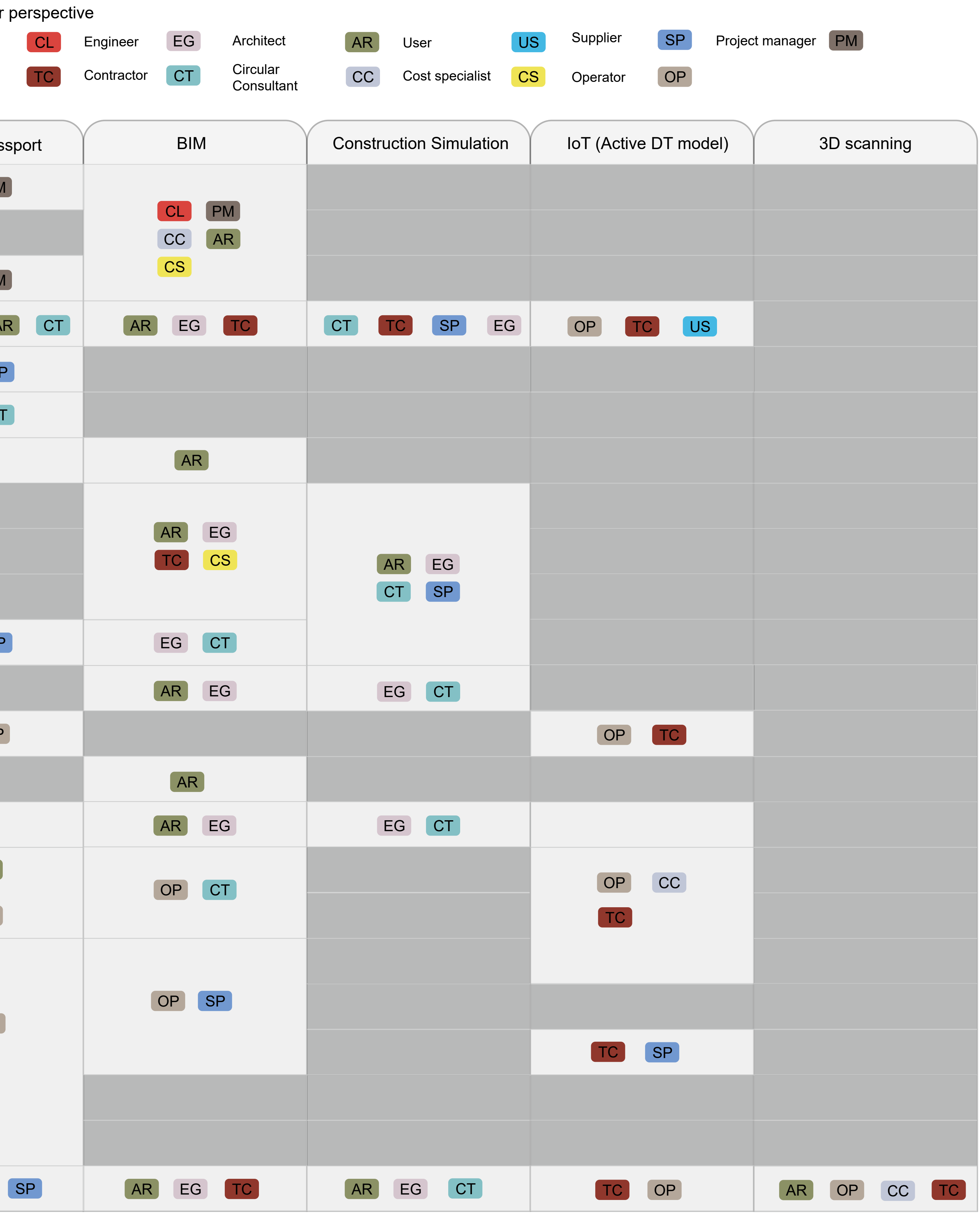


Figure VIII: DT-based C



C management framework (primary version) (own illustration)

4. Synthesis

The DT-based CC management framework, as shown in Figure IX, integrated the knowledge of project life cycle management and the primary DT-based CC management framework. Its structure follows the project management thinking, from feasibility to end-of-life. In the horizontal axis of each life cycle stage, the involved stakeholders, the applicable CC principles, the available DT technologies, and the relationship between DT and CC are shown. In practice, after learning about the circular value of the project, the project managers could use the management framework to filter the CC principles that align with the value. Then, they could know in which life cycle stages, what stakeholders might be involved in, and what DT technologies are available. For the specific information of the reason why the technologies could be used, they can always go back to the knowledge framework for detailed explanation. In this way, the management framework could help the project managers to better manage the stakeholder and the activities in realizing CC.

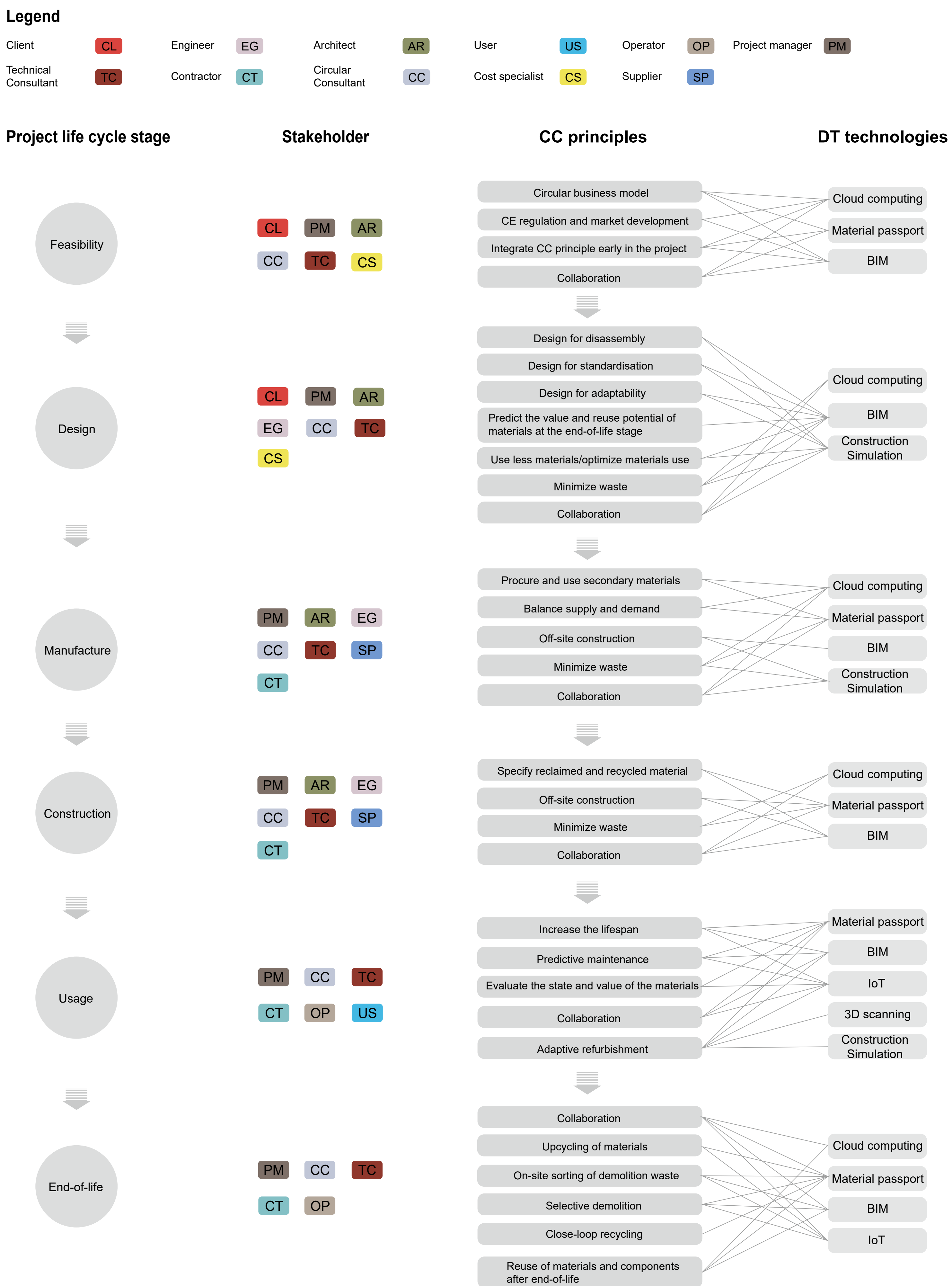


Figure IX: DT-based CC management framework (own illustration)

5. Conclusion

Under the trends of circularity in the built environment, it is crucial to integrate CC principles in all life cycle stages, from feasibility to end-of-life. DT technologies were proved as valuable tools in achieving CC. In order to understand the relationship between DT technologies and CC principles as well as its practical implementation, this thesis was structured to answer the research question, “How can Digital Twins be used in improving circular construction management?”. Three SQs was proposed in order to answer the main research question step by step. As a result, a DT-based CC management framework was developed.

SQ1: What is the role of circularity in the built environment?

With the development of the circularity theory, the circular strategies were extended to 10 Rs, including refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recovery (in order of priority). The 10 Rs could be related with the project life cycle in CC management. They are also translated to specific CC principles, such as integrate circular principle early in the project, applying Circular business model, balancing supply and demand, optimizing material use, design for disassembly, and selective demolition etc.

SQ2: What DT technologies are able to assist CC and why?

From the theoretical perspective, the use of DT can facilitate CC by supporting technical, managerial, informative aspects across the project life cycle. The knowledge framework gives an overview of what CC principles could be assisted by which DT technologies and the reasons behind that. For instance, the cloud platform across projects could benefit adopting circular initiatives. The cloud plotform within the project organization could facilitate effective and efficient collaboration. BIM modeling and construction simulation support circular design and construction. IoT sensor networks and 3D scanning monitor and replicate real-time conditions for predictive maintenance, adaptive refurbishment, and selective demolition to reduce waste. Material passport facilitates closed-loop recycling by tracking the information regarding individual components and materials for reuse and recycling.

SQ3: How to implement DT technologies in realizing CC?

The DT-based CC management framework was developed to answer SQ3. It includes four dimensions, DT technologies, CC principles, project life cycle, and stakeholder perspective. In practice, after learning about the circular value of the project, the project managers could use the management framework to filter the CC principles that align with the value. Then, they could know in which life cycle stages, what stakeholders might be involved in, and what DT technologies are available. For the specific information of the reason why the technologies could be used, they can always go back to the knowledge framework for detailed explanation. In this way, the management framework could help the project managers to learn the stakeholders and the activities they might manage so as to benefit the circular projects.

6. Discussion

This thesis focuses on DT and CC’s applications in both scientific and practical levels. Two frameworks, one knowledge framework and one management framework were developed in order to get a deep understanding of DT’s benefits in CC and maximize the benefits. These two frameworks fill the knowledge gaps that are mentioned in the problem statement. The knowledge framework sees the process of building a DT model as a whole, and provides a holistic and comprehensive knowledge base for applying DT technologies in CC. The management framework proposed facilitates the DT-based CC application by integrating stakeholder perspective and project management thinking in the knowledge framework. In this way, it increases the information accessibility during the CC management.

7. Recommendation

The academic recommendation of refining the knowledge framework are:

1. Consider the intermediate products, instead of only the final one, when discussing its benefits to CC.
2. Keep adding CC principles and corresponding DT technologies.

The academic recommendation of further developing the management framework are:

1. Conduct more case studies to make the results more concrete.
2. Add practical activities in the management framework as examples.
3. Organize focus groups with more experts for adding new perspectives in the management framework.
4. Organize focus groups with stakeholders in practice for refining the management framework.
5. Take financial feasibility into account to increase the practical value of the management framework. The most mentioned barriers and challenges in applying DT-based CC are regarding finance, such as lack of clear financial cases and financial support.

The recommendation for using the management framework in practice are:

1. Discuss the application of the DT technologies together when making strategies to maximize their benefits on circularity.
2. The stakeholders are possible but not necessary involved ones, therefore, it depends on the procurement strategy and other actual conditions in practice. The project managers could adjust it depending on the specific situation.
3. The management framework includes the available DT technologies for each CC principle, but if one needs to know the reasons behind that, the user could go back to the knowledge framework.
4. If possible, the practical users of the management framework can add real case examples in the framework to benefit refining the management framework.

Chapter 1
Introduction

1.1 Context

The attention on circularity in the built environment has increased in the last two decades due to the huge environmental impact and ineffective consumption from the construction industry(UNEP, 2016). According to Solís-Guzman et al. (2009), 35% of the waste to landfill across the world is generated by the construction sector. In the Netherlands, many people hold the impression that it has an almost circular construction sector because the recycling rate of the construction and demolition waste (C&DW) is 95%. However, it's not the case, only 3% of them are upcycled and returned to building construction, while the rest went to civil engineering, functioning as road base and filter materials. Therefore, the construction industry can hardly be called circular with the use of secondary materials only consisting of 3% to 4% of the total consumption (Schut et al., 2016). On the other hand, the increasing population and their demands also lead to the scarcity of resources and a lot of them can be lost for future use (Benton & Hazell, 2013).

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The notion of DT firstly came from the manufacturing industry where it is quite developed, it consists of four parts: physical product, virtual product, connected data that tie the physical and virtual products, and simulation capacity to make the model active (Tao et al, 2017; Focus group, 2021). There is no single software called DT, it consists of a set of technologies, including cloud computing, building information models (BIM), simulation, Internet of Things (IoT), 3D scanning, and material passport (Tobias, 2019; Tobias, 2020).

In the construction industry, the DT concept exists at three levels: building, city, and material. Building a DT model typically begins with BIM, which is the digital representation of the building. While the two concepts of BIM and DT are often confused. There are more elements in DT, such as simulation capacity, sensor networks, social systems, and urban artifacts beyond the scope of buildings, thus requiring a holistic approach that takes factors in dynamic data at different levels into account (Boje et al., 2020). At the building level, the most common working flow in practice is starting with building a digital model in BIM at the beginning of the design stage, which will be complete at the end of construction. Later, sensors and data points would be added to the building and connected with the model to form an active DT model of the building to optimize maintenance and operation. At the urban level, city scale information can also be gathered by IoT sensors to build a DT model of the city, which is the basis of 'smart city' (ARUP, 2019). The information all the way down to the components and materials can be used in the material passport to match the resources at a macro level. It partially overlaps with building DT but the scope goes beyond the latter (Benachio et al., 2019).

Using DT technology in assisting circular construction management, which is the DT-based CC, is expected to facilitate circularity through intelligent construction processes and smart life cycle management. To be more specific, cloud computing technology allows the creation of integrated platforms within projects and across projects to increase the accessibility of data at the city level and optimizes collaboration within the projects (Rocca et al., 2020; ARUP, 2019; Eadie et al., 2013). BIM, construction simulation, 3D scanning, and IoT sensor networks provide tools in supporting the circular design and its realization (Mellado & Lou., 2020; Adams et al., 2017; Pagoropoulos et al., 2017). Material passport balances the supply and demand and thus maximizes reuse and minimizes waste (Patterson & Ruh, 2019; Ghaffar et al., 2020). These technologies' benefits are interrelated and can enhance each other. The implementation of DT-based CC consequently further benefits the built environment through improved life cycle cost, higher built asset resilience, reduced environmental impact, optimized communication of stakeholders (Boje et al., 2020). Some efforts have already been made in practice, for instance, BIM has been widely used in design and construction in the past decades. IoT has been used in maintenance and operation in the past years (ARUP, 2019). While material passports also started to be applied in some representative projects (CE100, 2016).

1.2 Problem statement

Despite the benefits and efforts of applying DT-based CC, only limited research has been done so far concerning the value of DT in circularity ((ARUP, 2019; Eadie et al., 2013). As the trends of digitalization and circularity continue to grow in the market, there are some gaps needing to be filled.

Firstly, in the current construction industry, the concept of 'DT' is restricted to the traditional meaning, which is the building-level DT. This limits the application of DT to the usage stage. However, the embedded technologies in the DT concept all positively affect CC and, therefore, worth being discussed together. Secondly, insufficient awareness and capital lead to the limited and fragmented application of the DT concept across the project life cycle. Thirdly, in order to maximize DT's benefits, a framework in implementing it in CC is required.

1.3 Research objective

To sum up, this research aims to analyze the role of DT and CC in the project life cycle and to develop a framework for implementing DT-based CC.

1.4 Relevance

This research is intended to make both scientific and societal contributions. Circularity in the built environment has been researched in the past two decades but the practices are still at the very beginning stage. Most of the circular principles are only applied in representative projects. Although DT is considered an important enabler in CC, it is a rather novel topic in the construction industry. Most of the research only focuses on its benefits in the usage stage. Instead, this thesis filled the knowledge gap between DT's benefits and CC by seeing the process of building the DT model as a whole and analyzed all the embedded technologies' benefits to CC, which covered all the life cycle stages. The thesis also linked the theoretical knowledge of DT and CC with its implementation in practice, which can benefit circular project management.

1.5 Personal motivation

The built environment is complex due to the multifaceted fields and rapidly changing trends. From my previous study and work in architecture design, I realized a professional in the built environment should hold the awareness of not only technology but also finance, regulation, management and be able to coordinate multi-disciplines. That's why I chose MBE to continue my study and do my thesis.

In my previous experience, I was mainly involved in design but also touched on the communication with clients and suppliers. As kind of an extension of my previous work, I chose the field design and construction management in the thesis as it focuses mainly on the building scale.

During my study in the Netherlands, I was fascinated by the efforts on circularity in both education and practice in all industries. Circularity is not yet an attractive topic in China now due to the low price of raw materials and lack of relevant regulations, although there is already some great technical progress in the laboratories. Therefore, it motivated me to do the research under the Dutch context but also used a Chinese case study, to learn from each other.

What I also realized is that the working flow in the construction industry was changing these years due to the emergence of diverse digital technologies. Some researchers already reached the conclusion that digitalization can facilitate CE. I also want to make contributions in this field by studying DT.

1.6. Research questions

1.6.1 Main research question

How can Digital Twins be used in improving circular construction management?

1.6.2 Research subquestions

SQ1: What is the role of circularity in the built environment?
SQ2: What DT technologies are able to assist CC and why?
SQ3: How to implement DT technologies in realizing CC?

1.7. Conceptual framework

Following the research questions, the research is further divided into three steps. As shown in Figure 1-1. The three different colors in the diagram represent the three SQs. SQ1 aimed to understand the role of CC in the built environment, including its meaning and assessment criteria. SQ2 illustrated the role of DT in the project life cycle on the one hand and explained why DT can be used in benefiting CC. SQ3 was answered by an implementation framework, which worked as a catalyst in the process of using DT in achieving CC. The implementation framework was proposed by synthesizing the theoretical and empirical contributions.

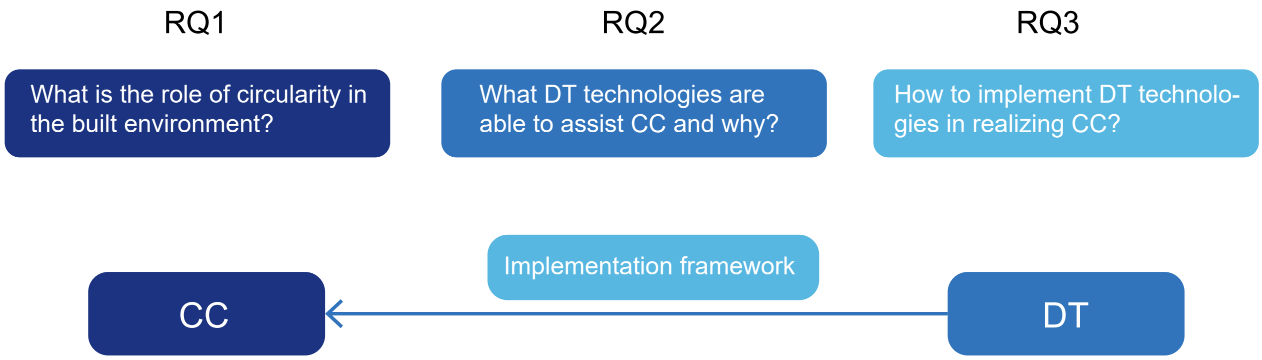


Figure 1-1: Conceptual framework (own illustration)

1.8. Methodology

This section presents an overview of the methodology of the research, including the research type, research design, and data collection methods. The specific methodology for each research stage was explained in detail in the corresponding chapters.

1.8.1 Research type

This study is based on a qualitative research method, which emphasizes an inductive approach to the relationship between theory and research and aims to gain an understanding of the social world through an examination of the interpretation from its participants (Bryman, 2016). Based on the pre-defined research questions and conceptual framework, the research was further divided into three stages, which are theoretical and empirical research, followed by a synthesis of the research findings.

1.8.2 Research design

Two stages of research, followed by a synthesis section, are designed to answer the research questions step by step. The methods applied are shown in Figure 1-2, in which blue texts represent data collection approaches.

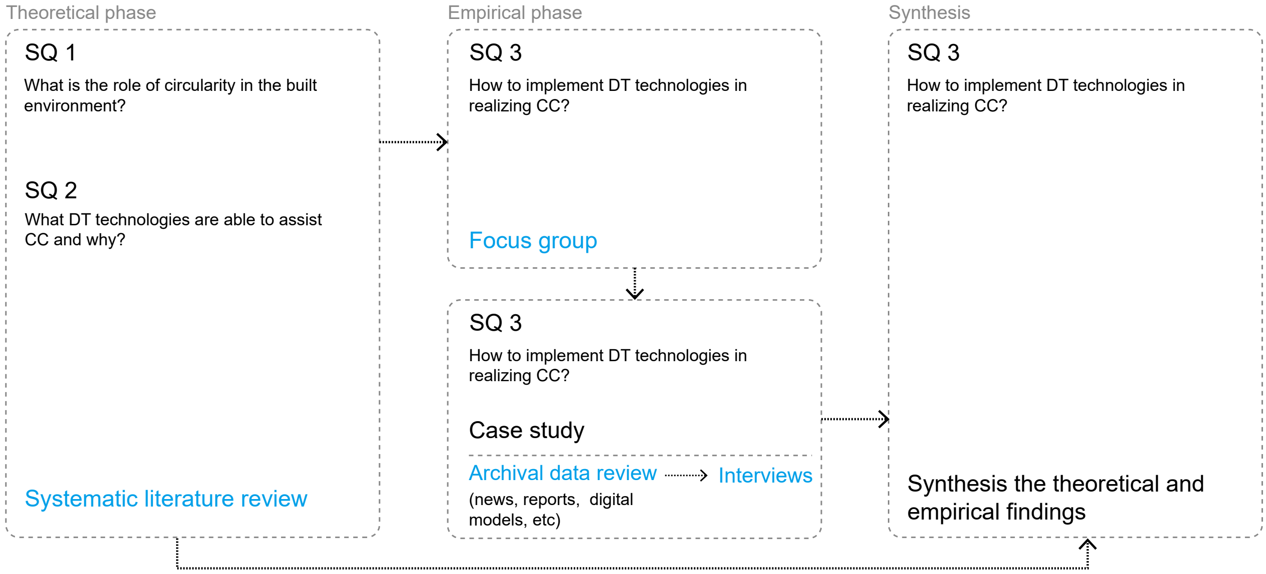


Figure 1-2: Methodology (own illustration)

1.8.3 Theoretical research

The theoretical method involves the creation of a theoretical system of analysis based on published sources for how groups of concepts evolve over time and relate to each other (Esterson, 2003). The objective of theoretical research is to address research SQ1 and SQ2. In order to do this, firstly, a systematic literature review, which is usually used to generate unbiased and comprehensive accounts of the literature, of journals, books, and reports, was conducted for the following concepts: 1) CC's role across the project life cycle, 2) assessment criteria of circularity, 3) DT technologies' roles across the project life cycle, 4) assessment criteria of DT and 5) the reason why DT technologies can assist CC. The structure of the literature review is shown in Figure 1-3. The secondary data gathered from the literature are essential to building a comprehensive understanding of the existing theoretical knowledge, which acts as a preparation for empirical research (Bryman, 2016). As a result, a knowledge framework of DT-based CC applications was proposed.

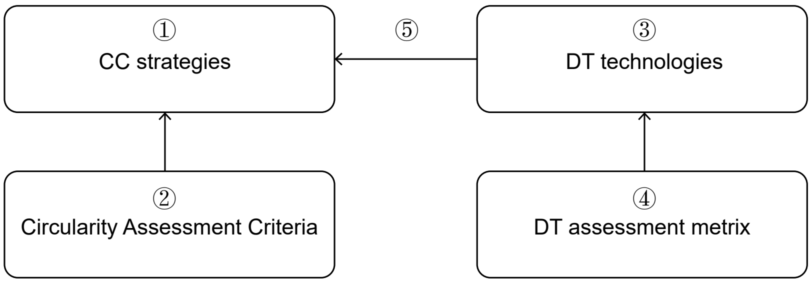


Figure 1-3: Structure of the systematic literature review (own illustration)

1.8.4 Empirical research

The empirical method aims to understand and produce knowledge and focuses on formulating explanations of past conditions (Barendse et al., 2012). The empirical research in this thesis aims to answer SQ3 and includes two steps. The first step is to discuss the theoretical finding, which is the knowledge framework, with relevant experts for their practical inputs in refining and implementing it. The second step is to further develop the implementation framework by conducting a case study.

1.8.4.1 Focus group

The knowledge framework was put in a focus group workshop, where four experts in the field of

DT and CC commented on the structure and content of it and suggested how it could be adjusted in implementation. Suggestions were used in reflecting and improving the knowledge framework, as well as inspiring the implementation framework development. As a result, a management framework canvas was delivered.

1.8.4.2 Case study

After the focus group, a case study was conducted. There are two objectives of the case study, the first one is to examine the application of the DT-based CC in the real case by reflecting on the knowledge framework from the theoretical research. The second objective is to learn from the case and inspire the implementation framework.

The selection of the case is based on criteria that both DT technologies and CC principles should be applied. Several possible cases are pre-selected, after a preliminary data collection of the cases, Leishenshan hospital (Figure 1-4) was selected for further research.

Figure 1-4: Leishenshan Hospital (Provided by CASDI)

Project name: Leishenshan Hospital
Location: Wuhan, China
Client: Wuhan municipality
Architect: CSADI
Contractor: China Construction Third Engineering Bureau Co. Ltd
Year of construction: 2020
Area: 75000 m²
Development type: New built
Main function: Hospital

Leishenshan Hospital is the COVID-19 emergency hospital located in Wuhan, China. Several CC principles were applied corresponding to the requirements, such as standardized design, using secondary materials, applying circular business model, etc. DT concept is applied throughout the construction and usage stages to support the realization of the CC principles. The collaboration of different disciplines in design and construction was done by cloud computing and BIM. Sensors were added afterward to monitor the energy consumption and the performance of the components and medical facilities for predictive maintenance and facility management. The sensor network also benefited the control of social distancing inside the hospital during the pandemic. Besides, as the temporality nature of the emergency hospital, the modular components have huge reuse potential after the end-of-life stage, which also benefits CC (Fan et al., 2020).

Data were gathered by two methods. Firstly, an archival data review was conducted to get an overview of the case. Archival data in qualitative research includes personal documents, official documents, mass-media outputs, and internet resources. Under the context of this study, news, reports, and drawings of the projects were collected and analyzed. Afterward, the unclear information and knowledge gaps were answered by organizing semi-structured interviews with the relevant stakeholders. The relatively unstructured nature of semi-structured interviews and its capacity to provide insights into how the participants view the world is crucial to the research (Bryman, 2016). The management framework canvas delivered from the focus group was used in analyzing the case. The findings provided practical inputs to answering SQ3 and further developed the implementation framework.

1.8.5 Synthesis

The knowledge framework, together with the practical contribution from the case study were synthesized to the DT-based CC management framework, as Figure 1-5 shows. Then, the management framework was analyzed from different perspectives to formulate the answer to SQ3, which is how to implement DT technologies in realizing CC?

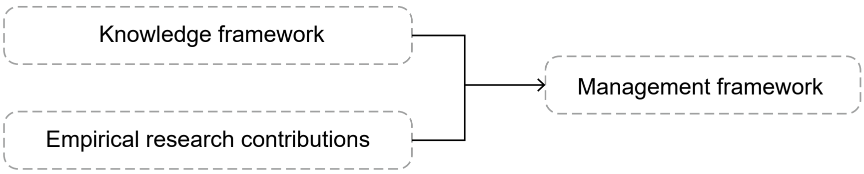


Figure 1-5: Synthesis of the research findings (own illustration)

Chapter 2
Theoretical research

This chapter aims to build a scientific basis for DT-based CC application. Following the literature review structure in Figure 1-3, it firstly answered SQ1, 'What is the role of circularity in the built environment?'. Then, it answered SQ2, 'What DT technologies are able to assist CC and why?. As a result, a DT-based CC application knowledge framework is developed.

2.1 The role of CC across the project life cycle

CC consists of three basic re-strategies: reduce, reuse, recycle (Ghaffar et al.,2020). With the development of the circularity theory, the three basic re-strategies were extended to 10 Rs, including refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recovery (in order of priority). They could be categorized into three groups of strategies, including smart use and manufacture of materials, extending lifespan and productivity of material and its parts, and useful application of materials (Potting et al., 2017).
To be more specific, under the context of this thesis, these 10 Rs strategies could be translated to the specific CC principles across the project life cycle, as shown in Table 2-1.

R0 Refuse

Refuse refers to making products redundant by abandoning their function or by offering the same function with a radically different product. It emphasizes the circular initiative at the early stage of construction and can be represented by design for disassembly, design for standardization, and design for adaptivity. According to Favi & Germani (2014) and Ghisellini et al. (2018), design for disassembly in the early design phase is an effective approach that can maximize the profit through selecting the best end-of-life solution and the number of reusable components, as well as minimize the amount of downcycling and impact to the environment. Adapting standardized components in construction could increase the materials' reuse rate because tradeable C&DW must be standardized (Lu et al., 2020; Pagoropoulos et al., 2017). Relocatable and adjustable modular could challenge the paradigm of ownership and increase the reuse rate by enhancing the sharing economy. Modularity could also bring high adaptability if both usability and circularity, within single modular and between modular units, are taken into account from design and life cycle management (Kyrö et al., 2019).

R1: Rethink

Rethink refers to making products use more intensively by developing innovative business models. In practice, it could be represented by adopting circular business models, integrating circular regulations and relevant market development into the projects, integrating circular principles early in the projects, effective and efficient collaboration, and balancing supply and demand.
The existing circular principles typically started from the design stage or even later, which limited the benefits of circularity (Adams et al., 2017; Lu et al., 2020; Ruiz et al., 2020). Under this circumstance,

Table 2-1: CC strategies and principles (own table)

CC strategy category	CC strategy		Explaination	CC principle
Smart use and manufacture of materials	R0	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product	Design for disa
				Design for star
				Design for ada
	R1	Rethink	Make product use more intensive (e.g. through sharing products or by putting multi-functional products on market).	Circular busine
				Integrate CE re
				Integrate circul
				Collaboration
				Balance suppl
	R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources	Minimize waste
				Off-site constru
				Use less mater
Extend lifespan and prodicivity of material and its parts	R3	Reuse	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function	Procure and us
				Reuse of mate
	R4	Repair	Repair and maintenance of defective product so it can be used with its original function	Increase the lif
				Predictive mai
				Evaluate the st
	R5	Refurbish	Restore an old product and bring it up to date	Adaptive refurb
	R6	Remanufacture	Use parts of discarded product in a new product with the same function	Upcycling of m
	R7	Repurpose	Use discarded products or its part in a new product with a different function	
Useful application of materials	R8	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality	Assess the val end-of-life stag
				Specify recycle
				On-site sorting
				Selective demo
	R9	Recovery	Incineration of material with energy recovery	Close-loop rec

the development and implementation of a business model that challenges the traditional linear model of "take, make, dispose of" is required from the beginning of the projects. The application of circular business models can build an economic system that replaces the "end-of-life" concept by reducing, alternatively reusing, recycling, and recovering materials in production, distribution, and consumption. It can also enable the high residual value of materials at the end-of-life stage to increase the secondary materials' competitive edge (Benachio et al., 2019; Kirchherr et al., 2017; Ghaffar et al., 2020).

Collaboration across the supply chain is crucial in applying the circular business models inside and across the project organizations. However, the level of collaboration between systems and actors who use it was still relatively weak, which led to the unbalanced supply and demand in managing the waste and secondary materials (Lu et al., 2020; Ghaffar et al., 2020).

assembly
ndardisation
ptability
ess model
egulation and market development
lar principle early in the project
y and demand
e
uction
rials/Optimize material use
se secondary materials
rials and components after end-of-life
fespan
ntenance
tate and value of the materials
bishment
aterials
ue and reuse potential of materials at the ge
ed/reclaimed material
of demolition waste
olishment
ycling

R2: Reduce

Reduce refers to increasing the efficiency of consuming materials. In practice, it could be related to minimizing waste, off-site construction, using less materials and optimizing material use. Minimizing waste is essential in C&DW management, which needed effort throughout the design and construction stage. For instance, off-site construction, which was applied in modular buildings, could benefit waste reduction. Using less materials and optimizing material use are also CC's enablers in terms of reducing waste and slowing the material loop (Ghaffar et al., 2020; Benachio et al., 2019; Ghisellini et al., 2018).

R3: Reuse

Reduce refers to material and components reuse by another consumer with their original functions. In practice, it could be realized by procuring and using secondary materials as well as reusing materials and components after end-of-life. Both of these principles can benefit a slower material loop and help with balancing the supply and demand across projects and sectors (Adams et al., 2017).

R4: Repair

Repair aims to make the product be used as its original function and refers to repairing and maintaining defective products. It could be represented by increasing the lifespan, predictive maintenance, and evaluating the state and value of materials at the usage stage. Predictive maintenance increased product accessibility and improved the possibilities for end-of-life collection, refurbishment, remanufacturing, and recycling (Antikainen et al., 2018). It can also help increase the product life span, in which process, evaluating the state and value of materials are necessary.

R5: Refurbish

Refurbish refers to bringing old products up to date. In practice, it could be used in adaptive refurbishment during the usage stage. As refurbishing provided lower environmental impacts than demolishing and new construction, adaptive refurbishment is an essential CC solution. Therefore, information regarding the states of the materials in the building could be analyzed to make them adapt to the new design, so as to align with circular goals (Khajavi et al., 2019; Ghisellini et al., 2018).

R6: Remanufacture & R7: Repurpose

Remanufacture refers to using part of the discarded product in a new product with the same function. While repurpose refers to using part of the discarded product in a new product with different functions. Both of these two strategies can be translated to upcycling of materials.

R8: Recycle

Recycle refers to processing materials to obtain new products with the same or lower quality. Although material loops could not be 100% circular given the system losses, according to Benachio et al. (2019), CC's objective was to facilitate a slowed and even closed-loop recycling (Ghaffar et al., 2020). Therefore, upcycling is important in dealing with the discarded products. In order to do so, at the design stage, the value and reuse/recycle potential of the materials should be predicted. The recycled or reclaimed materials should also be specified and stored in the material passport. After end-of-life, on-site sorting of demolition waste and selective demolition could be applied for upcycling. On-site sorting systems could increase the upcycling of materials and reduce the environmental impact of transporting the waste. To be more specific, selective demolition, contrary to conventional demolition, aims to obtain the separation and sorting of valuable building materials in waste sorting. It could also benefit the reuse of materials and components by increasing the secondary materials' availability and value (Ghisellini et al., 2018).

R9: Recovery

Recovery refers to incineration of materials with energy recovery. By using the materials without enough value for upcycling, recovery can help with closed-loop recycling. It might encourage material wastefulness and compete for resources with other Re strategies. Therefore, it might be the last choice in dealing with C&DW (Potting et al., 2017).

After connecting the 10 Rs strategies with the CC principles in the built environment to get a deep understanding, the 10 Rs is related to the project life cycle, as shown in Figure 2-1.

R0 Refuse and R1 Rethink are at a strategic level, therefore, they could be applied at the feasibility and design stage for a circular initiative. R3 Reuse, R6 Remanufacture, R7 Repurpose, R8 Recycle, and R9 Recovery focus on reusing or recycling materials after end-of-life. Therefore, they could be applied at the end-of-life stage. Reused or recycled materials and recovered energy could be sent back to the manufacturing stage for servicing another life cycle. R2 Reduce should be taken into account during the construction and usage stage. R4 Repair and R5 Refurbish focus on increasing the quality of the existing materials. Therefore, they should be considered at the usage stage. After the repair or refurbishment, the materials and components could be put back to the usage stage.

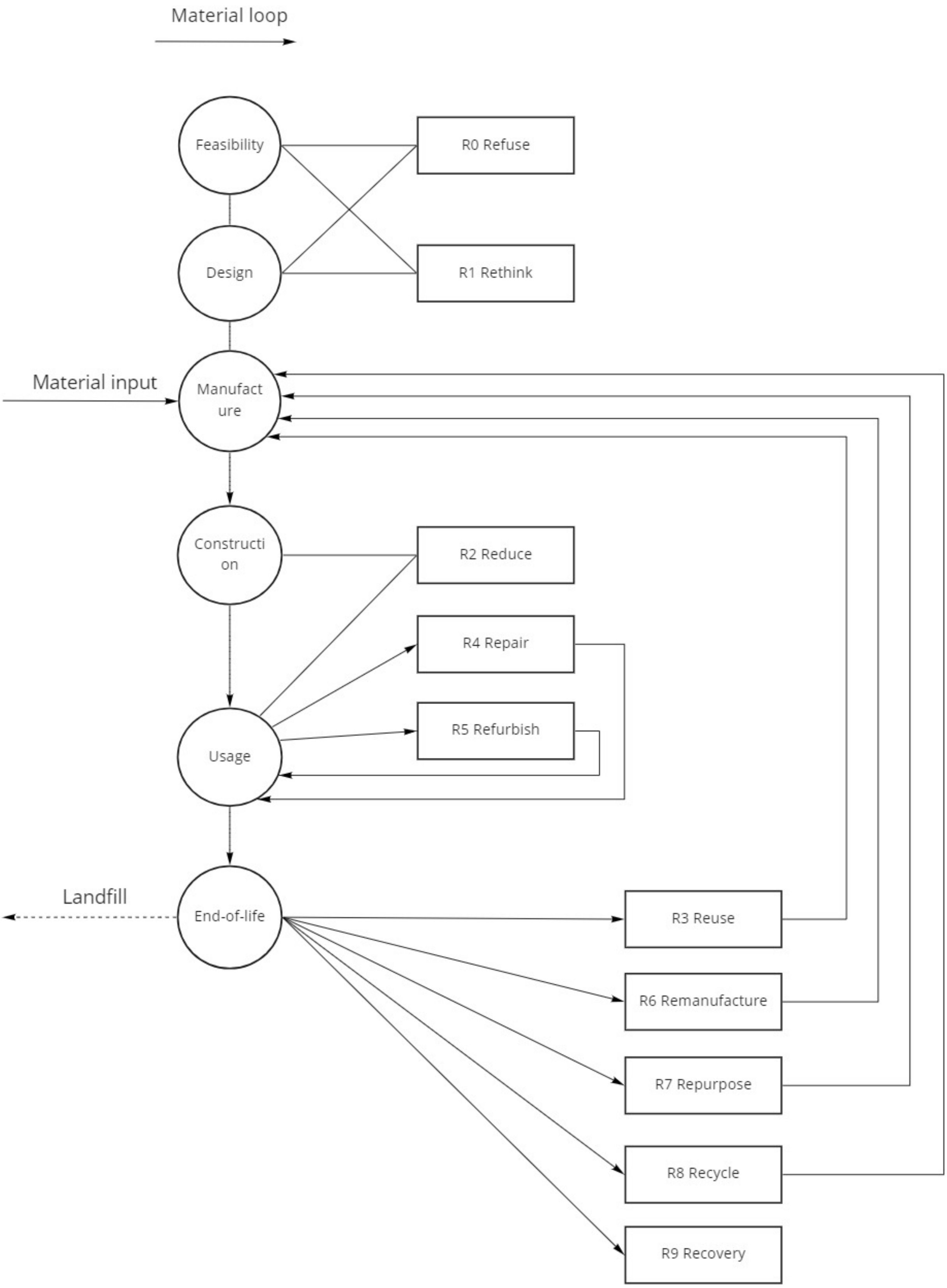


Figure 2-1: Circular strategies in the built environment (own illustration)

2.2 Circularity assessment criteria

When implementing the CC principles, it is important to evaluate the degree of circularity for reference in decision-making. Several qualitatively or quantitatively criteria derived from literature are shown in Table 2-2. Each of the criteria can be related to one or several of the 10 Rs strategies.

The residual value of the materials and the price of the secondary products can evaluate Reuse at the end-of-life stage. They are important indicators in anticipating the reuse potential and value of materials at the end-of-life stage (Akanbi et al., 2019; Britannica, 2020). They are also key elements of considering the financial feasibility of applying CC principles at the early stage. Whether or not adopting an innovative circular business model could be used in assessing if the projects consider Rethink and Refuse strategies, because they are at a strategic level (Kirchherr et al., 2017). Repair and Refurbish can be assessed by the lifespan period of the building components as the longer lifespan of modular components also leads to a high reuse rate and high adaptability (Antikainen et al.,2018).

In practice, reuse and recycle are always discussed and calculated together at the end-of-life stage. To be more specific, reused and recycled ratio, which can be represented by “total amount of recycled and reused material” to “total amount of Direct Material Input (DMI),” could evaluate the effect of Reuse, Recycle, Remanufacture, and Repurpose. In this sense, DMI is able to assess several reuse principles, such as selective demolition, reuse materials and components, closed-loop recycling, as well as procuring and using secondary materials, etc (Wang et al., 2018; Favi & Germani, 2014). Other assessment criteria in recycling are the percentage of waste being sorted on-site and the landfill-output ratio (Ghaffar et al., 2020). In terms of Reduce, the accuracy of maintenance prediction could be used to see if the waste is minimized (Tao et al., 2017).

Table 2-2: Assessment criteria of circularity (own table)

Strategy	**Assessment criteria**	**Reference**
Reuse	Residual value of materials at the end-of-life stage	*Akanbi et al. (2019)*
	Price of the secondary product	*Britannica (2020)*
Rethink	Innovative circular business model	*Kirchherr et al. (2017)*
Refuse		
Repair	Lifespan period	*Antikainen et al. (2018)*
Refurbish		
Recycle Reuse Remanufacture Repurpose	The ratio of “total amount of recycled and reused material” to “total amount of Direct Material Input (DMI)”	Wang et al. (2018) Favi & Germani (2014)
Recycle	% of waste being sorted on site	*Ghaffar et al, (2020)*
	Landfill-output ratio	*Wang et al. (2018)*
		Favi & Germani (2014)
Reduce	Accuracy of maintenance prediction	*Tao et al. (2017)*

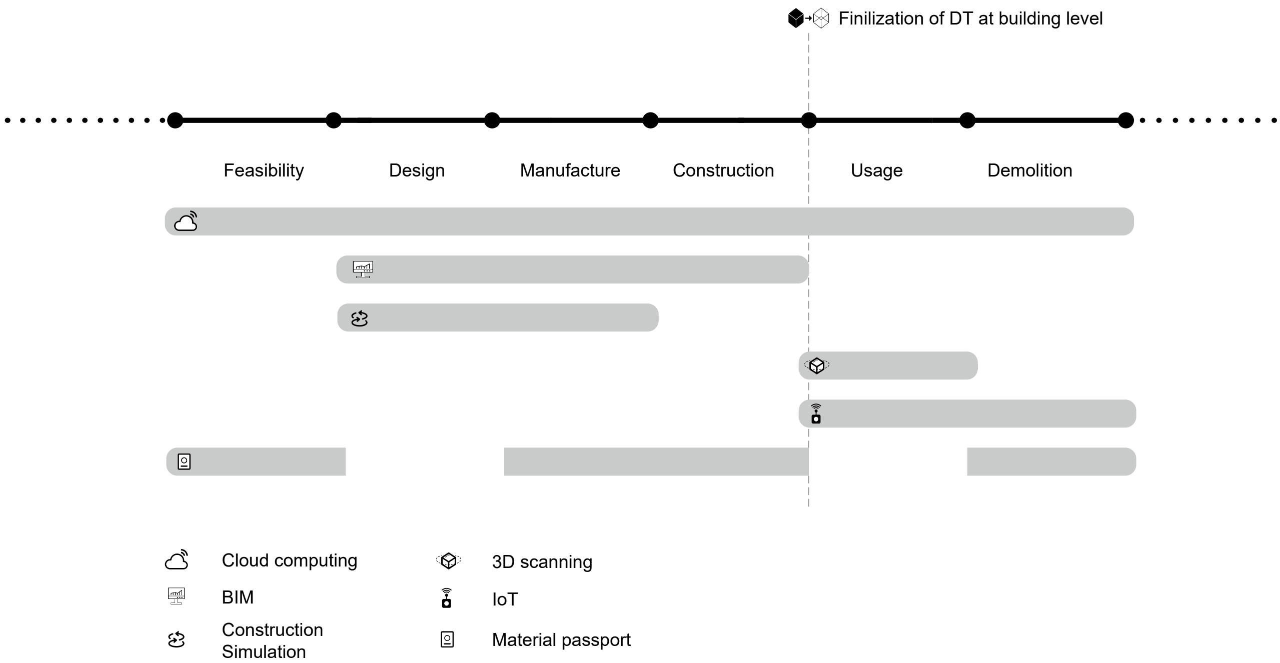


Figure 2-2: DT technologies applied across the project life cycle (own illustration)

2.3 Available DT technologies across project life cycle

DT's concept included a set of technologies such as BIM, cloud computing, IoT sensors network, 3D scanning, construction simulation, and 3D scanning, which means there was no single 'DT software' (Tobias, 2019). DT's current application in the built environment consisted of three levels: urban, building, and material. Therefore, in this research, the concept of 'DT' was not restricted to the traditional meaning, which is the building-level DT. Instead, the technologies embedded in the DT concept that are applied in the project life cycle are discussed, as shown in Figure 2-2.

Cloud computing

At the feasibility stage, an integrated platform consisting of rich historical and real-time information of city context could be built using cloud computing. It illustrated the activities of different actors across the supply chain and what is happening in the city. Under this circumstance, building DT can be connected with smart city DT, which enables: 1) the precise awareness of CE regulation from historical databases in the smart city, 2) public consciousness of CC by user-facing visualization, and 3) market dynamic knowledge and development through interaction between parts of the city. From the design until the end-of-life stages, cloud computing could build an integrated platform within the project organization to facilitate efficient and effective information exchange, so as to benefit the collaboration between different stakeholders in the projects (ARUP, 2019).

3D scanning

In the refurbishment of the existing projects, the goal is replicating the current installations as accurately as possible for adaptative refurbishment. 3D scanning is very useful for this task, together with IoT. Therefore, it is applicable at the usage stage (ARUP, 2019).

BIM

BIM, as a digital representation of a facility's physical and functional characteristics, is the most well-recognized and widely used DT technology (Khajavi et al., 2019). As mentioned before, the conception of DT began with BIM and was enriched by the addition of sensing capabilities, big data, and IoT information (Boje et al., 2020). However, it was most often used in the early stages with progressively less use in the later stages, for example, maintenance and operation (Eadie et al., 2013). Despite the limitation, it is still a mature technology supporting information circular design and realization, collaboration, and process management (Singh et al., 2011). In addition to the 3D modeling, BIM also integrated building specifications, time schedules, cost estimations, and maintenance management (4D, 5D, and 6D BIM). After the delivery, the BIM could be used at the usage stage by integrating with the sensor network (Khajavi et al., 2019).

Construction simulation

Construction simulation consists of linking a 3D model of building elements with the schedule of construction tasks in order to simulate the space transformation process over time. It could be used during the design and manufacture stage to optimize the design and manage the material production (Boton et al., 2013).

IoT

The next step in building a DT model following BIM 3D modeling is adding IoT sensors to collect active data. IoT provides a fundamental basis for evaluating the consequences of various stakeholders' actions throughout the life of the physical products through a dynamic feedback control loop. The information of the materials could also be used in supporting materials passports after end-of-life (Pagoropoulos et al., 2017).

Material passport

Material passport is an integrated approach in the micro-level that applied the DT concept, which goes beyond the scope of project life cycle. It aims to contribute to the mismatch of resources across the supply chain. By identifying the being used materials and updating the information on an information platform, the entire supply chain became transparent, consequently balancing the supply and demand. With more resources identified, it became easier and more attractive to procure and use secondary materials for better accessibility and clear awareness of their value. The identification could assist the on-site construction by providing components' information. It could also benefit on-site sorting of demolition waste in maximizing the potential of upcycling and recording secondary materials' properties. In this sense, the complex supply chain could be managed effectively to close the material loop (ARUP, 2019; Benachio et al., 2019; Rocca et al., 2020; Patterson & Ruh, 2019; Ghaffar et al., 2020).

2.4 DT assessment metrics

The degree of circularity represents the joint effort of DT and circular principles towards CC. In addition, the evaluation of the DT model itself is also helpful because DT models at different levels can lead to different effects on CC. The framework shown in Figure 2-3 is from ARUP (2019), including four metrics: autonomy, intelligence, learning, and accuracy, and each indicator has five levels.

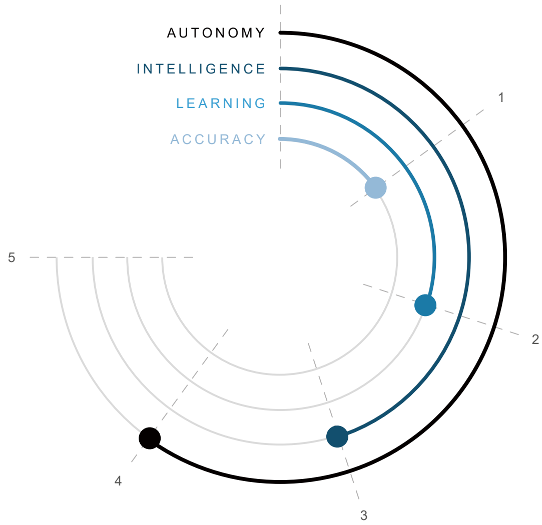


Figure 2-3: Arup's digital twins metrics framework (2019)

In the evaluation framework, autonomy refers to whether the DT can perform critical tasks and monitor conditions without human intervention. Intelligence represents whether the DT has the ability to alert and control the system by choosing specific solutions. Learning is the ability for DT to learn from empirical data to improve performance. Accuracy means how detailed the DT model mimics reality. In ARUP (2019), each of these four indicators is given five levels to measure the DT from basic to intellectual.

2.5 DT technologies' benefits to CC

After understanding the role of DT and CC across the project life cycle. The relationship between the DT technologies and CC principles as well as the reasons behind that is shown in Figure 2-4. It is the knowledge framework of DT-based CC applications (reference for the reasons see Appendix I).

Why this DT technology can assist this CC principle

Not applicable

	Cloud computing	Material passport	
Circular business model	Integrating circular intention across the project life cycle	Supporting circular business model across sectors and projects	Integrat requirer
Integrate CE regulation and market development	Optimizing decision-making by increasing awareness of circularity		
Integrate circular principle early in the project	Increasing awareness of circularity by providing revevant reference projects	Integrating circular intention from the beginning of the projects	
Collaboration	Enabling effective and efficient communication within the project organization	Enabling effective and efficient communication cross sectors and projects	Enabling communic organizati
Balance supply and demand	Supporting the redistribution of the resources	Matching the resources between different sectors and projects	
Procure and use secondary materials	Recording and providing materials' information	Recording and providing materials' information	
Specify recycled/reclaimed material			Working a storing m
Design for disassembly			Providing circular d
Design for standardisation			
Design for adaptability			
Off-site construction		Providing materials' information of assembly and suppliers	
Use less materials/Optimize material use			C
Evaluate the state and value of the materials		Recording and providing materials' information for evaluation	
Predict the value and reuse potential of materials at the end-of-life stage			D-DAS pr materials
Minimize waste	Minimizing rework by scheduling management	Recording materials' information for design optimization	
Increase the lifespan		Recording and providing materials' information	D-DAS pr materials
Predictive maintenance			
Selective demolishment			Working storing m
Reuse of materials and components after end of life	Supporting the redistribution of the resources		
On-site sorting of demolition waste			
Upcycling of materials			
Close-loop recycling			
Adaptive refurbishment		Benefiting reusing material from existing builidngs	Supporti materials

Figure 2-4: DT-based CC knowle

BIM	Construction Simulation	IoT (Active DT model)	3D scanning
ting diverse circular ments in design			
effective and efficient cation within the project on	Enabling effective and efficient communi-cation between certain stakeholders (contractor, suppliers,engineer)	Enabling effective and efficient communi-cation betweem certain stakeholders (operators and users)	
as supporting platform for aterials'information			
technical support for esign and its realization	Supporting the realization of the design		
Optimizing design	Simulating the construction process to minimize mistakes and reworks		
		Providing active information of materials	
edicts the value of the			
Optimizing design	Simulating the construction process to minimize mistakes and reworks	Facilitating energy efficiency by moniroting the interior environment	
edicts the value of the		Providing active information of materials	
as supporting platform for aterials'information			
		Providing active information of materials	
ng design and reuse of s	Supporting the realization of the design	Providing active information of the building's condition	Duplicating the building's condition precisely

edge framework (own illustration)

Cloud computing
The integrated platforms developed by using cloud computing benefits several principles. The cloud platform across projects could increase the decision-makers' awareness of circularity by providing references, so as to encourage the early involvement of circular principles in the projects. The materials' information stored in the cloud platform database across projects and sectors can also benefit resource redistribution, so as to facilitate balancing supply and demand, procuring secondary materials, and reusing materials after end-of-life (Benachio et al., 2019; Lu et al., 2020; ARUP, 2019).

The cloud platform inside the project provides a collaboration platform that allows stakeholder management, process management, scheduling management, and information management, which supports the application of circular business models and the integration of relevant regulations and market dynamics (Patterson and Ruh, 2019; Lim et al., 2019). These activities can result in the minimized rework and waste, as well as the optimized communication within the project organization (Rocca et al., 2020; Adams et al., 2017; Boje et al., 2020).

Material passport
Material passport records information of the materials and components. Adapting material passports from the feasibility stage of the projects enables the circular initiative to be applied in the projects (Ghaffar et al., 2020; Benachio et al., 2019). To be more specific, adapting the building as a material bank is one of the circular business models, which enables using secondary materials and reusing materials after end-of-life, so as to benefit balancing the supply and demand of resources (Damen, 2020).

Static information of materials are stored in the material passport, it could benefit procuring and using secondary materials, specifying recycled materials, reusing materials after end-of-life, reusing materials during refurbishment, on-site sorting of demolition waste, selective demolition, upcycling of materials, and closed-loop recycling (Benachio et al., 2019; Rocca et al., 2020; Bertin et al., 2020; Ghaffar et al., 2020). The information could also benefit other principles that are not directly related to materials reuse. For instance, providing information regarding component assembly can assist off-site construction and on-site assembly (Fan et al., 2020).

The active information of materials and components with the help of the sensor networks can benefit CC principles at the usage stage. For instance, it could assist evaluating the state and value of materials. In this way, the operators could conduct timely predictive maintenance and extend the lifespan of the components. Waste could also be minimized in the process (Benachio et al., 2019; Ruiz et al., 2020). During the refurbishment or end-of-life stages, the active and static information could help with reusing materials from the existing building and selective demolition (CE100, 2016; Ghaffar et al., 2020; Cobouw, 2014).

BIM
BIM, as a mature digital modeling platform, had the capacity to provide technical support in aligning circular goals in the project delivery (Patterson & Ruh, 2019). At the feasibility stage, it could already support building the cloud collaboration platform that can integrate the circular regulations, codes, and requirements for design reference (Mellado and Lou, 2020). The BIM-based platform also enables effective and efficient communication within the project organization (Papadonikolaki et al., 2019; Eadie et al., 2013). At the design and construction stages, BIM 3D modeling could be used to support circular design, such as design for disassembly, design for standardization, and design for adaptability. The tradable C&DW must be standardized to keep high value and to be flexible enough in further reuse, which can be taken into account in BIM modeling (Lu et al., 2020). These highly flexible and relocatable modular components could fit the leasing alternatives' short-

term needs (Kyrö et al., 2019). In manufacturing, BIM could assist in materials production in off-site construction by high-fidelity models (Landahl et al., 2018).

BIM also provides technical support for material reusing and recycling by storing materials information. The information of material passports can be embedded in BIM, which can be used in specifying recycled materials, reusing materials after end-of-life, and on-site sorting of C&DW. A plug-in in Revit called D-DAS (Disassembly and deconstruction analytics system) can also predict the recycling potential of building material for CC at the end-of-life stage (Krause & Hafner, 2019; Rocca et al., 2020). D-DAS provides an overview of the end-of-life performance assessment from the early design stage, which can optimize the design in terms of circularity and provide end-of-life reuse solutions simultaneously. In this way, the materials can be used efficiently and effectively to minimize new materials' input into the loop (Akanbi et al., 2019).

Construction simulation

The 4D construction simulation that integrates construction process visualization in BIM can benefit collaboration between contractors, architects, suppliers, and engineers, supporting the realization of design, optimizing materials use, and minimizing waste. In detail, construction simulation enabled collaboration by visualizing scheduling activities, constructability analysis, and site monitoring (Boton et al., 2013). It simulates the construction process for realizing the circular design (Landahl et al., 2018; Boton et al., 2013). By doing the simulation, the possible mistakes and reworks could be minimized so as to optimize the material reuse and minimize the waste of resources. In addition, not only the new construction, but also the refurbishment projects could be benefited from the construction simulation (Autodesk, 2018; ARUP, 2019).

IoT

At the building level, IoT sensor networks could continuously record the data produced in the building, monitor operations, and identify abnormal behavior, allowing human operators to react promptly, reduce downtime, and contribute to predictive maintenance. Some extra benefits were also generated in this process, for instance, interior comfort improvement, energy efficiency, and user satisfaction improvement (ARUP, 2019; Boje et al.,2020). As mentioned before, the monitoring of the materials' active condition and performance made it possible to evaluate the materials' state and value for optimizing further reuse alternatives. It could be used at the usage stage for predictive maintenance and increasing the product lifespan. It could also be used at the end-of-life stage in selective demolition because the reuse and recycling value are included in the sensor networks. In a word, IoT-based DT visualization enables CC by providing active information (ARUP, 2019).

3D scanning

During the refurbishment, IoT, together with SD scanning' assistance, could replicate the current installation of existing buildings accurately. What’s more, materials passport, BIM, construction simulation, can all be used in realizing the refurbishment design and reuse materials from the existing building (Tobias, 2019).

2.6 Conclusion

This chapter answers SQ1 and SQ2 by developing a knowledge framework, which is the scientific basis for DT-based CC application. Firstly, it examined the CC strategies and corresponding CC principles across the project life cycles. The 10 Rs circular strategies were related to the applicable life cycle stages. Secondly, the embedded DT technologies' roles across the project life cycle were discussed, including cloud computing, material passport, BIM, construction simulation, IoT, and 3D scanning. Then the reason why the technologies are able to assist the CC principles are presented in the DT-based CC knowledge framework. To sum up, cloud computing can provide integrated platforms within or across projects so as to facilitate collaboration and balance resources supply and demand. BIM modeling and construction simulation provide tools for the circular design and its realization. IoT sensors network, together with 3D scanning monitor and replicate real-time conditions for predictive maintenance, lifespan increment, adaptive refurbishment, and selective demolition. Material passport benefits the CC principles by recording and providing materials' information.

Although DT is considered an important enabler in CC, most of the research only focuses on the final DT model at the usage stage, which limits DT's benefits. The knowledge framework proposed in this chapter filled the knowledge gap in the current research by integrating the existing knowledge in relation to DT technologies' benefits to CC. In this way, it provides a holistic and comprehensive knowledge structure of DT's benefits in circularity by seeing the process of building DT models as a whole. In the knowledge framework, DT's applications in CC management are not fragmented anymore. In the next chapter, how to implement the knowledge framework is discussed, for maximizing the DT's benefits to CC in practice.

Chapter 3
Empirical research

This chapter is the second phase of the thesis, empirical research, and answers SQ3, ‘How to implement DT technologies in realizing CC?’. The objective of the empirical research is to adjust the DT-based CC knowledge framework in implementing it in practice. In order to do so, two steps of research were conducted, including a focus group discussion and a case study.

3.1 Focus group

A focus group is organized to discuss the DT-based CC knowledge framework with relevant experts. One of the goals is to minimize the mistakes and biases in the knowledge framework. The other goal is to inspire the implementation of the knowledge framework in practice.

3.1.1 Data collection

During the one hour workshop, four experts (Table 3-1) of DT and circularity from both practical and academic fields were invited to discuss the knowledge framework and exchange opinions from their perspectives. In the beginning, the moderator presented a short introduction to the research and the knowledge framework. Then, the participants exchanged their ideas on different aspects of the knowledge framework and also suggested on how it could be adapted in implementation.

The topics of the focus group are extracted from the knowledge framework, including the scope of DT technologies, the scope of circularity in the built environment, and the aspects that need to be taken into account in implementing the knowledge framework.

Table 3-1: Information of focus group participants (own table)

Participants	Professional field
A	Digital Twins; Sustainability (practice)
B	Digital Twins (Researcher)
C	Digital Twins (Researcher)
D	Digital Twins; Circular economy (Researcher)

3.1.2 Findings

The suggestions consist of five aspects, namely why, where, what, who, as explained below.

What

‘What’ refers to the available DT technologies in assisting circular goals, which is already included in the knowledge framework. It is the starting point of the research.

Why

‘Why’ refers to the reason for applying DT technologies in CC. It’s the fundamental question of the research and is answered by the knowledge framework, where DT’s benefits to CC are revealed. The correlation between these two concepts is the motivation of applying

DT technologies in CC projects.

Where
'Where' refers to the stages of applying DT technologies. In the previous research, the CC strategies and principles are related with the life cycle stages, and the DT technologies. Therefore, it is possible to link the life cycle stages with suitable DT technologies for better implementation. This is considered in the further development.

Who
'Who' refers to the users of the DT technologies. It is essential to know who is going to use the DT technologies or who is willing to pay for it. This part is absent in the knowledge framework but was mentioned several times during the focus group discussion. Therefore, it was taken into account in developing the implementation framework.

How
'How' refers to the specific activities of implementing DT technologies in realizing circular goals. Different stakeholders might have different approaches in realizing the circular ambition. Therefore, the activities depend on the role of the stakeholder, the stage of the project, the available DT technology, and the circular objective, which is taken into account in analyzing the case study and the implementation framework

The 'What' and 'Why' relate to the scope of DT and CC, and are used in reflecting and revising the theoretical research findings during the thesis process. 'Where', 'How' and 'who' are regarding the knowledge framework's implementation. As the 'Who' was stressed several times, the stakeholder perspective is firstly considered in implementing the knowledge framework. Therefore, the knowledge framework is adjusted to a management framework canvas (Figure 3-1), in which the reasons are left out, and only the relationship between DT and CC are kept. Then, the stakeholder perspective is integrated in the framework. This management framework canvas can be filled by further case studies to contribute to the further development of the implementation framework. The 'How' and 'Where' is considered in the later stage.

Figure 3-1: DT-based CC manageme

	BIM	Construction Simulation	IoT (Active DT model)	3D scanning

nt framework canvas (own illustration)

3.2 Case study

The second step of the empirical research is a case study. The ‘Leishenshan hospital’ project was analyzed by using the management framework canvas (Figure 3-1). An archival data review and four semi-structured interviews were conducted to collect the data. The findings examine the knowledge framework on the one hand and contribute to the development of the management framework on the other hand.

3.2.1 Data collection

Case study was conducted following the structure of the management framework canvas and includes three parts: 1) The CC principles applied across the project life cycle, 2) DT technologies used in assisting the CC principles, 3) DT technologies’ application activities in assisting CC. Based on the collected information, the degree of circularity as well as the the level of the final DT model was also evaluated.

The data from the cases was collected through a qualitative methodology, which emphasized an inductive approach to the relationship between theory and research and aims to gain an understanding of the social world through an examination of the interpretation from its participants (Bryman, 2016). The data collection was done by an archival data review and four semi-structured interviews.

3.2.1.1 Archival data review

The archival data review involved resources, such as news, reports, publications, and digital drawings of the project. It investigated the background information of the project, the CC principles applied, and the tools and activities in realizing the circular goals. However, this review was not sufficient. Therefore, knowledge gaps were defined and answered by the interviews.

3.2.1.2 Semi-structured interview

The semi-structured interviews were conducted with the stakeholders of the project, including the contractor, architect, and BIM specialist. The interviews were flexible and emphasized how the interviewee frames and understands issues related to the project. An interview protocol that covered a list of themes was defined. According to Bryman (2012), an interview protocol is based on a set of core questions and a few supplementary questions that vary according to the specific background of the interviewees. Therefore, it helped to answer the knowledge gaps from the archival data review.

The protocol (Appendix II) was structured in four main parts that include: 1) a general information of the interviewee’s background, role and value in the project, 2) the applied CC principles in the project, 3) the applied DT technologies in the project, 4) the performance of the project and other relevant insights generated during the interviews. The interviews were conducted in Chinese and the audio, with the consent of the interviewees, was recorded and transcribed (Appendix III) in English.

3.2.2 Case description

General information

Figure 3-2: Leishenshan Hospital (Provided by CSADI)

Project name: Leishenshan Hospital
Location: Wuhan, China
Client: Bureau of Housing and Urban-Rural Development of Wuhan
Architect: CSADI
Contractor: China Construction Third Engineering Bureau Co. Ltd
Delivery date:02/2020
Temporary closed date: 15/04/2020
Area: 75000 m²
Development type: New built
Main function: Hospital

Leishenshan Hospital (Figure 3-2), which is located in Wuhan, China, is analyzed in this master thesis. The reason for choosing this project is that it applied several CC principles, which were mostly achieved by applying DT technologies from feasibility to use stage. It also has high reuse potential after end-of-life.

The site plan in Figure 3-3 gives an overview of the Leishenshan hospital. It consists of three main parts, including the ward zone on the east side, the medical technical zone on the west side, and the logistics areas.

Figure 3-3: Leishenshan Hospital site plan (Provided by CSADI)

Project organization:
The stakeholder segment in Leishenshan hospital consists of internal and external stakeholders. For the internal stakeholders, as the delivery method is Design and Build (DB), the design institution and contractor together formed a consortium, which is responsible for design and construction. The internal stakeholders in the project organization across the life cycle stages are shown in Figure 3-4. External stakeholders in the project are the general public. As a representative project, Leishenshan hospital became the first project that live streamed the site during construction. In this way, it built a connection with the general public even though they weren't directly involved in the project (Interview A).

Development restrictions and requirements:
There are some restrictions and requirements during the development of Leishenshan hospital. Firstly, under the COVID-19 outbreak in January 2020, there was a huge ICU beds shortage in Wuhan, which was the initiative of this hospital and it had to be delivered within two weeks. Secondly, there were supply problems because the development was during a national holiday, when the local factories and logistics across the country were almost all closed. It led to a material shortage and high transportation costs. The third restriction is about stakeholder management. On the one hand, at the beginning of the construction, there was also a shortage of workers because of the holiday and lockdown. On the other hand, the involved 20.000 participants also made it difficult to manage the project.

3.2.3 Case study findings
Several CC principles and DT technologies were applied to deal with the restrictions mentioned above. For instance, under the time limitation, the standardized design was applied, which was supported by BIM modeling. For the supply problems, reusing materials was applied to ease the material shortage. For stakeholder management, minimizing rework and increasing efficiency and effectiveness was the goal, which was supported by cloud platforms.

The application of DT and CC in the case was summarized in Figure 3-5. which used the management framework canvas to show the CC and DT applications as well as the involved

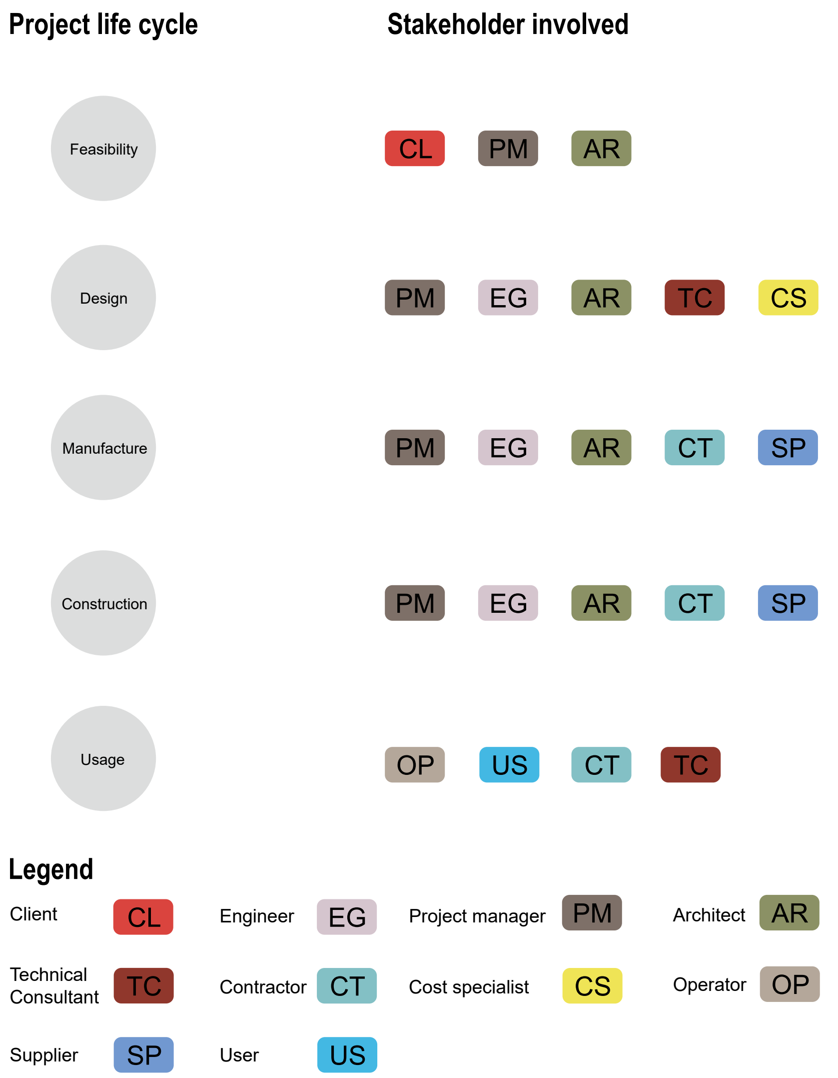
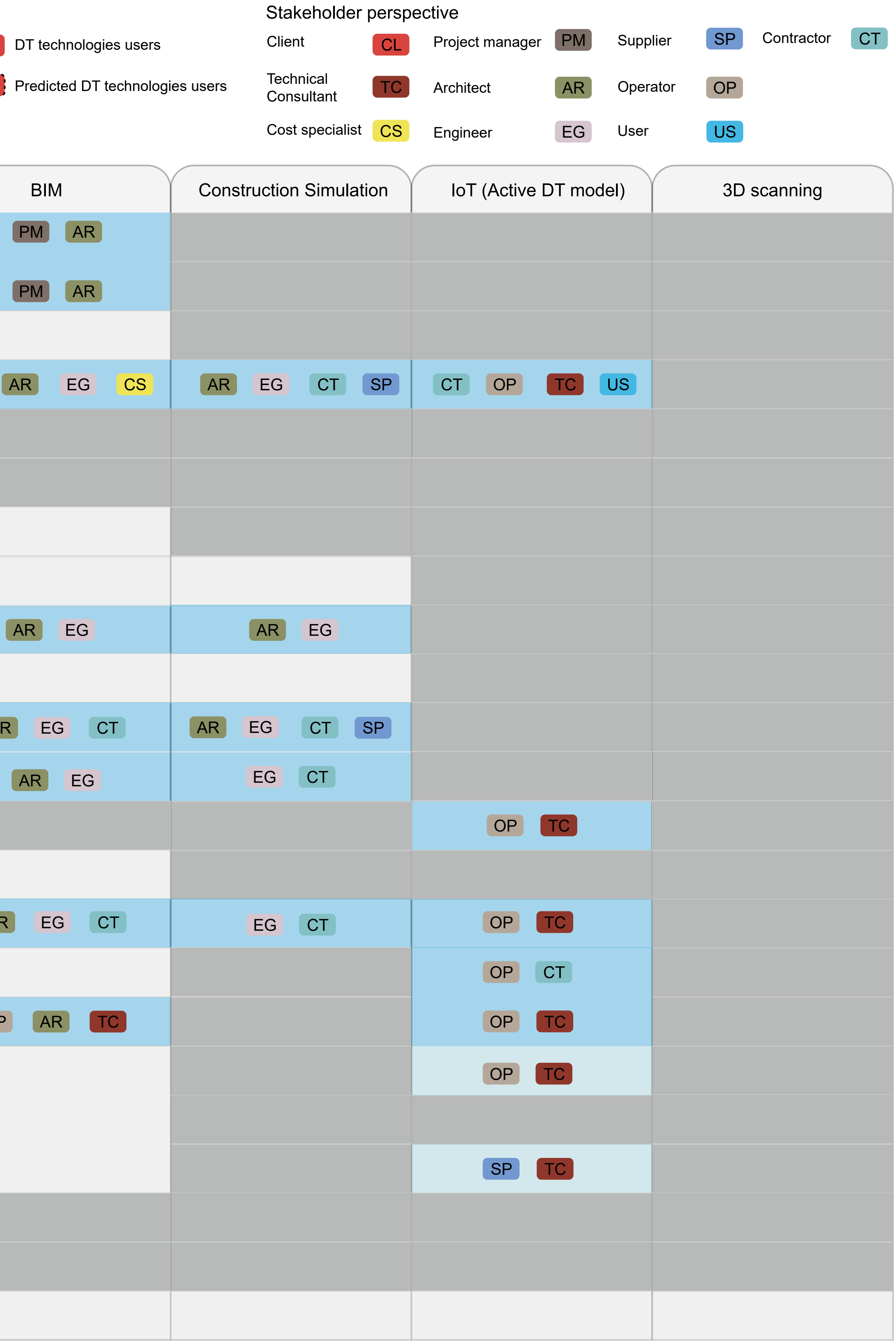


Figure 3-4: Leishenshan hospital project organization (own illustration)

stakeholders. The CC principles applied are categorized into three groups, the ones assisted by DT technologies, the ones applied without DT technologies' help, and the potentially applicable CC principles in the future, which are indicated in different colors in Figure 3-5.

Same with the knowledge framework and canvas, in Figure 3-5, the light grey cells represent the existing relationship between DT technologies and CC principles. However, in some circumstances, not all the applicable DT technologies were used. Therefore, the actually applied DT technologies cells are marked in blue, while the potentially applicable DT technologies are marked in light blue. The stakeholders who used DT technologies in realizing the circular goals are filled in the canvas, while for the potentially applicable CC principles, the stakeholders only mean that they could, but not necessarily, be involved in the future.

Figure 3-5: An overview of DT and CC applica



ation in Leishenshan hospital (own illustration)

3.2.3.1 Applied CC principles assisted by DT technologies

Circular business model

The business model applied in Leishenshan hospital is the product, organization, and process (POP) modeling approach. It includes three basic components. The first one is a product model that contains both the geometric and non-geometric attributes of the physical building and allows for necessary analyses. It is the basis of digital design and is realized by BIM modeling. The second one is a product-process model that integrates the product model with the construction process for seamless construction coordination and schedule management. It provides information for the design realization and is supported by construction simulation. The third one is an organization-process model that associates the specific project delivery tasks with organizational responsibilities at different project stages. It enables effective and effective collaboration in the project. It is realized by a cloud platform across the project life cycle, which starts from the very beginning of the project (Luo et al., 2020; Interview A, C).

Design and realizing the project

In the design and construction stages, several DT tools, including cloud computing, BIM modeling, material passport, construction simulation, and IoT sensors, were used in achieving the circular principles. They supported the circular design, its realization and also enabled a circular usage stage. The relevant stakeholders and their activities in the process of building the DT technologies are summarized in Figure 3-6.

At the beginning of the development, a BIM standard was approved within the project organization and integrated into the embedded collaboration platform in BIM. Then, three separate Revit models were made by the architects, structure engineers and MEP engineers. After these three models were integrated into one, it was put into the simulation process to check its effect on the surrounding environment. The construction simulation was done together with the suppliers and contractors, which means right after the structure calculation was approved, the information became available in the factories for production. The materials properties, such as supplier information, assembly sequence were also used in the on-site assembly. After the finalization of the construction, data points were added to finalize the DT model of the hospital and monitor the interior environment (Interview C, D; Luo et al., 2020).

Cloud computing was embedded in Autodesk Revit in the project. It made collaboration during modeling, schedule management, and communication across the organization more efficient and effective (Luo et al., 2020). It was also used in the use stage, when cloud computing and sensor networks enabled the operation monitoring (Interview D).

BIM modeling was also embedded in Autodesk Revit and Tekla Structure. It supported the effective multidisciplinary collaboration among designers and engineers in building the digital models. Regulations and standards were already integrated into the model from the beginning of the project. The standardized and adaptive 'fishbone' design is shown in Figure 3-7, which is flexible and allowed three times of modifications to provide 300 more beds (Luo et al., 2020).

After getting the integrated model, the engineers and suppliers used Tekla to simulate and calculate the structure (figure 3-8). Tekla was able to calculate the structure and generate construction drawings at the same time. It provided the detailed information directly to the suppliers for production. The simulation dramatically reduced adjustment at the construction stage and contributed to effective time scheduling, so as to avoid waste of resources and time(Interview C).

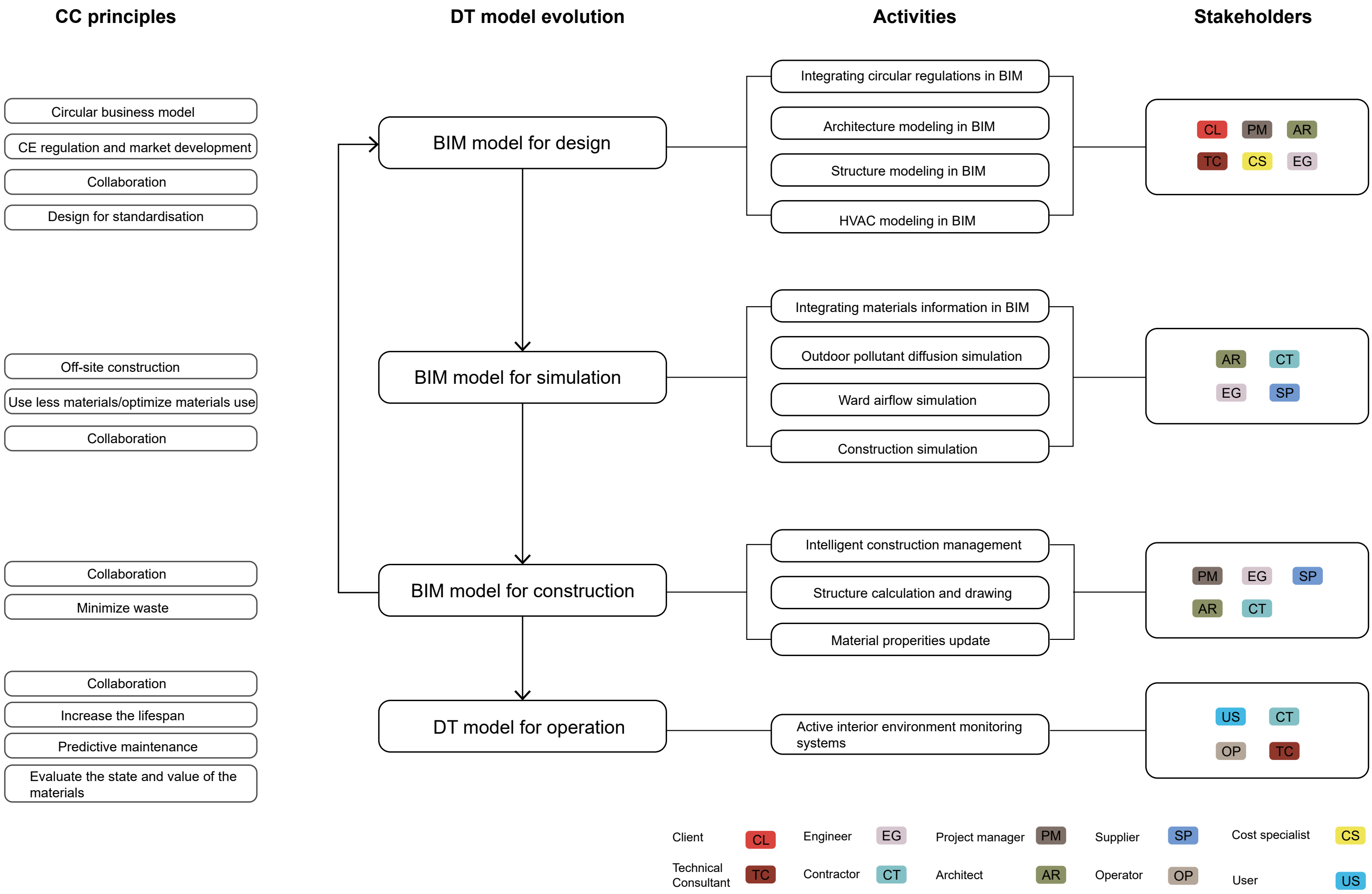


Figure 3-6: Activities of using DT in assisting CC in Leishenshan hospital (own illustration)

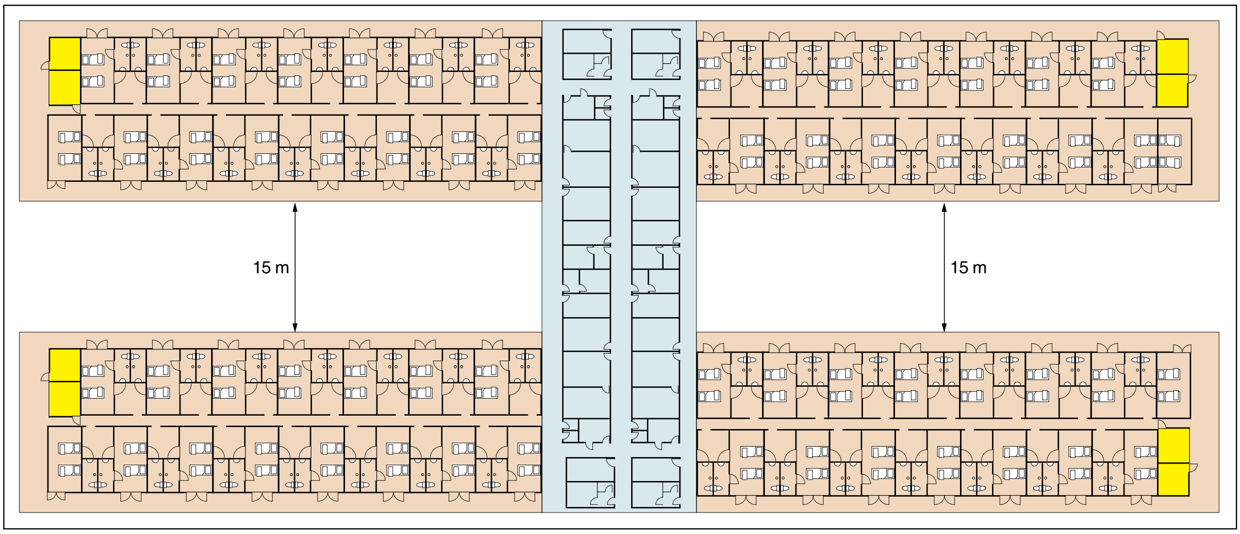


Figure 3-7: Fishbone layout of wards facilitated construction and operation (Zhou et al., 2020)

The information of materials concerning classification, size, methods of operation and supplier information were included in the digital model (Luo et al., 2020; Zhai & Zhang, 2020; Sogou, 2020). This recorded information further benefited the efficiency of the assembly process and avoided waste. They could also be used in further refurbishment or selective demolition.

In the usage stage, the model together with the IoT system formed the information center of the Leishenshan hospital. 17 information systems were included in the information center, such as video surveillance, hospital information systems, picture archiving and communication systems, radiation information systems, virtual reality telemedicine systems, and online interactive platforms. They are responsible for monitoring the performance of the facilities, social distancing and providing the visualized information to the end-users. With the help of the information systems, the materials' states were monitored for predictive maintenance, and the lifespan of the components were increased. What's more, they also enabled 0 infections of the medical personnel during the pandemic (Zhou et al., 2020; Luo et al., 2020; Interview C, D).

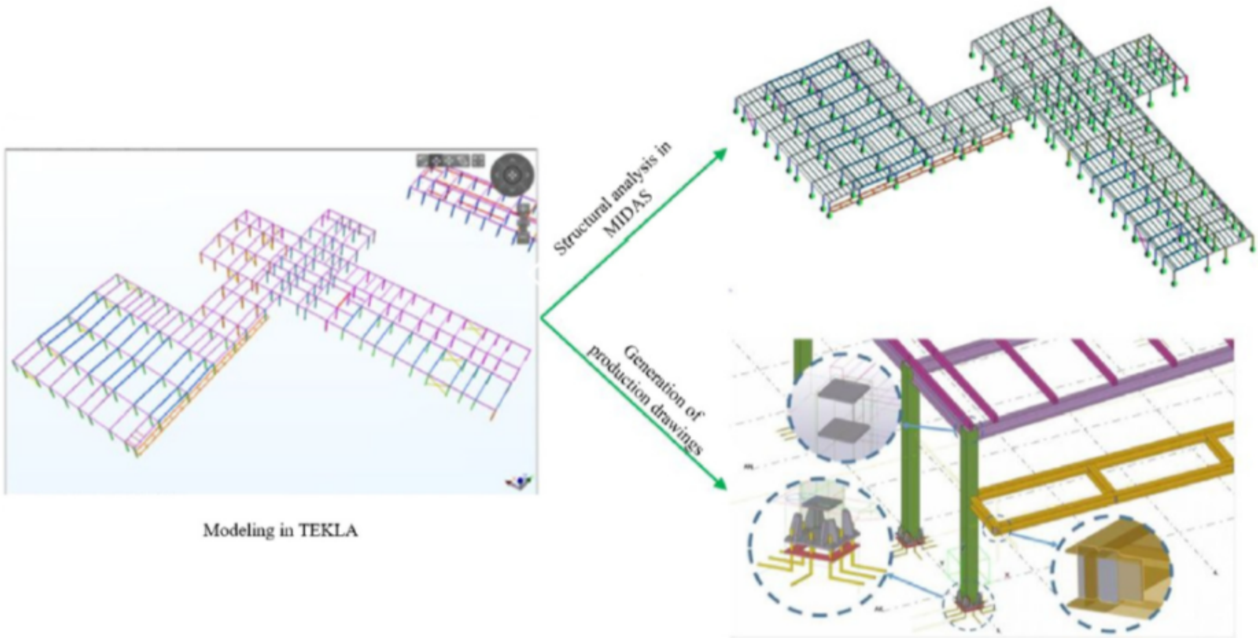


Figure 3-8: TEKLA structure analysis (Provided by CSADI)

3.2.3.2 Applied CC principles without DT's support

Procuring and using secondary materials was applied in the project as one of the circular goals. However, due to the time and technical restrictions, none of the DT technologies were used in assisting it. The intention of using secondary materials started from the design stage. Due to the material shortage, one-third of the total 3300 container-type mobile units were secondary materials. At the manufacturing stage, the contractor and their partner suppliers procured 1000 secondary units from their previous construction projects in Wuhan (Xu, 2020; Interview A). The size of these reused units was adjusted based on the design requirement (Interview D). Finally, the new manufactured and reused materials were together assembled on site, as shown in Figure 3-9.
Although the information of the above-mentioned standardized components was included in the BIM model and material passport of the building. The information was based on a single project and wasn't linked with other projects in the supply chain(Interview A).

Figure 3-9: Assembly of container-type mobile wards (provided by CSADI)

3.2.3.3 Potentially applicable CC principles

Besides the CC principles applied in Leishenshan hospital, there are several principles that have potential to apply after the end-of-life stage, including balancing supply and demand, reusing of materials and components after end-of-life, on-site sorting of demolition waste, and selective demolition.

Firstly, most of the materials used in Leishenshan hospital are standardized. Figure 3-10 shows the structure of the contain-type mobile units, the steel framework, and the wallboards were produced separately and then assembled on site. Basic units could be assembled alone or with different combinations in both horizontal and vertical directions.

The medical technology facility area required bigger and higher spaces for the facilities, operating theatres, and clinical laboratories. Therefore, the container-type mobile units were not suitable anymore. Therefore, prefabricated steel components are used (figure 3-12). According to Interview A and Zhou & Tian (2020), the lifespan of the steel parts is around 50 years, while the wallboards with a short lifespan are easy to replace. Therefore, the building components of these two zones all have high reuse potential and a high degree of adaptability (Zhou et al., 2020).

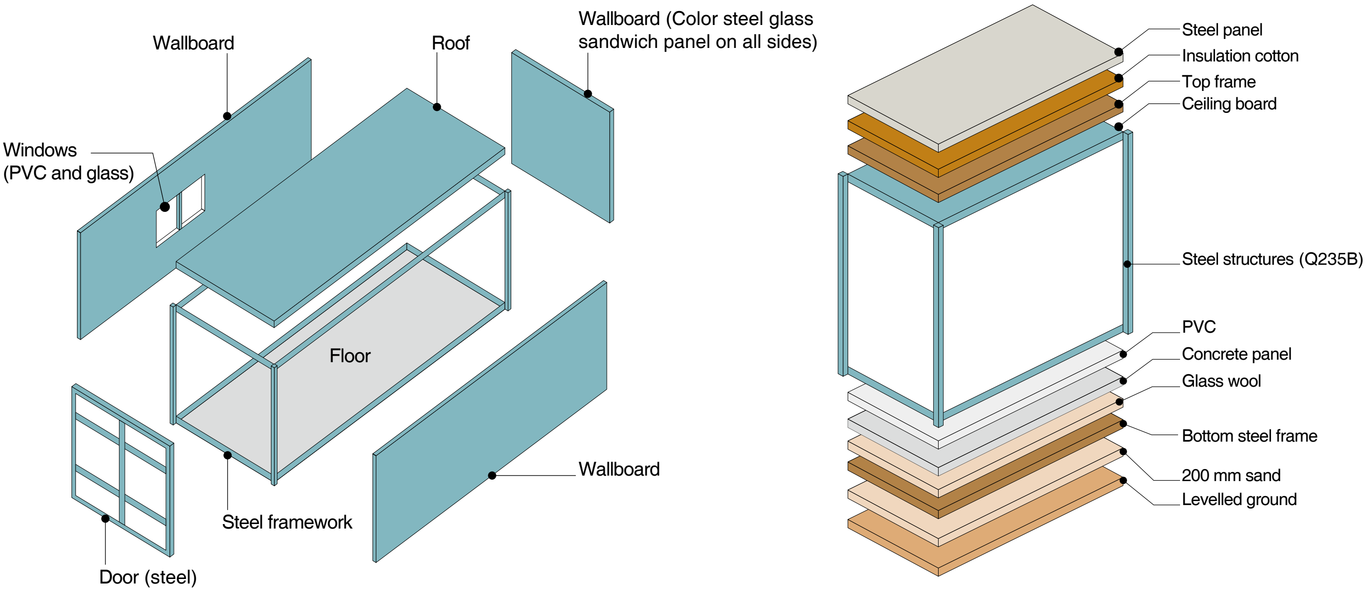


Figure 3-10: Structure of the container-type mobile wards(Updated based on Zhou et al.,2020)

Figure 3-12: Structure of medical technology facility area (provided by CSADI)

However, for reusing or recycling these modular components, the circular principles at the end-of-life stage are yet considered in the project. Although the hospital is temporarily closed at this moment, it is still uncertain when it will reopen or be demolished. However, what is certain is, a considerable amount of materials and facilities could be reused at the end-of-life (Figure 3-13, 3-14).

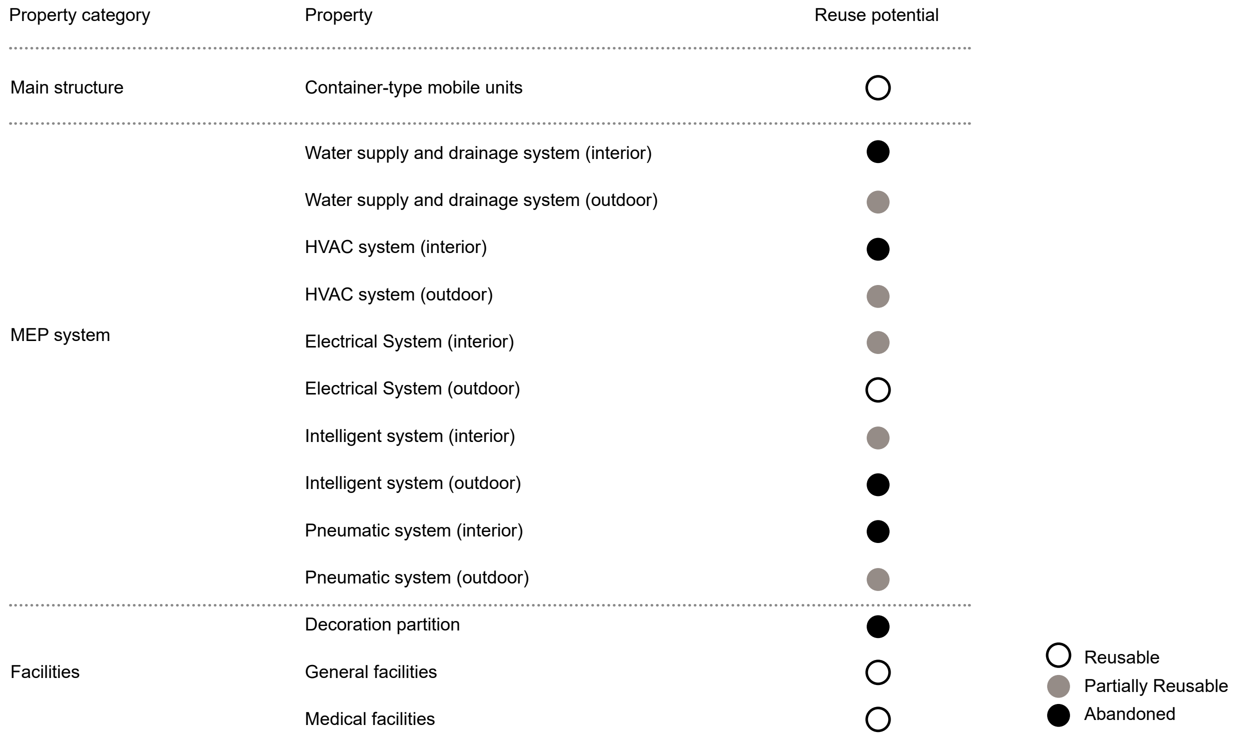


Figure 3-13: Reuse potential of all materials and properties after end-of-life (own figure)

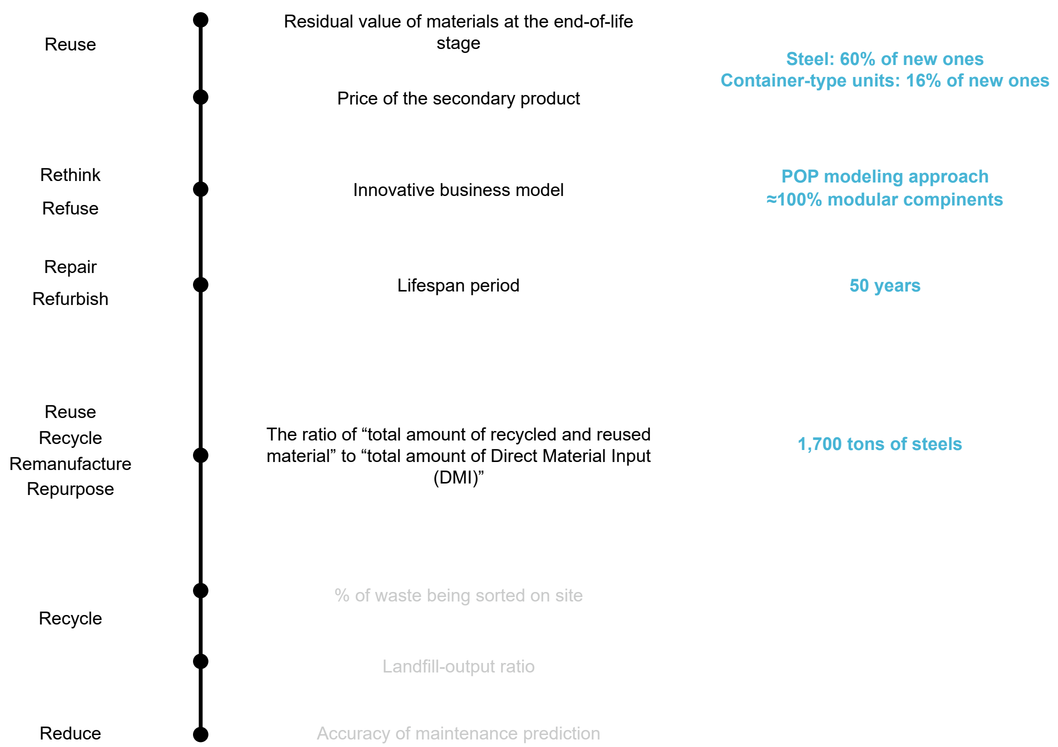


Figure 3-14: Evaluation of circularity (own figure)

The main structures, including the container-type mobile units and modular steel structures, are mostly reusable after end-of-life. Their designed lifespan is around 50 years, which means there is high reuse potential. There are 3300 container-type units in this project, whose residual value is around 16% of the new ones. While for the 1700 tons of steel, the residual value is around 60% of the new ones. Therefore, the reuse and recycle rate is considered high in the demolition or refurbishment stages (Interview A; Zhang, 2020).

Therefore, at the end-of-life stage, the static materials information stored in material passports and the active information of the materials could be used in assessing the reuse value of the materials, so as to benefit the reusing of materials and components after end-of-life. The valuable and reusable materials could be selected by applying selective demolition. They could be used in other projects to balance the supply and demand of the secondary materials market.

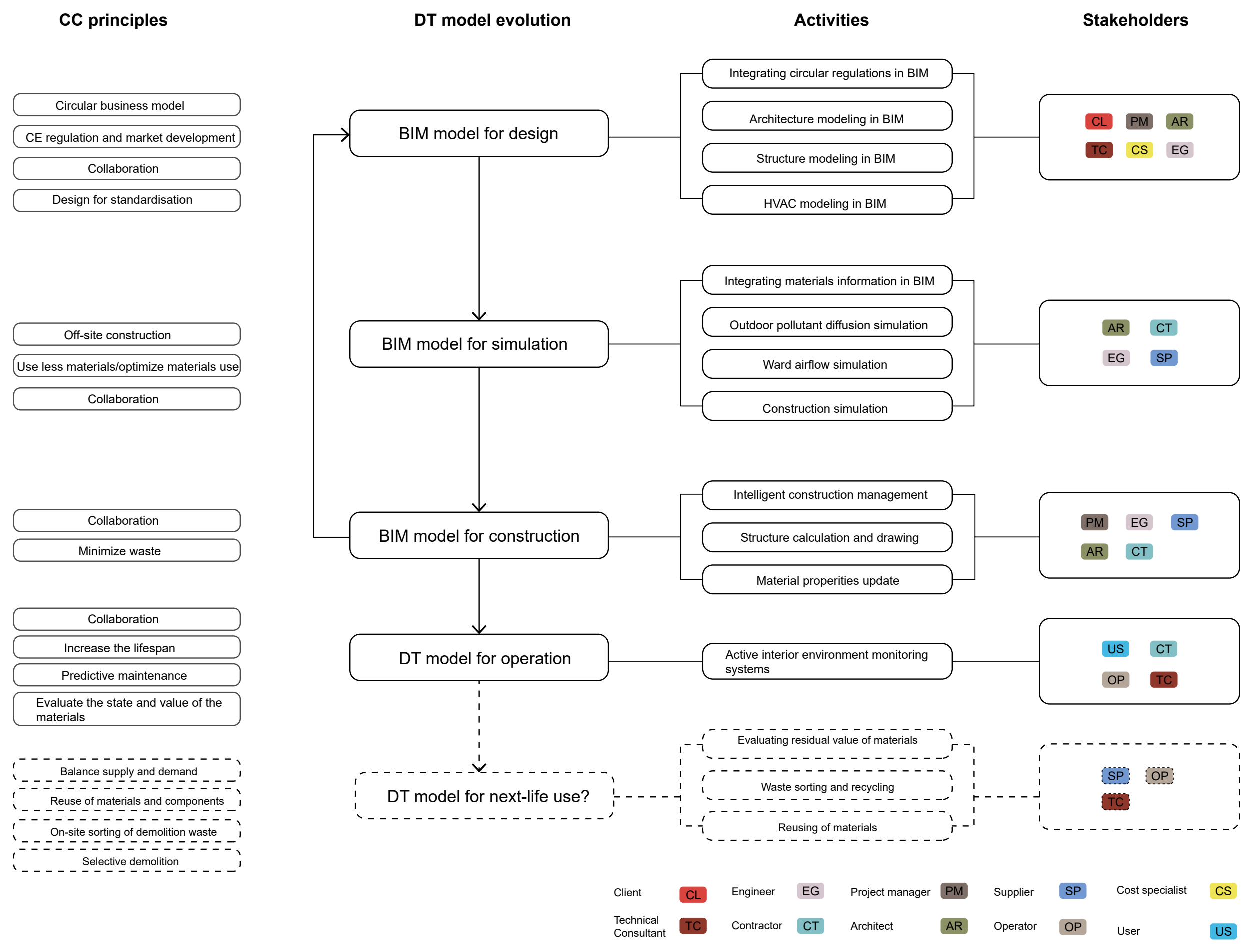


Figure 3-15: Potentially extension of the DT and CC applications after end-of-life (own illustration)

3.2.4 Discussion

3.2.4.1 DT model assessment

Figure 3-16 gives an evaluation of the final DT model in this case. The autonomy is at level 1, which means the user controls all aspects of the digital twin. The intelligence is at level 1, which means the DT model has almost no intelligence. The Learning is also at level 1, meaning that the DT model has no learning component, which is aligned with its autonomy and intelligence levels. The accuracy is at the highest level in this case, because the DT model has a high degree of accuracy compared to the real object, and can be used in the case of life safety and critical operational decisions. Therefore, the model works as a tool in providing information for decision-making, but not making decisions itself, which is aligned with the actual applications. The DT technologies in Leishenshan hospital mostly work as supporting tools in providing information instead of making decisions themselves.

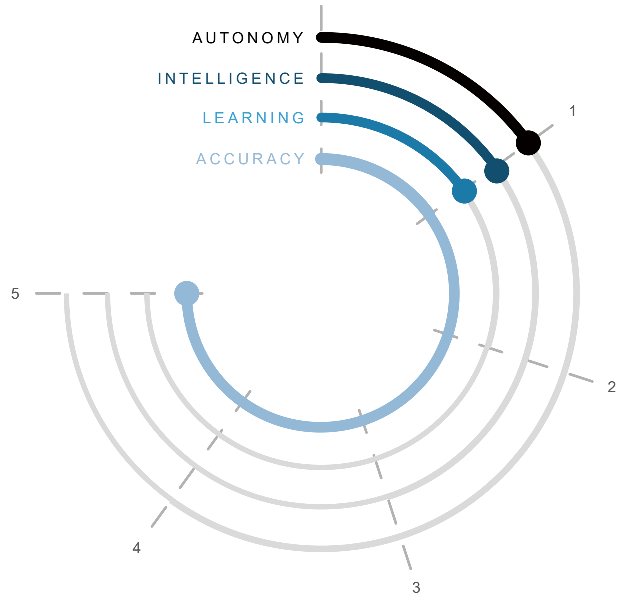


Figure 3-16: DT model evaluation (own illustration based on ARUP, 2019)

3.2.4.2 CC principles and DT technologies applications reflection

Several CC principles were applied under the requirements and restrictions, partly assisted by DT technologies. However, not all of the applicable CC principles were applied. Similarly, not all applicable DT technologies were used in the process. Therefore, this section discussed the application of the CC principles and DT technologies by reflecting them on the knowledge framework.

Possible improvement of the DT technologies applications

The circular business model of POP modeling approach was applied in Leishenshan hospital. However, the material passport was not integrated in the business model. It only worked as a tool in collecting information for off-site construction and on-site assembly. If it could be integrated into the circular business model, the whole process of using and reusing secondary materials in and out of the project could be improved.

Procuring and using secondary materials used traditional procedure, without the assistant of DT technologies. On the one hand, it is because of the lack of materials' information from other projects. On the other hand, the concept of material passport or material bank were not embedded from the beginning. If the importance of a material passport could be realized from the beginning, procuring secondary materials or reusing materials might be easier and can benefit future reuse rates.

Potentially applicable CC principles and corresponding DT technologies

As mentioned above, although the concept of material passport did not exist until the manufacturing stage, it was used in assisting the construction. Furthermore, the IoT networks made the materials' information active. Although when the building will reach the end-of-life stage is uncertain due to the global pandemic, what is certain is that the information could be used in evaluating the value of the materials for selective demolishment and reusing components after end-of-life.

Applicable CC principles under the context

More CC principles could be applied in the project if given more time (Interview B). For instance, emphasizing the importance of circularity early in the project could potentially benefit the circularity of the project. The design could also be optimized to design for disassembly and adaptability, which can increase the reusing and upcycling rate of the components in the future. What's more, the existing DT technologies applied have the capability to assist the above mentioned circular principles.

3.2.4.3 Contribution to the DT-based CC management framework

As mentioned above, the stakeholder perspective needs to be considered when developing the DT-based CC management framework. Although some stakeholder perspectives were located in the canvas, there are still some absences and biases. Therefore, a supplementary literature study that focuses on different DT technology users' roles in dealing with the circular goals. The results are summarized in Figure 3-17.

Figure 3-17 is the primary version of the DT-based CC management framework. It was developed by adding the possible DT technology users in the canvas (Figure 3-1). Compared to the knowledge framework, the stakeholder dimension is added, which could be useful in implementation. To be more specific, the project managers could have an idea of what could be taken into account in circular projects. They could also gain an overview of who could be involved in realizing certain circular goals. The involved stakeholders who hold circular goals could also find their suitable tools. In the next step, the 'Where', which represents the project management thinking, is integrated to restructure and complete the knowledge framework.

3.2.5 Conclusion

In conclusion, this chapter contributes to answering SQ3, ‘What DT technologies are able to assist CC and why?’ by conducting a focus group and analyzing Leishenshan hospital. The DT-based CC knowledge framework was put in the focus group discussion for adapting it to an implementation framework. As a result, stakeholder perspective was integrated into the framework as the management framework canvas.

Then, the management framework canvas was used in analyzing the case study. How the stakeholders used different DT technologies in realizing different circular goals were revealed by the examples from the case. In the case study, several DT technologies were used across the project life cycle, including cloud computing, BIM modeling, construction simulation, material passport, and IoT sensor networks. Several softwares, including Autodesk Revit, XFlow, and Tekla, were used to support the DT modeling process. The DT technologies assisted CC principles, such as integrating CC from the beginning of the project, collaboration, design for standardization and adaptation, off-site construction, recording materials information into the model, minimizing waste, predicting maintenance. There are also CC principles applied that were not supported by DT technologies, such as procuring and using secondary materials. Based on the evaluation of the circularity potential, CC principles such as reusing materials and selective demolition can also be applied after end-of-life.

Under the POP modeling approach, the early involvement of the BIM-based integrated platform facilitates the efficiency and effectiveness of information exchange across the project organization, so as to benefit the collaboration and minimize the rework. BIM modeling and construction simulation supports standardized design and construction, and enables waste minimization. Material passport benefits the time and waste reduction in on-site assembly on the one hand, and enables future material reuse on the other hand. IoT-based information systems benefit waste reduction and predictive maintenance at the usage stage.

However, in this case, DT’s benefits on CC are not as ideal as the relevant theoretical knowledge. Some benefits were limited due to realistic restrictions. For instance, most of the design and construction work were done simultaneously in an extremely short time. The limited time for the feasibility stage leads to the unsolid brief and inadequate knowledge of the site. As a result, the initial design was adjusted several times according to new requirements and conditions on-site. The reused materials' sizes did not all align with the design requirement, which also took time to adjust. In addition, the benefits of DT and CC in the use stage were not obvious because the hospital was temporarily closed from April, 2020. Besides, whether the hospital will be demolished or refurbished in the future is not decided yet. Therefore, although there is huge reuse potential of the modular materials, the CC principles application after end-of-life is still uncertain.

Knowledge from the case study and the supplementary literature study contributed to the primary version of the DT-based CC management framework. The primary framework includes three dimensions, DT technologies, CC principles, and stakeholder perspective. Therefore, not only the relationship between DT and CC, which is the same with the knowledge framework, is included, but who can use the technologies is also shown in the framework. This primary framework moves one step further in implementing the DT technologies in CC in practice.

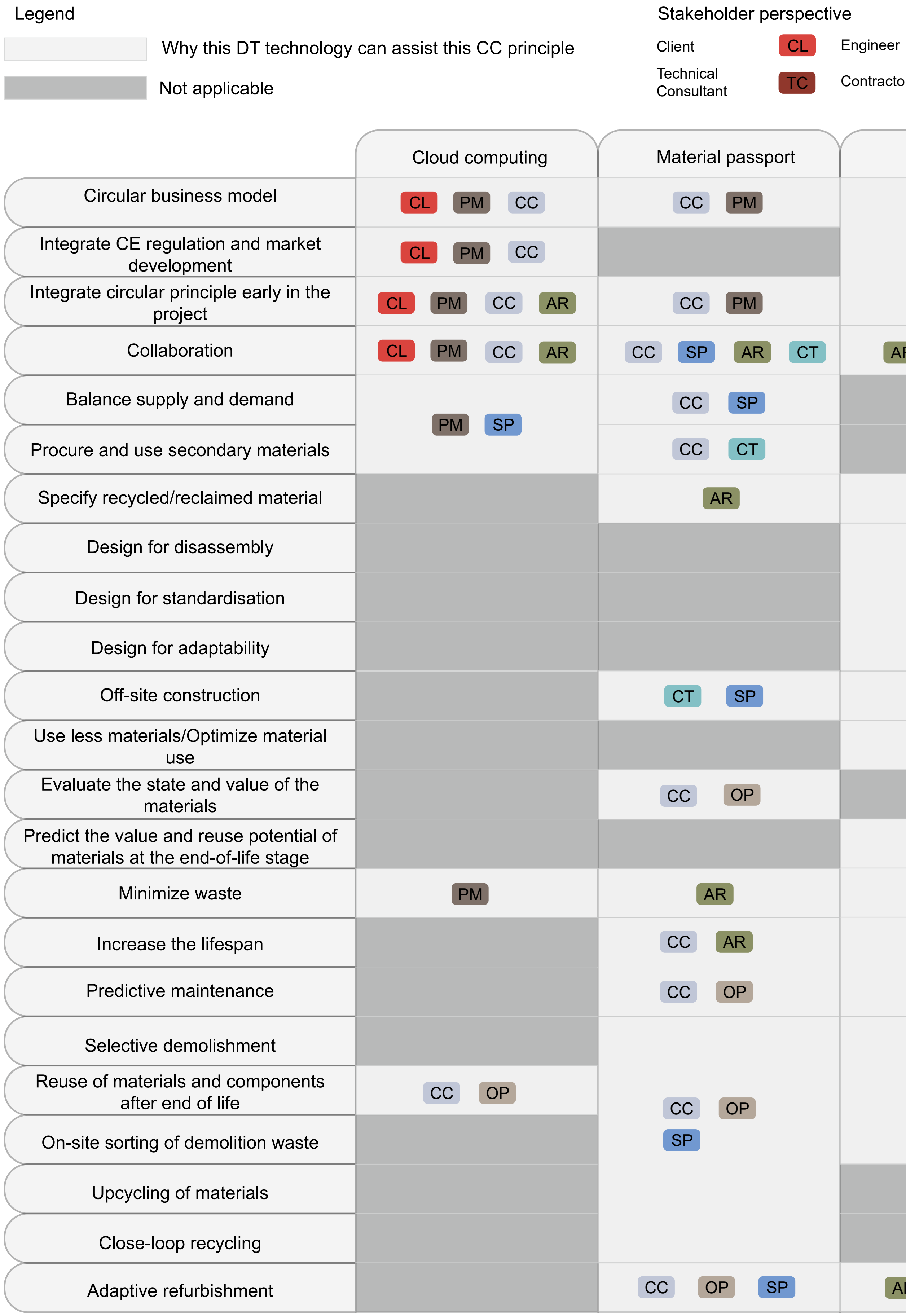


Figure 3-17: DT-based CC management fra

amework (primary version) (own illustration)

Chapter 4
Synthesis

In the theoretical research, a DT-based CC knowledge framework was developed. Then, in order to implement it, a primary version of the DT-based CC management framework was developed by adding stakeholder perspective to the knowledge framework. In order to make it more practical, the primary management framework was restructure by integrating with project life cycle management structure.

The DT-based CC management framework, as shown in Figure 4-1, integrated the information from 'Circular strategies in the built environment (Figure 2-1)', 'CC strategies and principles (Table 2-1), and 'DT-based CC management framework (primary version) (Figure 3-17)'. Its structure follows the project management thinking, from feasibility to end-of-life stage. In the horizontal axis of each life cycle stage, the involved stakeholders, the applicable CC principles, the available DT technologies, and the relationship between DT and CC are presented. In practice, after learning about the circular value of the project, the project managers could use the management framework to filter the CC principles that align with the value. Then, they could know in which life cycle stages, what stakeholders might be involved in, and what DT technologies are available in realizing the specific CC principles. For the specific information of the reason why the technologies could be used, they can always go back to the knowledge framework for detailed explanation. In this way, the management framework could help the project managers to learn the stakeholders and the activities they might manage so as to benefit the circular projects.

Besides the project managers, other stakeholders could also use the management framework in circular projects. They could find their role in the framework, then, their involved life cycle stages, the possible collaborators, the CC principles they might need to work on, and the corresponding DT tools are available. For instance, architects can find their role exists in feasibility, design, manufacture, and construction stages. However, it includes all the possibilities, the actual involved stages depend on the procurement strategy in the specific case.

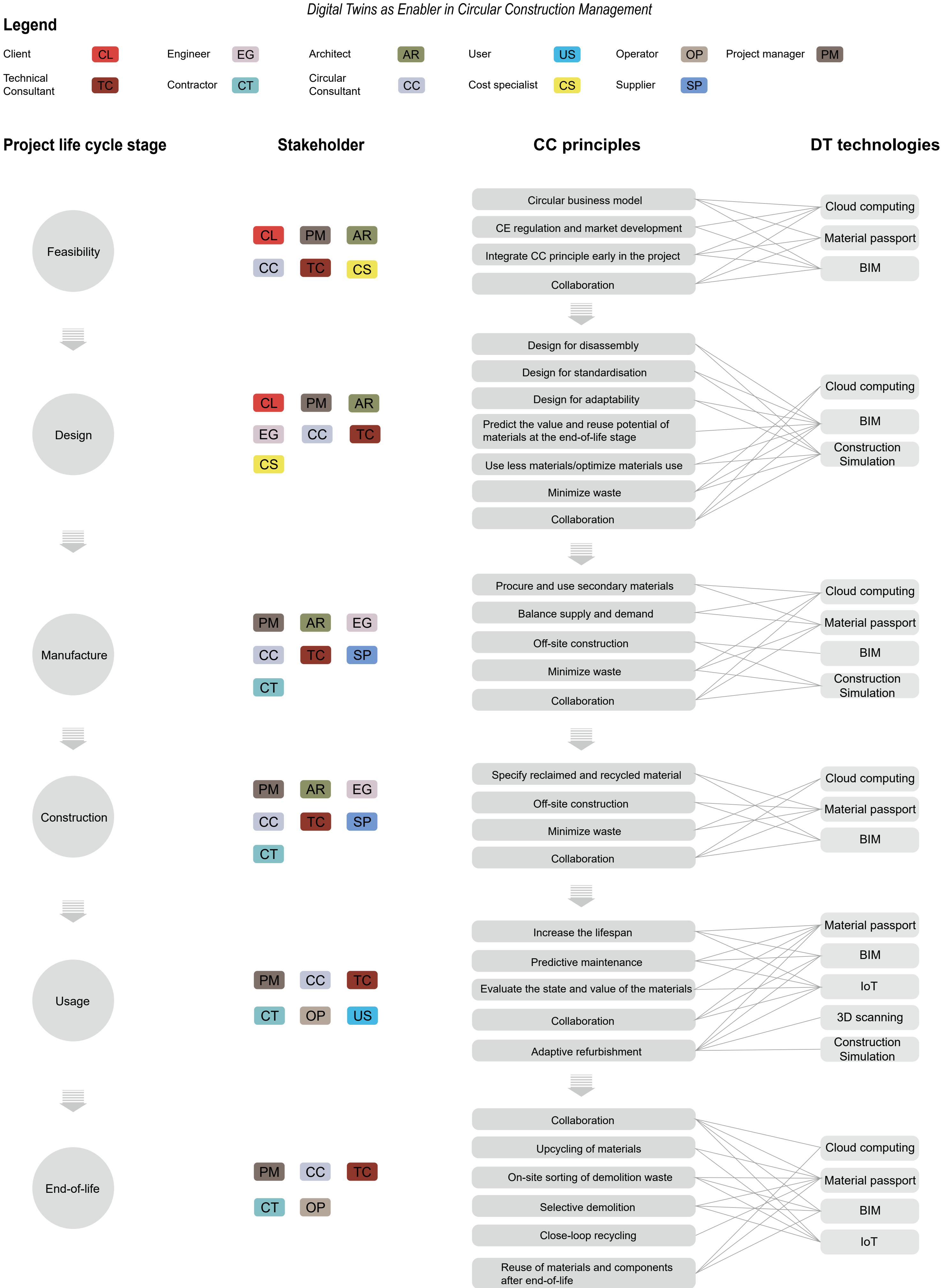


Figure 4-1: DT-based CC management framework (own illustration)

Taking a project delivered in DB strategy as an example, the architects are involved from feasibility until construction. By using the management framework, the architects can know at the feasibility, they will collaborate with the client, the project managers, the circular and technical consultants, and the costs specialist. Together they could integrate the circular principles in the project by apply the circular business model and the material passport concept. A BIM-based cloud collaboration platform could also help with adapting the circular business model. The relevant circular regulations and market dynamics could be obtained from the smart city database, which are supported by cloud computing and BIM.

At the design stage, besides the collaborators at the feasibility stage, engineers will join in the project organization. They work together in designing circular projects. BIM is widely used in this stage, for realizing design for disassembly, design for standardization, design for adaptivity, predicting the value of materials after end-of-life, optimizing material use, minimizing waste, and effective collaboration. The cloud collaboration platform, and construction simulation could assist in calculating and optimizing the design for using less materials and minimizing waste.

At the manufacturing stage, architects might collaborate with the project managers, engineers, consultants, suppliers and contractors for providing information on component production. In a circular project, they partly use secondary materials, which could be procured with the help of materials passport and cloud computing. For the new manufactured components or adjusting the size of the secondary materials, BIM and construction simulation can provide relevant information, in which processes, waste reduction and effective collaboration could be guaranteed.

At the construction stage, the same stakeholders as the manufacturing stage could be involved. The information stored in BIM and material passport could be used in on-site assembly of the pre-fabricated components. The cloud collaboration platform provides seamless scheduling management and site circulation management for minimizing waste of resources and optimizing the collaboration.

The way of using the management framework in circular projects for other stakeholders is similar to the architects' example. Therefore, the management framework can not only benefit the project managers, but also all the involved stakeholders could get transparent information of the circular project management process and the available DT tools. In this way, the collaboration could be optimized, as well as the delivered circular products.

Chapter 5
Conclusion

Under the trends of circularity in the built environment, it is crucial to integrate CC principles in all life cycle stages, from feasibility to end-of-life. DT technologies were proved as valuable tools in achieving CC. In order to understand the relationship between DT technologies and CC principles as well as its practical implementation, this thesis was structured to answer the research question, **"How can Digital Twins be used in improving circular construction management?"**. Three SQs was proposed in order to answer the main research question step by step. As a result, a DT-based CC management framework was developed.

SQ1: What is the role of circularity in the built environment?
With the development of the circularity theory, the circular strategies were extended to 10 Rs, including refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recovery (in order of priority). They could be categorized into three types of strategies, including smart use and manufacture of materials, extending lifespan and productivity of material and its parts, and useful application of materials (Potting et al., 2017). The 10 Rs could be related with the project life cycle in CC management. Refuse and Rethink are at a more strategic level and could be applied at the feasibility and design stage as circular initiatives. Reuse, Remanufacture, Repurpose, Recycle, and Recovery focus on reusing or recycling materials after end-of-life. Therefore, they could be applied at end-of-life stage. Reused or recycled materials and recovered energy could be sent back to the manufacturing stage for servicing another life cycle. Reduce should be taken into account during the construction and usage stage. Repair and Refurbish focuses on increasing the quality of the existing materials. Therefore, they should be considered at the usage stage. The 10 Rs are also translated to specific CC principles, such as integrate circular principle early in the project, applying Circular business model, balancing supply and demand, optimizing material use, design for disassembly, and selective demolition etc.

SQ2: What DT technologies are able to assist CC and why?
From the theoretical perspective, the use of DT can facilitate CC by supporting technical, managerial, informative aspects across the project life cycle. The knowledge framework gives an overview of what CC principles could be assisted by which DT technologies and the reasons behind that. For instance, the cloud platform across projects could benefit adopting circular initiatives. The cloud plotform within the project organization could facilitate effective and efficient collaboration. BIM modeling and construction simulation support circular design and construction. IoT sensor networks and 3D scanning monitor and replicate real-time conditions for predictive maintenance, adaptive refurbishment, and selective demolition to reduce waste. Material passport facilitates closed-loop recycling by tracking the information regarding individual components and materials for reuse and recycling.

SQ3: How to implement DT technologies in realizing CC?

The DT-based CC management framework was developed to answer SQ3. During the development process, firstly a management framework canvas was proposed by integrating stakeholder perspective into the knowledge framework. Then, the detailed information of the stakeholders were filled by conducting case study and an additional literature study, resulting in a primary version of management framework. It was then synthesized with the project management thinking and form the final version of management framework. The management framework includes four dimensions, DT technologies, CC principles, project life cycle, and stakeholder perspective. In practice, after learning about the circular value of the project, the project managers could use the management framework to filter the CC principles that align with the value. Then, they could know in which life cycle stages, what stakeholders might be involved in, and what DT technologies are available. For the specific information of the reason why the technologies could be used, they can always go back to the knowledge framework for detailed explanation. In this way, the management framework could help the project managers to learn the stakeholders and the activities they might manage so as to benefit the circular projects.

Chapter 6
Discussion

6.1 Reflection on existing knowledge

This thesis focuses on DT and CC's applications in both scientific and practical levels. Two frameworks, one knowledge framework and one management framework were developed in order to get a deep understanding of DT's benefits in CC and maximize the benefits. These two frameworks fill the knowledge gaps that are mentioned in the problem statement.

Circularity is one of the biggest trends in the built environment and has been researched in the past decade. However, the 10 Rs circular strategies are more at a general level instead of focusing on the construction level. This thesis translated them to specific CC principles by integrating with the circular principles across the project life cycle. In this way, the role of CC in the built environment follows the structure of 'Strategy category - circular strategy - CC principle'. The information from general to detailed level can benefit relevant decision-making from strategic to implementation levels.

Digitalization's benefits towards sustainability or circularity were discussed a lot in the past two decades. Particularly, BIM modeling is already seen as a mature tool in supporting circular design. Meanwhile, the research on IoT and material passport's role in CC also have started. However, the research on the above mentioned technologies is fragmented and hard to benefit each other. Instead, this thesis sees the process of building a DT model as a whole, by taking the embedded technologies into account. In this way, the research focuses on life cycle management. Therefore, the delivered knowledge framework is holistic and comprehensive.

Currently, due to the fragmentation of the DT technologies' applications, there is no management framework that focuses on the process of building DT models, which impedes DT's benefits to be realized in CC. The management framework proposed in this thesis facilitates the DT-based CC application by matching the CC principles in different life cycle stages and the available DT technologies, and integrating with the stakeholder perspective and project management thinking. It increases the information accessibility during the CC management.

6.2 Contributions of the research

This thesis contributes to both academic research and practice of DT and CC. For academic research, firstly, the thesis provides a better understanding of the benefits of DT's benefits in CC by proposing the knowledge framework. The structure of the frameworks is also flexible and can be extended or adjusted depending on future research. More technologies or principles could be added to the two axes. The cells could also be adjusted if more correlations are revealed.

The canvas proposed was used in integrating the stakeholder perspective in this thesis. It could be used in furture case studies. What's more, besides stakholder perspective, there could be more possibilities. For instance, the type of projects might also be interesting when discussing the management framework. Therefore, the canvas could benefit the development of different types of the management frameworks.

In order to collect the stakeholder perspective, this thesis conducted an extreme case study, which was developed under an extraordinarily short time limitation. In this way, the benefit of DT in effective collaboration in standardized design is obvious. This kind of condition was not mentioned in the existing literature. Therefore, the case study provides a new perspective.

The management framework fills the knowledge gap of applying DT in assisting CC in practice. Although it is an initial concept, it could increase the information accessibility in circular project management. The management framework works as an starting point in managing the DT technologies' applications in CC, which can be enriched by future research and practices. For instance, it could be explored by adding practical examples. Behind each correlation of the CC principles and DT technologies, the examples of activities in a specific case could be provided. In this way, the management framework could have higher practical value and become more convincing.

Chapter 7
Recommendation

7.1 Academic recommendation

DT is a relatively new notion in the construction industry without much scientific research. What's more, most of the research so far mainly discussed how the final building DT model benefits the usage stage. This thesis discusses the six embedded technologies in the process of building a DT model and relates their benefits with CC principles by developing a knowledge framework.

The academic recommendation of refining the knowledge framework are:

1. Consider the intermediate products, instead of only the final one, when discussing its benefits to CC.
2. Keep adding CC principles and corresponding DT technologies.

The academic recommendation of further developing the management framework are:

1. Conduct more case studies to make the results more concrete.
2. Add practical activities in the management framework as examples.
3. Organize focus groups with more experts for adding new perspectives in the management framework.
4. Organize focus groups with stakeholders in practice for refining the management framework.
5. Take financial feasibility into account to increase the practical value of the management framework. The most mentioned barriers and challenges in applying DT-based CC are regarding finance, such as lack of clear financial cases and financial support.

7.2 Practical recommendation

The DT-based CC management framework could be used in practice to benefit circular project management. There are several practical recommendations for using it:

1. Discuss the application of the DT technologies together when making strategies to maximize their benefits on circularity.
2. The stakeholders are possible but not necessary involved ones, therefore, it depends on the procurement strategy and other actual conditions in practice. The project managers could adjust it depending on the specific situation.
3. The management framework includes the available DT technologies for each CC principle, but if one needs to know the reasons behind that, the user could go back to the knowledge framework.
4. If possible, the practical users of the management framework can add real case examples in the framework to benefit refining the management framework.

Chapter 8
Reflection

8.1 Research approach

8.1.1 Reflecting on the methodology

The topic of the thesis is using DT in benefiting circular construction management. The thesis is based on a qualitative research method, including three stages, a systematic literature review, a focus group, and a case study.

Systematic literature review: knowledge base, find focus group participants

The advantage of the systematic literature review is to generate unbiased and comprehensive accounts of the literature. In this study, the findings from the literature review helped to build the knowledge framework, which is also the basis of the management framework. Besides, two participants of the focus group were recruited by contacting the authors of the literature.

However, there are some improvements that could be made to the theoretical research method. Firstly, a focus group that aims to collect general information on DT-based CC could be done in this phase. Questions like ‘What are the recent trends you've noticed in applying DT in circular construction and how they influence the construction industry? ’, ‘Which sources do you go to for information on circular construction?’, and ‘When do you think about circular construction, which brand or people come to mind first?’, could be discussed to inspire the frameworks development and the choice of cases. Secondly, more quantitative evaluation measures of the degree of circularity could be considered.

Focus group in inspiring management framework

The focus group was organized to discuss the knowledge framework and inspire the management framework development. Experts and researchers from different contexts were invited and discussed the knowledge framework. Part of the findings were used in refining the knowledge framework. Suggestions regarding implementing the knowledge framework were also generated, such as integrating stakeholder perspective, and life cycle management perspective. However, due to the time limitation, there is only a round of focus group. Discussion with more people could provide more ideas if given more time. Focus groups could also be organized in discussing the management framework to make it more concrete and applicable.

Case study give practical perspective

The case study gives a practical perspective of DT and CC’s role in the built environment and helps to add stakeholder perspective in the management framework. However, The case, Leishenshan hospital, has several limitations as a single case study. Firstly, different from some other circular projects which put circularity as their core value, the CC principles in the case were mainly applied for meeting the time requirement, with achieving circularity as a bonus. Therefore, to some extent, the degree of circularity didn’t reach the highest possible level. For instance, how to reuse or recycle the modular components was not taken into account during the development although it has huge potential. Secondly, although single case studies can yield invaluable insights, most multiple-case study designs are likely to be stronger than single-case study designs (Yin, 2009). Therefore, if multi-case studies under different contexts could be conducted, more unbiased and general findings could be generated.

8.1.2 Reflecting on the research findings

The findings from this thesis are bound to certain limitations regarding context, timing, methodology, and scope. These limitations provide opportunities for future research.

Context

The case study is based on the Chinese context. Although the supplymentary literature study compensates for the possible bias of the single case study, it is better to conduct more detailed case studies under other contexts.

Timing

The research is limited by the information available at the time of the study, especially for the case study. Leishenshan hospital is the COVID-19 emergency hospital, although it was temporarily closed now, with the global pandemic ongoing, it is hard to foresee whether it will reopen in the future. Therefore, the information about reusing or recycling the materials is inadequate. We can only anticipate the residual value, but it mostly depends on the actual condition in the future.

Scope

The deliverable of the research, which is the DT-based CC management framework, mainly focuses on decision-makers' perspective. However, in circular project management, the user participant is also important. Especially in the usage stage, which aims to minimize waste, positive collaboration between the operators and the users through DT interfaces could benefit circularity. Therefore, the scope of the management framework could relate with the user 's perspective.

8.1.3 Scientific, social, or practical relevance

Scientific relevance

Although DT is seen as an important enabler in CC from the previous research, it is still a rather novel topic in the field of construction. Besides, most of the existing research relates CC only with the final building DT in the use stage, instead of seeing the process of building a DT as a whole concept. Therefore, this thesis focuses on embedded technologies in DT, such as BIM, IoT, cloud computing, and material passport, to research their benefits on realizing CC. As these technologies are used in different life cycle stages, seeing them as a whole could benefit a circular life cycle management. This provides a new perspective for future research. What's more, the research on BIM is already quite mature, so it is already a good basis.

The canvas that was used in analyzing the case could be easily transferred to similar projects because it was based on the knowledge framework. By using the framework, the researchers can quickly get an overview of the current conditions and the gaps. The detailed analysis process can also follow the framework structure.

As mentioned before, a framework is absent in applying DT in CC. In this thesis, a management framework was proposed to facilitate DT's benefits in realizing CC. There is limited research in this field so far, so it is expected that the management framework could inspire future research, both from its structure and its content.

Social relevance

The application area of the thesis is circularity in the built environment. In the current built environment, little materials are returned or upcycled to the construction industry. Besides, the huge environmental impact of the C&DW and the resource scarcity all make CC a hot topic.

Therefore, this thesis proposed a management framework in implementation, which could facilitate CC, so as to contribute to a more circular and sustainable built environment.

Practical relevance

The management framework could be used in optimizing decision-making. By using which, at the front-end stage of the circular projects, project managers can get a clear overview of the stakeholder involved, the circular goals, and the available DT tools in each life cycle stage. It can also benefit other stakeholders' performance in CC management by increasing information accessibility. The stakeholders can get to know their collaborators, their possible CC principles and corresponding DT tools.

8.2 Impact of COVID-19

Impact of the research

The thesis was conducted during the COVID-19 period, therefore, several aspects were affected by the pandemic. The case study, Leishenshan hospital, was built for controlling the outbreak of COVID-19 in Wuhan. The time and resource restrictions made some of DT's benefits more obvious. For instance, DT enabling effective collaboration was proved in the case study, through delivering in 2 weeks.

COVID-19 also affects the research methodology. Due to the travel restrictions, although the case is in the Chinese context, all the interviews were conducted online. Because of working from home measures, the focus group was also done online. However, the online meeting makes it possible to let participants from different countries join, benefiting perspective diversity.

Impact of practice

As working from home became the new normal, more and more employees prefer to work from home for certain days per week even after the pandemic ends. In this case, the DT-based collaboration platform follows the trends and can benefit the information exchange in the future. The actors can get access to the updated data anywhere, instead of going to the site or others' offices for meetings.

DT can also benefit COVID-19 related measures. As mentioned in the case study, the sensor network and information systems enable zero infection of medical personnel by monitoring the social distancing. In other projects, DT can also be used to monitor social distancing to minimize the risk of COVID-19.

8.3 Ethical dilemmas

There are almost no ethical dilemmas in the research process, because the information of the case study, even including the construction drawings, is almost all open to the public. However, data sharing would be an ethical dilemma in applying the result in practice. To be more specific, unwillingness to share information and data security are often mentioned barriers in CC, while building a circular cases knowledge depot or material exchange platform all need information sharing. Therefore, it should be taken into account when continuing the research or putting it into practice.

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Appendix

Appendix I

DT-based CC knowledge framework reference

Appendix II

Interview protocal

Appendix III

Interview transcripts

Appendix I

DT-based CC knowledge framework reference

DT technologies	Benefit CC principle	Reason
Cloud computing	Circular business model	Integrating circu
	Integrate CE regulation and market development	Optimizing deci
	Integrate circular principle early in the project	Increasing awar projects
	Collaboration	Enabling effecti organization
	Balance supply and demand	Supporting the
	Procure and use secondary materials	
	Reuse of materials and components after end of life	
	Minimize waste	Minimizing rewo
Material passport	Circular business model	Enabling the cir across sectors
	Integrate circular principle early in the project	Integrating circu
	Balance supply and demand	Matching the re
	Collaboration	Enabling effecti projects
	Procure and use secondary materials	Recording and
	Specify recycled/reclaimed material	
	Reuse of materials and components after end of life	
	On-site sorting of demolition waste	
	Upcycling of materials	
	Close-loop recycling	
	Off-site construction	Providing mater
	Evaluate the state and value of the materials	Recording and
	Minimize waste	Recording mate
	Increase the lifespan	

	Reference
ular intention across the project life cycle	*Rocca et al. (2020)* *Patterson and Ruh (2019)*
sion-making by increasing awareness of circularity	*ARUP (2019)* *Lim et al. (2019)*
reness of circularity by providing revevant reference	*Benachio et al. (2019)*
ve and efficient communication within the project	*Adams et al. (2017)* *Boje et al. (2020)* *Rocca et al. (2020)*
redistribution of the resources	*ARUP (2019)* *Lu et al. (2020)*
ork by scheduling management	*Mellado and Lou (2020)*
rcular business model of material reuse and exchange and projects	*Rocca et al. (2020)*
ular intention from the beginning of the projects	*Ghaffar et al. (2020)* *Benachio et al. (2019)*
sources between different sectors and projects	*Damen (2020)* *Lu et al. (2020)*
ve and efficient communication cross sectors and	*Adams et al. (2017)* *Damen 2020*
providing materials' information	*Benachio et al. (2019)*
	Rocca et al. (2020)
	Bertin et al. (2020)
	Ghaffar et al. (2020)
	Rocca et al. (2020)
rials' information of assembly and suppliers	*Fan et al. (2020)*
providing materials' information for evaluation	*Antikainen et al. (2018)* *Benachio et al. (2019)*
erials' information for design optimization	*Ruiz et al. (2020)*
	Benachio et al. (2019)

	Predict maintenance	Recording and pr
	Selective demolishment	
	Adaptive refurbishment	Benefiting reusin
BIM	Circular business model	Integrating circula reference
	Integrate CE regulation and market development	
	Integrate circular principle early in the project	
	Collaboration	Enabling effective organization
	Specify recycled/reclaimed material	Working as suppo
	Reuse of materials and components after end of life	
	On-site sorting of demolition waste	
	Design for disassembly	Providing technic
	Design for standardisation	
	Design for adaptability	
	Off-site construction	
	Use less materials/Optimize material use	Optimizing desig
	Minimize waste	
	Predict the value and reuse potential of materials at the end-of-life stage	D-DAS predicts th
	Increase the lifespan	
	Predict maintenance	
	Selective demolishment	Working as suppo
	Adaptive refurbishment	Supporting desig
Simulation	Collaboration	Enabling effective stakeholders (cor
	Design for disassembly	Supporting the re
	Design for standardisation	
	Design for adaptability	
	Off-site construction	

oviding materials' information	Benachio et al. (2019)
	ARUP (2019) Ghisellini et al. (2018)
g material from existing builidngs	CE100 (2016)
ar regulations, codes, requirements for design	Mellado and Lou (2020)
e and efficient communication within the project	Adams et al. (2017) Papadonikolaki et al. (2019) Eadie et al. (2013)
orting platform for storing materials'information	Rocca et al. (2020) Bertin et al. (2020)
al support for circular design and its realization	Akanbi et al. (2019) Lu et al. (2020) Patterson and Ruh (2019) "Mellado and Lou. (2020) Adams et al. (2017)"
n	Eadie et al. (2013) Mellado and Lou (2020) Ruiz et al. (2020)
he value of the materials	Akanbi et al. (2019)
orting platform for storing materials'information	Bertin et al. (2020)
n and reuse of materials	Ghisellini et al. (2018)
e and efficient communication betweem certain ntractor, suppliers, and engineer)	Boton et al. (2013)
alization of the design	Landahl et al. (2018) Boton et al. (2013)

	Use less materials/Optimize material use	Simulating the co
	Minimize waste	
	Adaptive refurbishment	Supporting the re
IoT	Collaboration	Enabling effective stakeholders (ope
	On-site sorting of demolition waste	
	Evaluate the state and value of the materials	Providing active i
	Minimize waste	Facilitating energ
	Increase the lifespan	Providing active i
	Predictive maintenance	Providing active i
	Selective demolishment	Providing active i
	On-site sorting of demolition waste	Providing active i
	Adaptive refurbishment	Providing active i
3D scanning	Adaptive refurbishment	Duplicating the bu

	Autodesk (2018)
nstruction process to minimize mistakes and reworks	*ARUP (2019)* *Boton et al. (2013)* *Ruiz et al. (2020)*
alization of the design	*ARUP (2019)*
e and efficient communication betweem certain erators and users)	*ARUP (2019)* *Boje et al. (2020)* *Rocca et al. (2020)*
	ARUP (2019)
nformation of materials	*Rocca et al. (2020)*
y efficiency by moniroting the interior environment	*ARUP (2019)* *Boje et al. (2020)* *Antikainen et al. (2018)*
nformation of materials	*Antikainen et al. (2018)*
nformation of materials	*ARUP (2019)* *Boje et al. (2020)* *Patterson and Ruh (2019)* *Khajavi et al. (2019)* *Antikainen et al. (2018)*
nformation of materials	*ARUP (2019)* *Ghisellini et al. (2018)*
nformation of materials	*Antikainen et al. (2018)*
nformation of the building's condition	*Patterson and Ruh (2019)*
uilding's condition precisely	*Ghisellini et al. (2018)* *Tobias (2019)* *ARUP (2019)*

Appendix I

DT-based CC knowledge framework reference

General introduction to the interviewee's background and role in the project;
- What is your role in the project?
- What do you think is the most important value (economic, environmental, social) of this project from your perspective?

The applied CC principles in the project;
- Various aspects of this project align with circular construction principles, such as waste reduction, using modular components, using secondary materials. Although those are more the consequence of the time restriction than a conscious circular strategy, how do you think about the role of circularity in this project?
- What elements regarding circularity would be taken into account in the COVID temporary hospital if given more time?
- How was the performance of the reused components?
- As the designed lifespan of the building is 20 years, do you have any idea about what will happen to the materials after this timeframe?

The applied DT technologies in the project;
- What kind of information of materials is included in the BIM model? Is this information only being used during assembly or also later during maintenance? Could it be used for recycling or reuse at the end-of-life stage?
- What do you think about the role of public participation through Livestream in this project?
- I read from the papers that it is very complicated and included 17 systems for the information systems. Are they integrated into one model, and can they be visualized, or how does it work? (example)
- For the information system, does it show the notification when something goes wrong? Or does it adjust automatically?

The performance of the project;
- Is there any data available on the circularity in this project? For instance, the percentage of reused components, percentage of waste reduction, the portion of components that have reuse potential in the future, percentage of work done on the shared platform, etc.
- Typically for hospitals, the cost of operation and maintenance is way higher than construction. Is this the case in this project?
- What is the overall cost of the design and construction? (sensitive - order of magnitude)
- As the life cycle is not long in this case, is the life cycle cost increased or decreased, and why? Is there any reason for this increase or decrease related to DT technologies or circular principles?

The applied business model.
- How did all these disciplines collaborate together? Through BIM or also with other cloud computing platforms?
- Besides the Leishenshan hospital, the design institution was also responsible for 21 temporary clinics for COVID, Was any resources shared across these projects?

Appendix III

Interview transcripts

Interview A:

- Interviewer:

First of all, thank you very much for the interview, and then I would like to briefly introduce myself. I am currently doing my master's degree in Built Environment Management at the Delft Institute of Technology in the Netherlands. This interview is for my master's thesis, which is about the positive effect of digital twin on the lifecycle management of circular buildings. Then it mainly discusses the role of digital twin technologies, such as B and then cloud, computer, and IoT, and then It discusses the role of digital twin technologies, such as cloud, computers, IoT, etc., in promoting circular buildings to reduce waste and also to reduce project lifecycle costs.

And then because Leishenshan hospital uses some project painting techniques, industrialized construction, and communication and cooperation, it will be more in line with my thesis. Then, because my dissertation is in the direction of management, I will focus more on the cooperation of different professions in the project than on the technical aspects, as well as the use of some business models and cooperation models, etc., and then emphasize the role of circular architecture and lifecycle cost in the project.

This is a brief introduction, and then we will start the interview and ask questions. Then it will be more flexible, in addition to the questions I sent you before. If there are relevant questions related to the content of the interview, you can also speak freely if you think of it. Then I will need the recording to do that uh, one is the paper required for the dissertation, but the content will only be used inside my master's thesis, and it is in the form of anonymous.

- Interviewee:

OK

- Interviewer:

Well, I'll start by asking because the Leishenshan hospital project has a lot of circular principles, and then I see that it's reducing waste by 80%. And then basically, a lot of the modular construction was used, like the houses, and the larger spans were also modular assemblies. Then there were also some recycled materials used. But it was more like a consequence of the pressure of a very tight schedule, so in this case, how would you consider the role of recycled building principles like waste reduction in this project, and was the role of these emphasized during the project?

- Interviewee:

I will start with the overall embodiment of a mobile life hospital. Because it can be said that in the world, its whole project is very simple, it is the main structure of the use of box-type panels, and then spliced together, and then in a variety of he may be an installation, may mean that we mechanical and electrical aspects, including these aspects of ventilation and HVAC, maybe as long as a negative pressure system, which is a relatively important role of a highlight. But it was a unique project because the environment was such that all the passages were closed. Then the government was pressured to build a hospital as big as a dozen soccer fields within 10 days so that in that environment In that environment, there is only one project in the world that can be used as a reference. Still, it is not a very good one. Beijing's Xiaotangshan Hospital Xiaotangshan stock market in 2003, from our 2020 this has basically passed 20 years, we only have nearly 20 years ago a project as a reference then we also got the drawings at the very beginning.

Then that just said the management, we are divided into two aspects, the first is in the government, in the government of a layer of supervision and then supervision, and then said at that time by the Wuhan Real Estate is the only one of our government's real estate company. Then as one of our owners, your first management what the owner is the total integrator of all management. Then you can say that you determine to the national level as the overall commander and operator of thought. Then according to the following, we are divided into the design side and our general contractor, which is our three management principles. Then the design side of our construction site is also the first time to get the drawings, the first time to get the small Tangshan drawings found that only because the small Tangshan is very small, maybe 10,000 to 20,000 square meters, but we want to borrow 20.2 million square meters of a thing. Then in this environment, so that we can only say feel the stones to cross the river. Then our construction is also a participant in the whole process because maybe he designed something, such as some resources, just said the pattern Then, we are the domestic compartment. Generally, a quarter is 3 meters x 6 meters a holding approach, like stacking blocks. At that time was more than 3,300, and then the summary achievement is one by one is the ward zone, and then this is a more complicated point of the design at that time. Then it was also completed overnight, relying on BIM to do.

- Interviewer:

OK, I see.

- Interviewee:

Because the China Construction Group's resources are still quite a lot, we gathered in Wuhan city boarding house to do, and then at that time set a then that one is to say the module is 3 meters x 6 meters, 6 meters long, and then 3 meters wide, and then the height should be about 2 meters 6, and then so a modular, and then the middle aisle is the center aisle, and then we use is the frame type, also 3 meters x 6 meters, and then both sides We can put the drawings do not know, you get the drawings inside both sides of the drawings on both sides of the aisle, and then is 1 m 5 x 6 m when uh, 2 m x 6 m 1 m 8, and 1 m 8 x 6 m, and then it was with the main these three formats, and then after lifting, and then the main structure, this is then the main structure of a number of ideas, and then but inside said a ward area to be frank a total of about There are 20 wards, each ward layout we put it on the small Tangshan this idea slightly optimized three three words as a small small b area, and then by abcabcabc and then composed of countless more than 20, and then composed of a large ward, and then ABC what do you mean? A is a ward where two people live, c is also a ward where two people live, it is just a symmetrical relationship, and then the middle b a buffer room of the ward, and then the other side of the partition of their that is to say the shower bathroom side to do a partition of it. So at that time, the whole is by our ABC BCD on so hanging up. Then at the time of the collective words, we use modularity, and then just you mentioned the green construction in the primary phase, in fact, is reflected in our container-type mobile units.

The transport of concrete is the kind of concrete tanker, so many tankers in the above walk, this thing on the traffic organization pressure is enormous, so we adopt the green construction concept. Our outer perimeter is a strip foundation as the outer frame, and the inside is a steel structure.

- Interviewer:

I have a question, first of all, about the green construction, because the whole seems to be the construction process, according to the complexity of the terrain or some difficulties, anyway, more complicated. How is it that you have done some planning beforehand or have done some construction simulation or?

- Interviewee:

Building the hospital in 10 days has very high pressure so that it was not possible to do the push immediately. We all encountered for the first time can say so.

- Interviewer:

How do you communicate with the design side or the A side or something like that? Because I have read various reports before that, it may be through BIM?

- Interviewee:

Our communication is generally based on a sound management system. Then we are on the site side because the city side we have we have about a few dozen. There are about technical staff technicians, and then we divide it into very fine because if we just engage in engineering on top of the project, we divide it into very fine.

Our brief time is a deepening design group. Then they are dedicated to then is dedicated to communicating with the design side and then the design side. If it is waiting for me to find I look for the video. Well, then a lot of things are actually by what we just said such as those base what, in fact, because we say that directly with CAD to draw it out of the drawing, and then we send them, and then they to determine on this can not, and then can, and then they will send us this thing, and then on.

- Interviewer:

I've read some interviews with people involved in this project, and I know that the designer will build a model, and then the contractor will also have a model. Then, at the end, when the project is relatively late, the two models will be combined, and then check the collision or check some other things, so the beginning may be separate work. Then, later on, they will be connected.

- Interviewee:

Yes, there are some process BIM models. But our main just said that this thing can be successful, or mainly rely on our a modular.

- Interviewer:

Yes, and then because modularity is actually my biggest concern in this case. You just mentioned that there are more than 3,300 units. Then because I saw a lot of firefighting from other temporary projects and then reuse, I want to know these recycled materials. Then the pressure will be enormous to transform them into those requirements that need wards will not cost a lot of money, update the new What will it be like compared to a completely new one, and how will they perform?

- Interviewee:

First of all, it is very flexible, such as just said 3 meters is 6 meters, right? Then it is needed in the compartment. The compartment, because first of all it is made of 4 there are several main beams, secondary beams uh will adhere to, so that it these several box-type panel room it is to say that the slats it is flexible to change, for example, for example, the compartment is a conventional one, the square grid right? So, for example, I tend to transform the coin side inside simple, he may play, for example, a centimeter is three meters, I spaced a knife from it, into a 3 m x 3 m two squares, right? What do I need to do? I directly below buried one by one is the type of aluminum alloy an angle on the line. Then I will directly on the top, and then put the slats and then assembled. It's that simple. That is, the pressure of the whole change is minimal. Let me give you also show you the photo. This is the entire compartment of an internal structure.

- Interviewer:

So it's actually not easy to transform it into what it needs to be now.

- Interviewee:

Yes

- Interviewer:

This project does have a waste reduction, and then there's the question of how long is the life cycle of this type of fire protection in general? About how long does it last?

- Interviewee:

The general is generally called a box board room. Its life cycle is generally only because we are originally temporary works. He is also about the same if you say put empty words, 3 to 4 years.

- Interviewer:

Quite short. Because Leishenshan hospital is temporarily closed now, so maybe because the global epidemic is also not very stable in the past two years, it will still remain in that place. So do you think he will be dismantled temporarily or?

- Interviewee:

In the short term, one or two years after the end of the global epidemic, it will basically dismantle. Then I, just said the box this room, it has been he said life, that is, considering very unfavorable factors, such as thunderstorms, rain all the time, in fact, so that the words can use four or five years no problem at all, and it can be said to renovate.
There is actually a big frame. It is outside the board, it will say because the iron will be subject to some overlooking, and then inside is the panel or something like that to be replaced with a new one.

- Interviewer:

So it steel skeleton actually steel life is still relatively long.

- Interviewee:

Right. In September last year, our company went to renovate again. At that time, it was mainly because of the rainy season. We went there in September. It is no problem with the outside frame.

- Interviewer:

For this type of materials, when this temporary project is over, they generally will be shipped to other places, other projects on to the material, or how to recycling or reuse?

- Interviewee:

It can be 100% available, right? So it could be seen as green construction. The steel after demolition can be reused. Concrete is not possible. Then the other one also said that the overall framework is possible to reuse—these panels inside it, such as those that can be used. If not, they can be used for secondary renovation. In fact, the utilization rate of the whole body is very high.

- Interviewer:

I also have a question about cost. You are responsible for the construction site, so you have some knowledge about some costing issues because I also study life cycle cost. I wonder if you have some knowledge about that?

- Interviewee:

The cost is probably close to almost 1 billion RMB, he must be because at that time the environment is undoubtedly must be expensive, but if we say the same environment, such as we now see some hospitals, is certainly relatively placed to be cheaper, because at that time because our workers are basically close to 1000 RMB a day.

- Interviewer:

Labor costs and transportation costs, right?

- Interviewee:

Transportation is close to four or five times. And we have around 20,000 participants, so the labor cost is also huge.

- Interviewer:

It is still tricky for 20,000 people to form a temporary management team, and then there is information to be transmitted very accurately.

- Interviewee:

Later we thought that is to say that we believe it is better to act as a net format, to establish a multi-dimensional and diversified one so that the communication is powerful and effective. Then when the two destinies clash, this time promptly ask for advice from the superiors. Please take a look at is Iranian secret mainly. Then actually there is not a so actually there is no flatter an information transmission, or a more vertical.

- Interviewer:

How do you think the live streaming?

- Interviewee:

So, in fact, the public is conducive to is a role in monitoring. That is, the main work schedule, in our own words, is pressure. I think the more pressure, the more motivated. Because everyone is isolated, we are actually very bored, and then this is also the enterprise is also correct, so that the state gives us a pastime.

- Interviewer:

And then the last question, because from your perspective as a technical person of the construction site, what do you think is the most essential value of this project?

- Interviewee:

I would say social value to benefit the city's image, even the country, at the very beginning of COVID-19. And it also helped in easing the bed shortage.

Interview B:

- Interviewer:

Leishenshan hospital's project uses many circular building principles, such as waste reduction, modular construction, and the use of recycled materials. Still, these are more a consequence of schedule pressure than an intentional consideration of circular building at the beginning of the project. How do you see the role of recycled building principles in this project in this context?

- Interviewee:

Circular construction is more commonly referred to in China as reusable and recycled construction, which is subsumed under green building. Research in this area began early in China and has yielded a wealth of research results, which have become a basic concept and requirement for architectural design. The design of Leishenshan Hospital is both a requirement for design solutions under extreme construction conditions and a reflection of our long-term design philosophy, which is already a fundamental design choice to adopt modular and industrialized buildings.

- Interviewer:

If there had been more time to refine the plan and design, what aspects of the circular building might have been considered?

- Interviewee:

Our team put a lot of time in summarizing the project management process, which of course could have been better in many ways, just an appropriate choice in terms of manpower, materials, and construction conditions at the time, if not for these constraints, it must have been some other approach, for example, the choice of the foundation program under the conditions at the time, if it was normal conditions, perhaps there would have been a more economical construction program to save costs.

- Interviewer:

The design life span of the building is 20 years. What do you think will happen to the modular materials after that time?

- Interviewee:

The Leishenshan Hospital's design was defined as a temporary anti-epidemic hospital, not a permanent building, so it was not the typical design cycle of 50 years, nor was it necessary. This treatment does not mean that these modular products cannot be utilized after 20 years. These modular products are still designed for 50 years of use, and if they are designed for 20 years, they will be recycled and reused when they expire, which is a characteristic of steel buildings.

- Interviewer:

How do the various disciplines in the planning, design, and construction collaborate to update drawing information and make changes? Through BIM or other platforms?

- Interviewee:

Under special conditions, all professional design teams of the project work together with all construction, procurement, installation, supervision, and other related parties at the construction site for instant communication and immediate processing.

- Interviewer:

What do you think the live streaming of the construction site means to the project?

- Interviewee:

The Leishenshan project is a national critical construction project highly concerned by the whole country and the world. The project operation is almost hourly as a progress control node, so it is meaningful to use live broadcast, which can let the whole country witness the project's progress and urge the project team and all reference units to step up the construction and complete the related work together.

Interview C:
(Interviewee responses based on the questions sent beforehand)

Thanks for the invitation to the interview. My topic is the BIM application of digital twin hospitals in Leishenshan Mountain Hospital. I work in CASDI. I am a structural engineer and have been engaged in some BIM-related work in recent years, and I currently serve as the director of the company's BIM design institute.
Throughout the epidemic, we have been involved in 21 square cabin hospitals and 14 in addition to the Leishenshan hospital, providing a total of about 30,000 beds.
A brief introduction of the project is that Wuhan Leshan Hospital is located in the Jiangxia District in the south of Wuhan City, which should be said to be in a suburban area away from the city's densely populated main urban area, as you can see it is divided into two sides, the eastern side is designed to isolate the medical area, in the western side is the living area of medical care, the total land area is 220,000 square meters, the total construction area is 79,900 square meters. It is the most significant protest emergency hospital in China, specially designed to collect patients with severe and critical illnesses from the new coronavirus pneumonia. The number of beds is 1,500, and the number of medical and nursing staff is more than 2,300. Our BIM application is still mainly based on this project's serious difficulty to go around the serious complication of this project.

The first is that the system of the medical building itself is complex, especially for infectious disease hospitals, and its design is different from that of general hospitals. The second one was that it needed to be built quickly in a brief period. Because we say the epidemic is the order, prevention and control are the responsibility. The third is to prevent contamination of the environment. The fourth is to avoid cross-infection of some internal staff and medical staff, which is the main difficulty of our four projects. Our BIM is also around to develop.
Thanks to the unique nature of this project, we could work together with the construction unit from the beginning, so also CCBC and CSCI have rich experience in the application of BIM technology.

So we can quickly assemble a team and set standards. We want BIM to be actually involved in the whole design process of the project, and the entire BIM team has 16 people.
The whole ward zone is a kind of herringbone arrangement. The ward model is relatively simple because it is all standardized modules, but the medical technology area will have different requirements for space. So this piece is a different structure. Both zones adopt this kind of assembled fixed module, which can facilitate its construction and achieve such a purpose of a quick completion.
We used air simulations inside and outside the hospital to finalize the plan for the prevention and control of the epidemic. An information system was also used to monitor the use phase. The hospital started to admit patients on February 8 and closed on April 15, with 67 days of operation. However, our entire process is zero accident, zero pollution, and zero infection during production and work.
Then there is the construction phase of maintenance. The main part is still assembled. The compartment is like a container house to stitch together. It can achieve the purpose of rapid construction. We split it through BIM technology, its skeleton is cold-formed thin-walled profiles of steel structure, and then the 4 perimeters are composed of color steel plates. There are mainly two scales, one is 6×3×2.8m, and the other is 6×2×2.8m, and the model of these two scales is spliced.

BIM shows all such integrated things. It is convenient for the factory to process directly and send to the site when it is already a finished product now for installation. We generally do the design of the steel structure required by the designer to model calculations to draw construction drawings, form processing details, and finally design and then approved, and finally in the engineering processing. But this set of process down may take a week or two weeks, but in such a particular period is not allowed to spend so much time. Then our model is to directly use Tekla to build this model together with our construction team, then import it into the structural calculation software for calculation, and deliver the processing steel structure to the factory for deep processing detail drawing.

On the other hand, the construction site is optimized itself is a large parking lot for the military games held in Wuhan in October, but we have to spread 79,900 square meters of almost one-story buildings on the whole site, so the use of the site and the layout of the site directly affects our entire construction period. We simulate the traffic flow of the crane through BIM technology because this crane is essential. It is a box-type room. You are lifted by this long-arm crane.

Another is for the optimization of the foundation, you can see the following I-beam piers, I-beam piers, is the foundation of our similar houses, our original design is these concrete piers, but through full communication with the construction unit, we adopted this steel structure of the light, because the detachment of the following but also laying the laying of pipeline networks such horizontal and vertical and under the cross workload of the pipeline network is very large. We are also through BIM technology to complete his such coordination work. Through such a deepening can reduce the use of concrete, is also dramatically enhances this construction's speed.

As a temporary emergency hospital for the new coronavirus pneumonia, the Leishenshan Hospital will definitely be demolished after its mission is completed because it is temporary accommodation. Its durability does not reach the same age as our regular ordinary buildings. But we use BIM technology to build this digital twin hospital that can be used as a reference for future projects.

Interview D:

- Interviewer:

My master's thesis is mainly focused on digital twin and circular economy. I chose the case of Leishenshan hospital because it uses BIM technology and almost all modular materials, and the benefits are apparent, for example, very short delivery time, so I think it is an excellent case.

- Interviewee:

We can follow the order of your protocol.

The first you ask in the design and construction process to use which DT software, said in which phase because this project it is exceptional, it is too short, you equivalent to a day to do the program, two days to do the construction drawings. Then 10 days is the construction, that is, in fact, certainly in the design phase is not done, that is, in the construction phase to do some of the software he used one is Revit, one is Tekla. Next is the steel structure, and then there is a simulation analysis software with the X-Flow, and information systems software, etc.

We do the design, in fact, it rushed time, one is to speed time, the second is subject to the constraints of the site conditions, that is, we were able to have what materials to use what materials, what equipment can be used what equipment, and the conventional design is very different, right?

The conventional design we can give priority to our design of some of the most favorable equipment, these materials, but we are now in no condition to fight the time war, the faster, the better, what materials can be shipped over, which manufacturers it can provide we will use which, and then certainly out of the drawings than the conventional is to be worse than some. Maybe in the construction phase is to use BIM to improve the design to improve the project.

- Interviewer:

What do you think about this, and how does BIM technology help the project, for example, to make it faster or to make it better in terms of quality?

- Interviewee:

There must be very obvious that is because the time is too tight, and then in front of the calculation out of the drawings to the builder, but the construction and design are basically synchronized, that is, on the first day of construction, we began to do the design, they began to assemble, right? We started to do the design, and they started to assemble, right? They all grabbed time, and then they got the drawings and started construction, and then several construction teams were working at the same time.

But the site's conditions are also changing every day. We changed more than a dozen versions. I would hate to change the drawings every day. Then the construction is also introduced to introduce our new drawings. Then according to the container, the container is also a lot of sizes, and finally unified into three sizes, but in fact, there should be on 10 kinds of sizes.

We because the design and construction are very sense of panic, and then through BIM technology can be able to find some problems in the design and construction, then correct it, and then also a very good correction, and perfect this project. Because at that time also appeared a situation, the last part of your construction is the construction is finished found that piece with the design drawings has a very big discrepancy, that is, they may have been at that time do not know what the reason is, it is not according to the construction drawings. But then is the use of BIM to find this problem, we are still in the BIM is actually more perfect than the stock index some.

Then there is a part like steel structure, on the medical technology area, because once inside its floor height is quite high, it is still made of steel structure. Like the ward area is used in the container, once inside, he wants more than 4 meters high container is not satisfied, he still used the steel structure. Then this piece was using Tekla to build a model directly, and then the drawings came out inside the model. This is the forward design, Tekla words. It is equivalent to the design side, and then just done, and then immediately the factory can do the construction side. Construction biochemical is equivalent to the construction of steel construction biochemical is the construction unit himself directly with this model inside the design, and then out of the drawings, and then on the material construction.

- Interviewer:

About Tekla, because before there are some published results, the factory produced sick dishes, modular materials, some, for example, to mention the supplier information or installation of some information, I do not know your side is not clear in this regard.

- Interviewee:

Because the whole process it supplier is very much, including what I said before, the container model is also a lot, but we later unified it into.

- Interviewer:

So and the model is equivalent to having only one structural thing in it. There is no other additional.

- Interviewee:

It also has electromechanical and other aspects of information, just that it means that it may be less information about the properties inside this because it is after all only a temporary a time, so short a time to catch up a project, it is not possible to go to the information like a normal project so complete model fine.

- Interviewer:

You just said that there are many kinds of materials, and these dozens of containers are finally unified into three kinds of materials. I would like to ask you how this process was done? I'm a little curious.

- Interviewee:

Because a lot of dimensions are very fragmented numbers, right? We were doing construction drawings when asked, to the project department which can be mobilized to which size of the container, and then because of the supplier a lot, so it is a lot of sizes, broken figures, we will be a little regularized, it became three is 3 m × 6 m, 2 m × 6 m and 1.8 m × 6 m, mainly with these three.

- Interviewer:

And then I had uh interviewed a technical staff of CCBC at that time. Then he said that there were some recycled materials called from other construction sites that CCBC might be responsible for, so do you have any understanding of these materials and this recycled material?

- Interviewee:

I do not know much about it because my side also got the three bureaus to write the information inside is not to say this piece of.

- Interviewer:

So you're in charge of the BIM section because the BIM should have information about the materials, like he would write his properties as concrete or steel brick, so yeah. I would like to compare because I am doing recycled construction like steel is recyclable. Still, concrete is not so good, so I would like to know if it is clear here what the approximate percentage of recyclable materials is used? Or the weight of it, a final total count of a number is fine.

- Interviewee:

My side is not quite clear. I may have to ask the contractor.

- Interviewer:

Yes, and want to know if you have the use phase and built after the use phase? Is there anything you know about this project?

- Interviewee:

It is because also the time is used after is at that time we actually also did is a platform is, want to go in the operation and maintenance stage to do somewhat monitoring. But because one is the Leishenshan hospital, it was originally open for a very short time, it is a few days in March and closed, right? It was only a month or so, and then we just built a model out. Then it was with the cooperation with the university professor, only studied an environmental monitoring platform, want to monitor it what ah, humidity, temperature, illumination, and then can show how many patients in each area inside the medical staff how many um, for overall monitoring. In cooperation with Tsinghua University, indoor environmental monitoring is to optimize the ventilation system and optimize the operation of purification equipment to optimize the hospital's daily operation. But maybe it's just a start, just a concept, not a lot of practical results.

- Interviewer:

To do this, you should put some kind of sensors and so on.

- Interviewee:

I think this is quite interesting. Will it be combined with the physical model of the Leishenshan hospital, the hospital structure model? Or is it a separate thing?

- Interviewer:

It can achieve a linkage with BIM and a relationship. In the physical world, it has sensors. In the digital world, it also has a linkage, so that the information is transmitted, can accurately reflect the monitoring platform above, telling personnel which place and which area, right? What is the change of equipment, and what is the change of personnel?
First of all, this project to do BIM is the biggest advantage that he can do in such a short time an imperfect design, including the construction of some regrets. He can use this digital model method to improve it for a data summary. And it is a temporary, temporary hospital, right? We do not know when he demolished, we make a digital model to be able to be permanent it is a data to save it. He did in the process of building the model, we found these drawings or construction of the actual do not do a good place, but we are in the model to make it more perfect and enhance it a little bit, our model is better than the actual may also be a little bit better. The actual work we do may be limited by the material or the time constraints, not to do it well, but we are in the model to improve it.

- Interviewee:

In fact, in that case, it is equivalent because this project is very urgent and has been separated from Xiaotangshan for very many years. So if there are similar emergency projects like this in the future, actually the model of Leishenshan hospital.

- Interviewer:

We are now working on a project on how to quickly build a medical hospital in response to such a large epidemic, and we are now in the process of researching it, trying to take it one step further, to summarize a set of methods to respond more quickly to such an epidemic.

- Interviewee:

- Interviewer:

I think there may need to have a previous project like Leishenshan hospital, and then let him that model is more flexible, more convenient to change, and then so that there can be similar projects appear then.

- Interviewee:

First of all, we can put some of its things, because it is originally composed of many repeated modules, right? Its isolation ward area is 30 isolation ward area, it each area is this structure is similar, we put it together in a certain logic to put it together, and then mainly it is inside the flow line, clean flow line, contamination flow line medical care flow line and patient flow line these flow line is its core, and then is to use the standardized method to modularize, split it, and then in the next time again encounter the epidemic When the time comes, it is possible to carry out a relatively quick assembly and reuse, remember to such a role, so you can save time. You make things will be better quality.

- Interviewer:

Suddenly with BIM or some so many people to work together, because I heard that there are 20,000, including workers and technicians or architects and so on, a total of 20,000 participants, what kind of difficulties are there?

- Interviewee:

Yes, and that means that many of us at that time because of the quarantine period and can not come to the office, and then some people in the field is, but everyone is called what telecommuting, very difficult is.

That is to say, because we also have to be based on on-site conditions, we hate to change every day. And then they are also during construction. He must be the first to take the construction of the drawing, right? Now the construction of the drawing and then found that there are problems he will respond, and then this side of the model, and then found a with which a version of the diagram does not match, or the design and construction of the wrong place, he will also go with the site staff to reflect him, let him start how to change over.

- Interviewer:

I feel that there is still including that software as you introduced is also very useful because I need to analyze the whole a delivery process. So the last question is whether the government and the design institute will cooperate or the design institute will take the lead, and then the design institute will come down and cooperate with the builder.

- Interviewee:

It should still be to the owner he came, but at that time, to be honest, ah one is a tight schedule, the second is that the difficulty is also quite large, but nothing is right? It is also during the closure of the city, the owner of the project is not enough to anticipate the difficulties, he also does not have he also has no experience in this kind of construction infrastructure experience, so a lot of design and construction to discuss together were to change, where to engage in how are the contingency measures inside this thing. In fact, uh, the A party is the Wuhan Municipal Government, and then appointed the Central South Institute as the design party.

The construction design immediately mobilized all the people to engage in this thing, and then because I think the greatest difficulty is still in the construction, right? Although you draw out the plans, you have to turn it into reality, and you are saying that it is a temporary hospital, but its functional indicators are all following the highest standards. Infectious disease hospital to do, the design is not to reduce its difficulty but rather to increase its difficulty.

Your strongest and most stringent design standards to design, but the reality of the conditions do not allow, time does not allow, material suppliers are not allowed under the circumstances. In fact, the majority of the pressure is on the construction site, right? In their side, and then what problems the owner may not be able to solve, or he does not know how to do or design and construction together, discuss how to modify, if there is a change involved, so it is generally following the requirements of the construction to change it changed. Then there are places where the design can not be changed. We also insist that it can not be changed and can not violate the specifications, right. The leading words or I think the construction is still appropriate to lead together.
It is this time, the owner's side is a little weaker.

- Interviewer:

I recalled the previous interview with the construction site of the people. He said he also thinks to take the container because the container is a steel structure, those Ben can change well. Feel this is very clever, because the hospital it is like you said its specifications are very high, on the infectious disease is very expensive very high specifications of the hospital, so it is a lot of the kind of more sophisticated instruments and so on, but his original containerboard quality is not very good, sometimes it may rain what is easy to have some damage. So like this more flexible and replaceable structure, then it may be broken, and then replaced on the good, it will not say that there is too much impact, I feel. Also more clever in this regard.

- Interviewee:

Another point is that atthere is no roof on top of the container at the beginning of the design, but later found that it does not work. After several spots of rain found that because the container is a very short space, its roommate ducts are in the basic top. The air ducts are on the top, and then so many groups put together, it is not such uniform specifications, right? High and low, the size is not the same. Then there is equipment, the result after the rain found leaking, and then hurriedly added a light steel structure on the top of the shoes of the metal fabric surface, look like a solution to the problem of drainage, which is based on the site of the situation to make changes I am.

- Interviewer:

Thank you.

- Interviewee:

Bye.