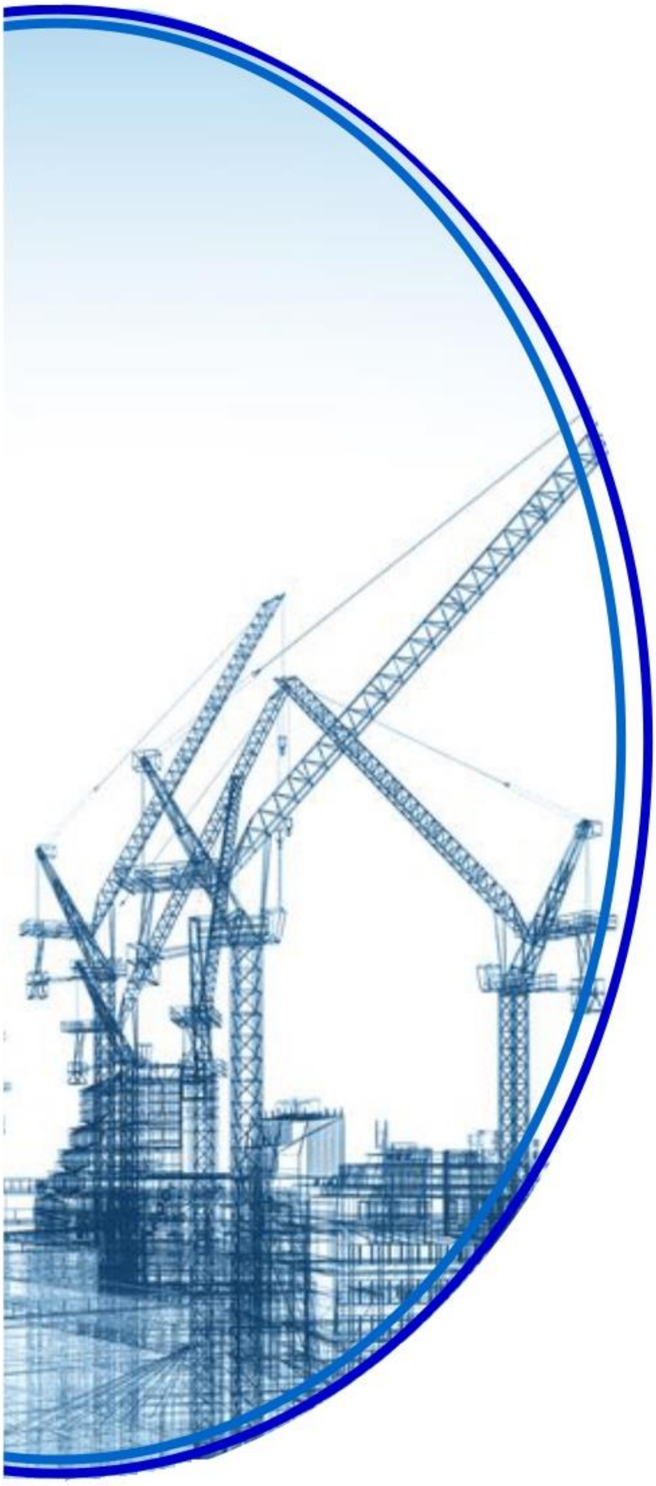

Circular Industrialized Construction

The current situation and its potential for expansion in Switzerland

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Graduation Thesis Industrial Ecology
University: Delft University of Technology & Leiden University
Course Code: 4413TRP30Y
Research Period: September 2019 – September 2020

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Executive Summary

The construction industry accounts for 40% of material resource use and produces 40% of global waste. Within this industry, various solutions have been attempted to lower the environmental impact. Two of these concepts are the circular economy (CE) and industrialized construction (IC). CE refers to an approach that embraces circular supply chains as opposed to a "take-make-dispose" system. IC can be defined as a "construction technique in which components are manufactured in a controlled environment, transported, positioned and assembled into a structure with minimal additional site works".

The IC approach offers three potentials to overcome several barriers compared to circularity in traditional buildings. (1) The IC nature of supply chain integration supports the notion of shared responsibility for a CE. (2) IC is characterized by a longer planning phase to coordinate assembly on-site providing an opportunity to plan for disassembly in order to recover the material in the future. (3) IC focusses on standardization of prefabricated parts which supports adaptability and flexibility, thereby anticipating future modifications.

Research on the combination of the Circular Economy and Industrialized Construction remains very limited. This thesis identifies opportunities to accelerate the integration of CE principles in industrialized construction methods within a Swiss context. This research is structured along three parts: (1) a literature review to assess the main developments of circular industrialized construction. (2) A conceptual framework combining two qualitative frameworks – the Strategic Niche Management and the Multi-level Perspective is developed to study and compare case studies demonstrating circular IC (UMAR unit, ICEhouse and ECO Solar Houses) including the external factors facilitating or impeding this development. (3) Finally, a list of recommendations providing a pathway for scaling up circular IC in Switzerland is presented. Data is collected through literature review, desk research and semi-structured interviews with stakeholders directly involved in the projects and industry experts.

The findings indicate that five circular strategies should be present and work together to increase the circularity potential of IC: circular materials, product as a service, product lifetime extension, sharing platforms and resource recovery. At the start of a project, the use of comprehensive material database and increased documentation is crucial to make informed decisions about retaining value at a building's end-of-life phase. Building layers should be separated and specifically for a building with many different materials and components, a higher level of pre-assembly is favored to increase control of construction to achieve higher reuse of recovered materials. Business models need to be reconfigured by extending ownership of components and modules. Transformation in design is recommended by incorporating standardization and design for disassembly practices to enable future reuse.

The study showed that the establishment of demonstrator projects is key to facilitate the development of the circular IC niche. Specific network characteristics need to be present: a facilitator providing financial capital and flexibility and a diverse multidisciplinary team with stakeholders who are involved early in the process to create a common circular mindset. Finally, the initator(s) will have to demonstrate leadership through sharing the mission and vision explicitly to attract more stakeholders, who in turn can supply resources. Governmental involvement through VAT reductions on secondary raw materials and the provision of financial incentives is crucial. A regulatory framework for the input of construction materials will be essential and needs to be developed. In support of such a framework, a secondary raw material marketplace, outcomes of research programs and certification labels may be developed. By adopting these measures, circular industrialized construction can be scaled up through new projects, and in doing so contribute to a more sustainable construction industry.

Acknowledgements

Working on this thesis has been simultaneously challenging and rewarding and it would not be possible to complete this research without the help and guidance of many people. Especially during these difficult times, in which our daily lives have changed drastically, finalizing a thesis has not been easy. And for this reason, I am deeply grateful for all the support I have received.

First and foremost, I would like to thank my main supervisor Dr. ir. Jaco Quist for your continuous guidance, feedback and encouragement challenging to take my work a step further each time. You have been extremely supportive and understanding, especially when responding to last-minute queries. Your expertise considering the theoretical concepts applied in this thesis has been vital and for that, I owe a great deal of this work to you. I also want to thank my second supervisor Dr. ir. Els Leclercq for your insightful comments and enthusiasm during the development of my research work.

I greatly appreciate the opportunity I was given to conduct my thesis in collaboration with the Chair of Innovative and Industrial Construction at ETH Zürich. Thank you Prof. Dr. Daniel Hall and Firehiwot Kedir for introducing me to the topic of Industrialized Construction and for your supervision and valuable suggestions, which helped me a lot in writing my proposal, the thesis chapters and a conference abstract. Firehiwot, thank you for your patience with me.

Moreover, I would like to express my appreciation to the IC Chair for interesting discussions and constructive feedback during presentations and meetings. It has been a great learning experience and an opportunity to become acquainted with the world of academia. I am also thankful for all the friendships I have made in Zürich which have been a constant motivation.

I would also like to express my gratitude to the participants involved in this study. Their names will not be disclosed, but I want to acknowledge their help and transparency during my research. Most of all, I would like to thank the interviewees who offered their time so generously to show me around the building locations.

All my friends and family back home - thank you for your interest and support during the countless FaceTime calls and visits to Zürich. Last but not the least; I would like to thank my parents Ellen and Leon and my boyfriend Diederick, for their unending support, encouragement and useful advice throughout my years of study and especially whilst writing this thesis. This accomplishment would not have been possible without them.

Table of Contents

List of Abbreviations

- BIM - Building Information Modelling
- C2C - Cradle to Cradle©
- Circular IC - Circular industrialized construction
- CE - Circular economy
- DfD - Design for disassembly
- EMF - Ellen MacArthur Foundation
- EOL - End-of-life
- IC - Industrialized construction
- ICEhouse - Innovation for Circular Economy house
- IE - Industrial Ecology
- IS - Industrial symbiosis
- MLP - Multi-level Perspective
- MP - Material passport
- OSB - Oriented Strand Board
- Prefab - Prefabricated
- SNM - Strategic Niche Management
- UMAR - Urban Mining and Recycling

1. Introduction

The building industry is one of the most resource-intensive industries, using approximately 40% of the global material resources and generating 40% of the world's total waste by volume (Becqué et al., 2015). Since buildings require large quantities of resources (energy, water and construction materials) the environmental impact of this sector is extremely high, responsible for as much as one-third of the global greenhouse gas emissions (Nußholz et al., 2019).

Traditional construction methods, adopted by many urban structures currently in use, consume high volumes of primary materials (Bukowski & Fabrycka, 2019). By improving resource efficiency in the building industry, the adverse environmental impact of the sector can be reduced. Industrialization of the construction process could provide one of the solutions. The concept of industrialized construction (IC) is considered a "construction technique in which components are manufactured in a controlled environment (on or off-site), transported, positioned and assembled into a structure with minimal additional site works." (Fathi et al., 2012). IC offers many benefits - improved efficiency of production and quality, shortening of the construction period and lower environmental impact due to the use of fewer resources, thus creating less waste (Jiang, Li, Li, Li, et al., 2018). To illustrate, a study concluded that prefabricated residential buildings in comparison to traditional residential buildings could achieve a reduction of 20% in total energy consumption and between 25% and 85% in waste during construction processes (Cao et al., 2015).

Although the contribution of IC for resource efficiency in the industrial economy is not sufficiently studied in research yet, applying a circular economy approach could potentially enhance the sustainability of IC even more (Minunno et al., 2018).

The relevance of a circular economy (CE) is gaining more traction in the world as a way to decouple economic growth from material extraction and the use of energy (Ellen MacArthur Foundation & McKinsey Center for Business and Environment, 2015). The concept of CE seeks to reduce, reuse and recycle materials and components. However, CE has been predominantly applied to products such as electronic equipment and consumer goods and to a lesser extent in the built environment (Adams et al., 2017). Moreover, the knowledge and tools for bringing CE into practice remain largely undeveloped (Bet et al., 2018; Leising et al., 2018; Lemmens & Luebkeman, 2016). Specifically for the construction sector – where innovation diffuses slowly due to fragmented structures of the industry - the focus has primarily been on tackling issues such as energy demand, efficiency and waste generation (Adams et al., 2017; Ürge-Vorsatz et al., 2014). For example, recycling rates of construction and demolition waste are currently very high, but have low value due to down cycling practices, where the value, quality and functionality deteriorate compared to the original purpose of the material (Di et al., 2018). Circular economy principles can further be integrated to potentially increase the environmental impact savings as well as economic benefits for buildings significantly (Eberhardt et al., 2019).

1.1. The Circular Economy and Industrialized Construction

Academic research on the integration of circular economy principles into industrialized construction methods is very limited as hardly any literature has been found (Minunno et al., 2018). There are only a few examples, primarily in Europe, showcasing the combination of these two concepts (Kozminska, 2019). Current research has reviewed the sustainability of IC (Aye et al., 2012, 2014; Pons, 2014), whereas work on CE in the built environment tends to focus on applications in traditional construction (Adams et al., 2017; Eberhardt et al., 2019).

However, CE in industrialized constructed buildings could overcome several barriers compared to CE in traditional buildings (Minunno et al., 2018). Traditional construction is more complex, using more non-standardized components as well as monolithic structures with chemically bonded connections, hindering the design for disassembly. By contrast, IC focuses on standardization of prefabricated parts sourced from long-term partners in the supply chain and assembled together on the building site (Bonev et al., 2015). The use of off-site manufacturing in IC enables waste to be better controlled at the production source, enabling the possibility to return into closed-loop supply chains (Jaillon et al., 2009). This can allow for safe storage and inventory of materials and components (Hosseini et al., 2015; Pushpamali et al., 2019). Furthermore, reduction of construction waste by design for disassembly and the use of recycled materials in industrialized construction could present a solution in substantially reducing the environmental impact of construction even further (Rios et al., 2015).

1.2. A Case for Switzerland

In particular for Switzerland, having a long tradition of acting as a knowledge, innovation and technology hub, the development of such initiatives offers great potential (Embassy of the Kingdom of the Netherlands, 2018). The country's biggest waste stream, at over 15 million tons per year, is caused by construction and demolition waste (OECD, 2017). This has been further exacerbated due to the increased population growth (and thus a higher demand for housing) over the past 15 years - an increase of 17% from 7.2 to 8.4 million in 2016 (Bertram et al., 2019; Swiss Federal Council, 2018). Moreover, the environmental impact per capita is relatively high and well above the global average due to the high level of raw material consumption. Lastly, the Swiss building stock is responsible for approximately 50% of the national CO2 emissions and 40% of the total end energy demand (Richner et al., 2018).

Despite these circumstances, Switzerland is attempting to reduce the environmental impact of the industry, for example, by reintroducing three fourths of the annual volume of demolition material in 2015 into the economic cycle as secondary raw materials. Industrialized construction has attracted the interest of Switzerland, and the share of turnkey solutions in the prefabricated segment is expected to be the highest compared to the rest of Europe (J. Goulding & Pour Rahimian, 2019; Roland Berger, 2018). A turnkey solution refers to an IC project that is constructed in order to be sold as a completed product to any buyer.

Furthermore, Switzerland is a pioneer in creating timber constructions, completing the first multi-story timber buildings twenty years ago (Ciamberlano, 2019; Martin & Perry, 2019). Wood is a more sustainable alternative to conventional construction materials (i.e. concrete and steel) because of its relatively low carbon footprint. More importantly, it is well suited for industrialized construction due to its speed and installation efficiency and high thermal performance (Think Wood, n.d.). As such, there are some large industry players, such as Renggli AG, Implenia and SWISS KRONO, who specialize in the construction of prefabricated and modular timber buildings – promoting sustainability within IC.

However, the total share of industrialized construction in the Swiss construction industry is very low with concrete remaining the dominant material for new construction. Therefore, IC remains a niche – a protected space allowing for experimentation of a technology - within this sector (Schot & Geels, 2008). Even more so is the practice of applying circular economy principles in IC. As circular IC is a subcategory of industrialized construction, circular IC can be considered a *niche-within-a-niche* or *sub niche*, which for the sake of simplicity will be referred to as *the niche* in this thesis.

1.3. Problem Definition

As of 2020, Switzerland will have reduced the buildings-related CO2 emissions by 40% compared to the 1990 level. Over the long term, the country's building stock should become

CO2-free. Switzerland has the potential and aim to expand the development of circular industrialized construction further. A limited number of organizations and companies recognize the opportunities of this niche, experimenting with pilot and demonstration projects. Nevertheless, integrating circular economy principles entails a complete systems change at all levels of the economy consisting of economic, technical, cultural and political change (Ellen MacArthur Foundation & McKinsey Center for Business and Environment, 2015; Ghisellini & Ulgiati, 2019). Together with the construction industry slowly adopting new technologies and counting many players at various stages, the transition to circular IC is a very complicated process (Mohd Nawi et al., 2014; van Egmond - de Wilde de Ligny, 2009).

By creating and regulating niches and its processes, innovation trajectories can be facilitated as insights are given into the reasons why new technologies may be successful or fail (Schot & Geels, 2008; van Egmond - de Wilde de Ligny, 2009). Ultimately, this will lead to the expansion of the circular IC niche diffusing into society. However, the multi-dimensional nature of such a sustainability transition entails numerous changes occurring at different levels (F. W. Geels, 2011; Leising, 2016). To fully breakthrough, attention should therefore also be paid to external processes (F. W. Geels, 2011). A niche transition perspective combining different frameworks is an appropriate method for analyzing the different layers of the development of circular IC. This thesis will offer the change to take a closer look at this innovative sector and the context in which it is embedded. In doing so, the study contributes to fostering the transition of sustainable, circular industrialized construction.

1.4. Relevance to Industrial Ecology

Industrial Ecology (IE) was first introduced by Frosch and Gallopoulos (1989). The authors identified the concept as a shift from a traditional model of industrial activity in which individual manufacturing processes take in raw materials and generate products to an industrial ecosystem for which energy and material flows are optimized and waste generation is minimized. Notably, IE begins its journey with an emphasis on closing material loops and increasing resource efficiency, which in turn relates to the concept of the Circular Economy (Bocken et al., 2017). In general, research about Industrial Ecology has focused on the application of industrial symbiosis (using waste or by product of an industrial process as raw material in another industrial process) and the development of eco-industrial parks (Hond, 2000). Until now, CE applied to the built environment and in particular industrialized construction has received very little attention from IE researchers (Blomsma & Brennan, 2017). Nevertheless, the projects presented in this thesis are comparable to industrial-symbiosis practices that center around closing material system loops in the industrialized construction sector.

Similarly, IE applies a systemic approach viewing interactions between industrial and ecological systems as a whole instead of considering them as individual elements of a system (Choudhary, 2012). This systems perspective is illustrated by applying a transition perspective to analyze the different layers and perspectives of the niche. Insights into the expansion of circular industrialized construction are found not only by managing niche processes through real-life experiments but also by studying the current developments taking place that can offer new opportunities for circular IC to breakthrough.

Furthermore, Industrial Ecology has an interdisciplinary character, synthesizing different concepts in order to solve a sustainability problem (Li, 2018). The same applies for this thesis, combining the field of industrial ecology and civil engineering, and in turn contribute to reducing the material consumption impact of one of the most-resource-intensive industries – the building sector. In this report the technical perspective of construction is touched upon, together with the environmental benefits and social standpoint of circular IC, for example through stakeholder engagement and its viability.

1.5. Research Aim and Research Questions

The research aim is to identify opportunities to foster the transition of integrating CE principles in industrialized construction methods in Switzerland. The research objectives are to investigate the current state of CE in IC, conduct case study methodology to investigate three case of circular IC practices and the external factors that play a role. The final outcome will be to derive high-level principles on the enablers and barriers on the integration of the two concepts in order to derive recommendations for scaling up and further diffusing circular IC in Switzerland. The main research question is formulated as follows:

What circular practices can be adopted in industrialized construction and how can this integration be more widely diffused and scaled up?

Four sub questions have been formulated to structure the research design and the thesis altogether. The order of the sub questions will determine the steps as a means to answer the main research question.

1. What are the main developments of integrating the Circular Economy in Industrialized Construction?
2. How can niche initiatives in circular industrialized construction be researched from a niche transition perspective?
3. What practices and strategies can be observed from emerging circular industrialized construction case studies in Switzerland?
4. How can the outcomes of the practices in circular industrialized construction be scaled up in Switzerland?

The overall structure of the thesis report is categorized in three parts, illustrated in Figure 1.1. The first part of the research represents the introduction and literature review. The research domain of the Circular Economy and Industrialized Construction is explored as well as the theory about Innovation and Transition Frameworks.

Based on literature study, a conceptual framework is designed to study three case studies in Switzerland using a Strategic Niche Management transition approach. A cross-case comparison follows, marking the end of the second part of the thesis.

In the final part, an analysis of the Multi-level Perspective framework is presented, ultimately leading to the scaling up of circular IC in Switzerland including its enablers and barriers. The thesis is discussed, and the conclusion and recommendations are presented.

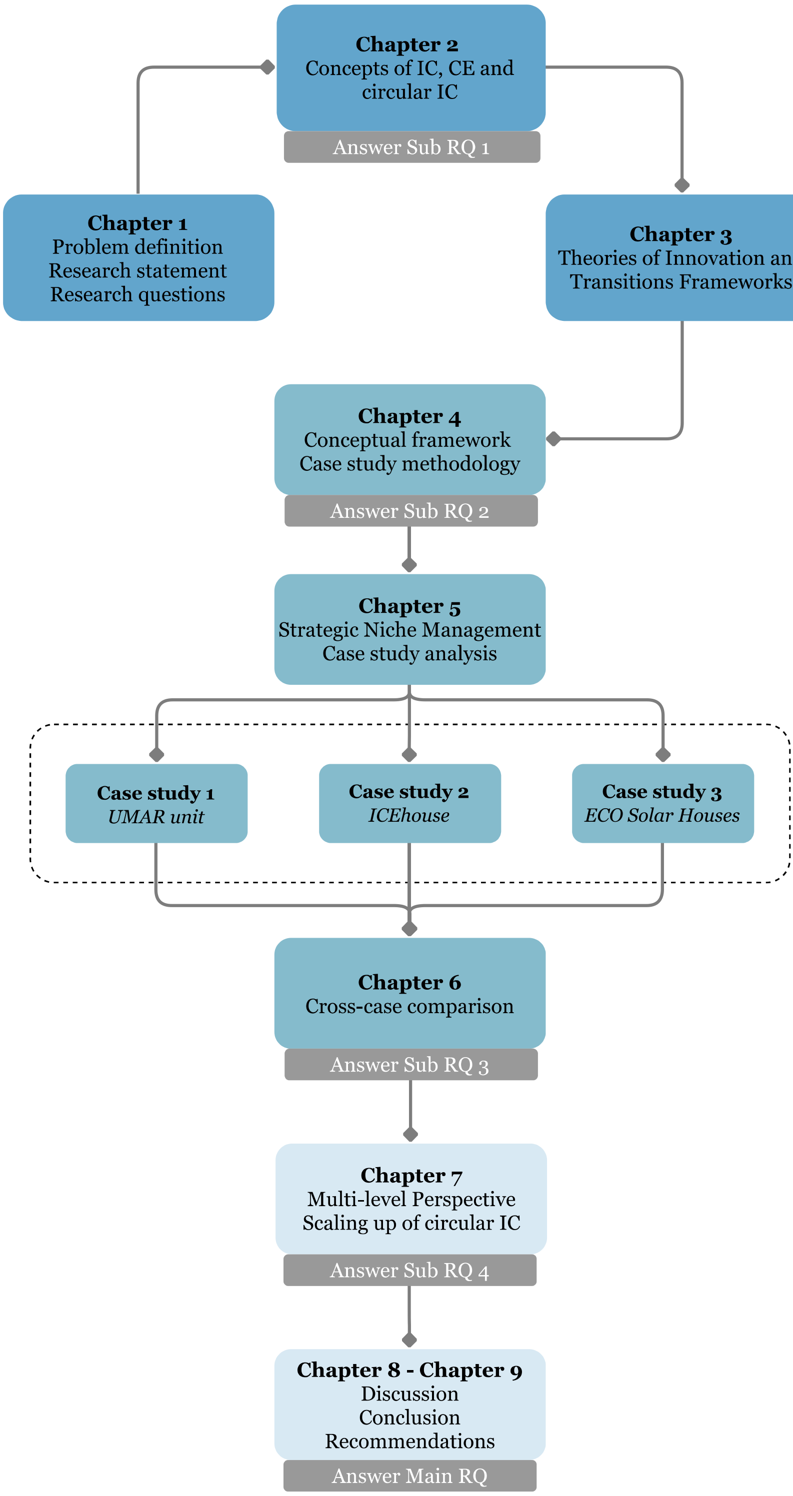

Figure 1.1. Structure of the thesis (own illustration).

1.6. Scope of Thesis

The geographical boundary is formed by the context of Switzerland. The case studies that have been selected in Chapter 4.2 are each located in different Cantons of Switzerland. No distinction is made to include or exclude a specific Canton. Moreover, the case studies must highlight a pilot or demonstration project that is not subject to operating at a commercial scale yet. Regarding the temporal boundary, the cases under investigation have been developed and executed within a five-year period - between 2015 and 2019.

The focus of this thesis gravitates toward a social science nature with topics considering niche transitions and developments. A selection is made from the numerous niche transition approaches in order to study the chosen frameworks in greater depth. Furthermore, the environmental value of the three case studies will not be expressed in terms of environmental impact e.g. GWP, but by identifying the learning processes regarding sustainability or CE approaches applied to each individual project. This is based on the assumption that insufficient data and time is available to provide a comprehensive overview.

1.7. Report Outline

Chapter 1: Introduction
This chapter serves as an introduction to the problem statement (1.1 – 1.4), the research questions (1.5) and scope of thesis (1.6).

Chapter 2: Literature Review
This chapter provides insights into the specific concepts of industrialized construction methods (2.1) and the circular economy (2.2) as well as the integration of CE into IC (2.3). The section is summarized and discussed, answering the first sub question (2.4).

Chapter 3: Innovation and Transition Frameworks
This chapter gives an overview of two innovation and transition frameworks, namely the Strategic Niche Management (3.1) and Multi-level Perspective (3.2) followed by a short conclusion (3.3).

Chapter 4: Conceptual Framework and Methodology
This chapter discusses in the first part (4.1) the conceptual framework based on the findings in Chapter 3, which will be used to assess the case studies. The second part (4.2) presents the research methodology and provides an answer to the second sub question (4.3).

Chapter 5: Developments in Circular IC in Switzerland: Case Study Results
This chapter is concerned with the analysis of the UMAR unit, ICEhouse and ECO Solar Houses using a Strategic Niche Management approach in 5.1, 5.2 and 5.3, respectively.

Chapter 6: Cross-case Analysis
This chapter presents a cross-case comparison of the three case studies categorized according to technical characteristics (6.1) and the three internal niche processes (6.2 – 6.4), which ends with answering the third sub question (6.5).

Chapter 7: Multi-Level Perspective Analysis and Scaling Up Circular IC
This chapter examines the socio-technical landscape (7.1) and regime level (7.2) as part of the Multi-Level Perspective framework. The analysis is summarized (7.3) and additional enablers and barriers for growth of this niche are identified (7.4), which leads to the scaling up of circular IC (7.5). The fourth sub question is answered in this section as well.

Chapter 8: Discussion
This chapter addresses the discussion including the limitations (8.1), novelty (8.2) and implications (8.3) of the conducted research.

Chapter 9: Conclusions and Recommendations
This chapter concludes the thesis (9.1) and ends with the recommendations (9.2).

2. Literature Review

The literature review consists of three parts - first, the concept of Industrialized Construction and its main developments are introduced (2.1), followed by the concept of the Circular Economy and its drivers and barriers applied to the built environment (2.2). Thirdly, the integration of CE principles into IC methods is studied (2.3). Lastly, the literature review is concluded highlighting the identification of the knowledge gap and challenges for integrating the concepts (2.4).

2.1. Industrialized Construction

To apply circular economy principles to Industrialized Construction methods, it is of important to understand the concept of Industrialized Construction. The question “What is Industrialized Construction?” will be answered in this subchapter.

Predominantly, a short history is given to the reveal the development of this technique of construction (2.1.1). The definition is provided (2.1.2) as well as the different methods that are related to Industrialized Construction (2.1.3). To be able to understand how circular IC can further develop, it is essential to recognize the current barriers to IC adoption (2.1.4). The distinction between tradition construction and industrialized construction is made comprehending the difference between the two techniques and their supply chains (2.1.5) and finally the current IC market is analyzed, zooming in on the Swiss context (2.1.6).

2.1.1. The Origin of IC

Industrialized construction is not a new concept in the building industry. During the mid-1800s, early developments took place in industrializing the construction of housing (Lessing, 2015). Prefabricated components were shipped from the East coast of the United States to California and Australia during the time of the gold rushes (O’Brien et al., 2000). During the start of the following century, the American company Sears Roebuck introduced pre-cut kit houses and became the largest producer of prefabricated homes at that time. However, it was only until the aftermath of the World Wars that the adoption of industrialized construction began to rise rapidly (Grills, 2013). In the United States, the demand for housing soared due to the flood of veterans returning to their home country. Distinctly, during the 1940s and 1950s, there was an urgency for new housing coupled with insufficient labor force (Lessing, 2015). Partly for that reason, the building sector evolved from traditional, on-site, craft-based methods to automated and technologically developed industry (Lessing, 2006; McCutcheon, 1989). Large-scale projects took place to tackle the problem countries were facing. For example, Levittown in New York, was developed by the Levitt Brothers to accommodate roughly 16 million Americans with housing (O’Brien et al., 2000). An assembly line process was incorporated to construct a limited number of standard models leaving restricted variations for residents to select. In Sweden, the government introduced the Million Homes Program to build 100,000 apartments per year over a time span of 10 years, albeit the development plummeted in the early 1970s due to a surplus of apartments available on the market. Consequently, the housing projects were criticized for being socially and technically poor which lead to a sudden change in the housing industry (Lessing, 2015). A shift occurred towards the rapid production of single-family houses utilizing extensive prefabrication. In the 1980s and 1990s, another type of industrialized construction emerged, namely modular housing. It became a well-developed product leading to a high level of consumer acceptance (O’Brien et al., 2000).

Industrialized construction has continued to evolve ever since (Grills, 2013). New forms of IC methods have appeared integrating different approaches including automated manufacturing, integrated building services and the consideration of environmentally sustainable designs such as renewable energy storage (Mansouri, 2007).

2.1.2. The Definition of IC

There is a broad definition of industrialized construction (IC), yet the concept has lacked a clear definition (Lessing, 2006). The working definition for IC in this thesis, as mentioned before, goes as follows: "construction technique in which components are manufactured in a controlled environment (on or off-site), transported, positioned and assembled into a structure with minimal additional site works." (Fathi et al., 2012). Multiple aspects related with industrialization, as described by the International Council for Research and Innovation in Building and Construction (2010), include:

- Use of mechanical power tools
- Use of computerized steering systems and tools
- Production in a continuous process
- Continues efficiency improvement
- Standardization of products
- Prefabrication
- Rationalization
- Modularization
- Mass production

Various terms are often interchangeably used to describe IC – off-site construction or manufacturing, prefabrication, pre-assembly, industrialized building and Modern Methods of Construction (see Appendix A) (Anuar et al., 2011; Gibb, 2001). Regardless of the name, the terms imply that manufacturing of structure components for the construction of buildings occur in a controlled environment (e.g. a factory) rather than on-site.

2.1.3. Concepts of IC

There are several concepts that fall under the umbrella-term of industrialized construction. The most prominent methods applied in the construction industry are discussed.

Prefabrication

Prefabrication entails the manufacturing process in which various materials are joined to form an element that is part of the final installation (Gibb, 1999). Prefabrication happens in a factory. Subsequently, elements will be transported fully or in parts to the construction site to be assembled on-site (Chodor, 2018). Prefabricated techniques cover a wide range of applications, ranging from a simple prefabricated site hut to designing integrated volumetric units into a building structure (Hui & Or, 2005).

There are multiple benefits of applying prefabrication:

➔ **Price reduction:** One of the fundamental advantages are the total financial savings that typically range from 10% up to 50% compared to the conventional construction (Bertram et al., 2019; Chodor, 2018). In particular, the labor-related savings can drastically lower the costs, varying between 30% to 60% of the total installation costs. As construction moves from the construction site to a factory, conditions are more stabilized, which is considered to be more efficient and cheaper (Chodor, 2018). Furthermore, the reduced cost of maintenance is facilitated as components are assembled in the optimum layout for access and servicing.

However, transportation costs can increase significantly if a facility is located far from the construction site (Tony & Kokila, 2018). Moreover, the capital costs were found to be higher due to the establishment of an off-site plant but once these investments are amortized, mass production of prefabricated elements will lower the costs drastically (Chiang et al., 2006). In the end, the financial advantages of prefabrication will outweigh the costs of traditional methods.

- **Time control:** Previous experience has demonstrated that the installation's execution time is significantly limited, speeding up the process by as much as 50% (Bertram et al., 2019; Navaratnam et al., 2019). Errors during the execution stage and the elimination of failures and re-works are limited because of a meticulously planned design and manufacturing process.
- **Site management:** Improvements are made concerning site activities and management since less materials and labor force is required on the construction site. Additional issues related with onsite operations such as workers health and safety, fire risks, influences of (severe) weather conditions and accidental product damage can be reduced or even eliminated (Hui & Or, 2005). Furthermore, the occurrence of fewer accidents is the result of strict regulations in the facilities and better coordination on-site, with less workers competing for the same space (Bertram et al., 2019).
- **Quality control:** Shifting the majority of the works to the factory in order to obtain a controlled and unchanging internal environment leads to enhanced quality of the product by improved control of value chain processes (Lessing, 2006). In addition, site staff is able to continue other essential works on-site without any disturbances.
- **Environmental impact:** Prefabricated construction systems also benefit from less construction waste produced (Pons, 2014). As 80% of the operations occur in a factory, waste materials can be controlled, reused and recycled (Aye et al., 2014; Navaratnam et al., 2019). The movement of trucks transporting components is an important factor to consider as well. Up to 60% of vehicle deliveries to the site can be reduced, which in turn reduces road traffic – one truck carrying prefabricated components can be equivalent to 38 trucks delivering elements in traditional construction (Chodor, 2018; Fraser et al., 2014). This can potentially lead to great benefits, such as limiting additional congestion, air and noise pollution.

Standardization and customization play a key role in the prefabrication process. *Standardization* is a function of mass production and ancillary to prefabrication (Hui & Or, 2005). It entails a rehashed generation of standard dimensions and designs of elements or complete structures (Baghchesaraei et al., 2015). However, standardization on a large scale is uncommon due to the uniqueness of each building project.

Mass customization

Mass customization achieves economies of scale by high-volume, efficient production of personalized products and elements which meet the needs and requirements of each customer based on their order (Shafiee et al., 2018). Its principles rely on standardized production, yet still maintain flexibility for individual products (Gerhard Girmscheid, 2005). Barriers that have hindered the expansion of mass customization in the construction industry include its market size, managing stakeholders and challenges regarding the creation of a good business case (Shafiee et al., 2018). Yet, the use of an integrated system delivery tool such as Building Information Modelling (BIM) can aid in employing mass customization approaches in the building sector. BIM is a virtual model carrying accurate geometry and data required to support the fabrication of building components (Pereira Stehling & Coeli Ruschel, 2018). The model can manage massive amounts of information, which are required for mass customization considering the uniqueness, and complexity of a building project.

Pre-assembly

Although the elements can either be assembled on-site or off-site, pre-assembly indicates that assembly happens in a controlled facility, in which the prefabricated components are joined together to form a specific structure. There are different degrees of pre-assembly, categorized in four levels in order of complexity: component manufacturing and sub-assembly, non-volumetric, volumetric pre-assembly and modular building (see Appendix A). Figure 2.1 reveals the different categories, corresponding definitions and examples.

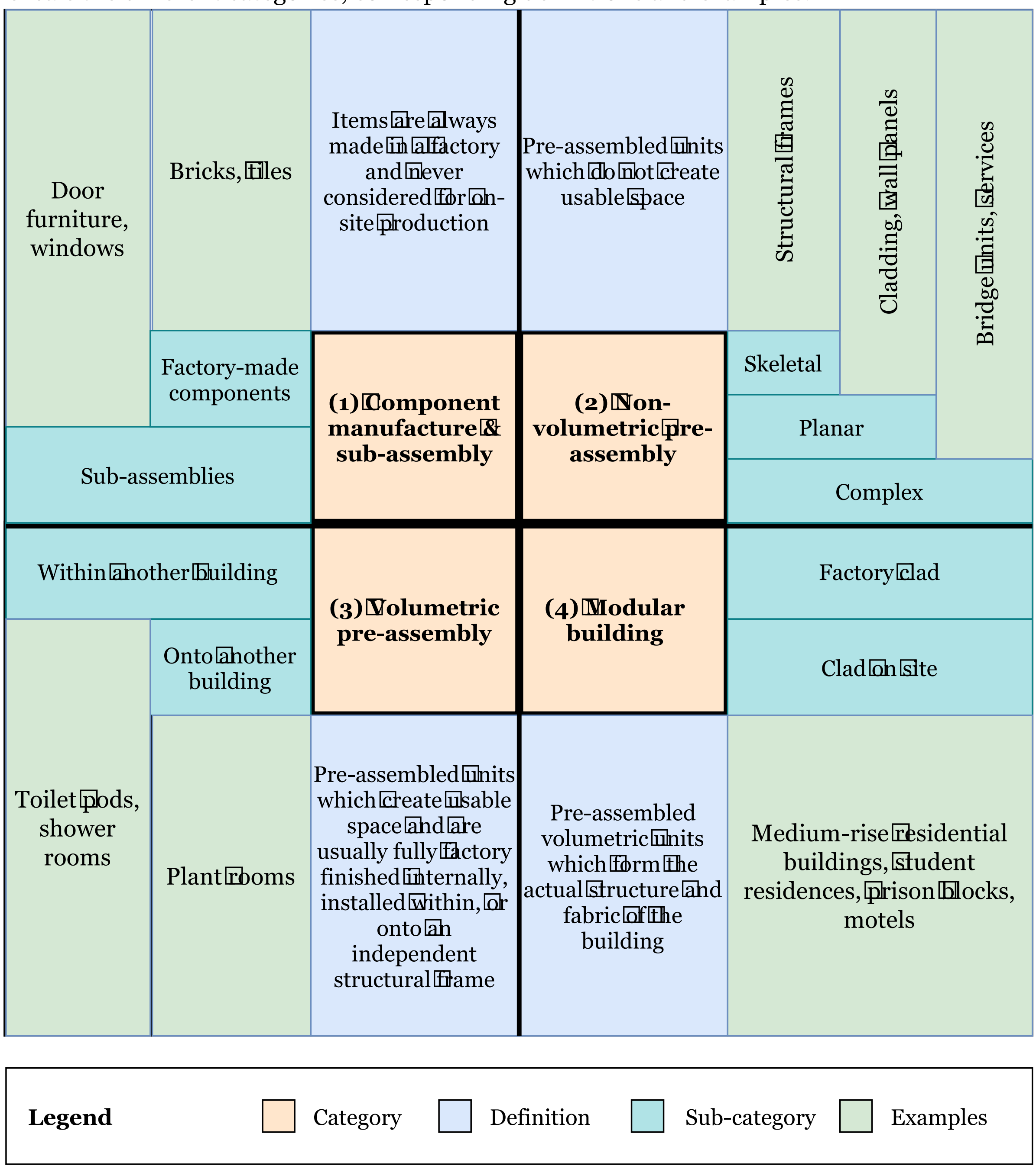

Figure 2.1. Definitions of pre-assembly terms. Adapted from (Gibb, 2001).

2.1.4. Barriers to IC adoption

Different innovative companies have proved successful adoption of industrialized construction in countries including the UK, Japan, Sweden, Malaysia, Germany and Poland, to name a few (J. S. Goulding & Rahimian, 2020). Nonetheless, this type of construction method accounts for a relatively low percentage of the market, i.e. 3% in the U.S. (Modular Building Institute, 2011). The reason for this low share varies from market to market. Based on extensive literature review, the most common barriers have been identified:

- ➔ **Cost-related issues**: To manufacture off-site, initial costs are high to set up a facility and to purchase all materials at the start of the project (Chiang et al., 2006). Other costs need to be covered as well including the recruitment of highly skilled workers, complex techniques, additional space for accommodation prefabricated components and extra transportation costs if facility is not in the vicinity of the construction site (Hong et al., 2018).
- ➔ **Time-relates issues**: In contrast to traditional construction, pre-project planning is quite extensive for industrialized construction systems (Navaratnam et al., 2019). Different processes need to be considered, including the transportation of elements to the construction phase and how the building will be assembled.
- ➔ **Supply chain integration**: Multiple stakeholders are required to work together on an industrialized construction project to ensure deliveries arrive on time at the designated location. Thorough and effective coordination is needed in all stages of the building – including project planning, procurement, supply chain scheduling, construction and installation and delivery (Kamali & Hewage, 2016). Yet, in practice, involved actors work separately without communicating and sharing information among others due to the fragmented nature of the industry, making supply chain integration very complex (Jiang, Li, Li, & Gao, 2018; Rahman, 2014). The growing number of both professions (i.e. architects, contractors) and organizations involved in the processes of a building project has led to this separation(Mohd Nawi et al., 2014).
- ➔ **Reputation**: During and straight after the World Wars, there was a high urgency for housing and prefabricated houses were built to satisfy these needs (Bistouni et al., 2018). However, the focus was on quantity rather on quality, which formed the general perception that prefab, is linked to low-quality housing. There are long-held perceptions about the poor quality of prefabricated construction, partly due to the lack of awareness and understanding, hampering the upscale of technology (Brennan & Vokes, 2017; Cassidy, 2019). In Germany, the first generation prefab houses were considered be "cardboard houses", yet this image has improved through the use of certification schemes and promotion of the benefits of IC (Lu, 2007; Venables & Courtney, 2004). However, Japan is an exception to the rule as most customers have positive attitudes towards prefabrication, reflected in the governmental financial and legal support for IC.
- ➔ **Regulations and building code**s: Because many IC methods are regarded relatively recent innovations, quality assessment tools and accreditations remain to be developed and thus not yet included in many planning and building regulations (de Laubier et al., 2019; Rahman, 2014). Other regulations, including health and safety regulations and mortgage or insurance requirements hinder the development of IC. Due to the local nature of such rules; it is very difficult to change those codes.
- ➔ **Risk aversion**: The construction sector is very slow in embrace innovation. This is because the industry is embedded in local laws, rules, regulations, institutions and most importantly in long-established professional practices (van Egmond - de Wilde de Ligny, 2009). The fragmented structure does not foster implementing new or different technologies either (Adams et al., 2017). Construction is project-based and

cyclical, with constant cost pressures and low margins (de Laubier et al., 2019). This leads to an aversion to invest large amounts in R&D and end up with high capital expenditures. Builders and clients as such have been reluctant to experiment and test new construction methods and technologies.

2.1.5. Traditional Construction versus Industrialized Construction

In contrast to IC, traditional building method encompasses the fabrication of components of the building exclusively onsite (Haron et al., 2005; Sardén & Engström, 2010). The locus of traditional construction is the recognition of individual components forming the building. It is believed that optimizing each one of the components separately will ultimately lead to the optimization of the whole process. In prefabricated construction systems, the stage of site preparation and construction of the elements or modules can occur simultaneously (see Figure 2.2) (Schoenborn et al., 2012). Traditionally, these two phases have to be carried out consecutively. Moreover, during on-site construction, walls cannot be set until the floors are positioned or ceilings cannot be added until the walls are erected. In turn, this will significantly increase the duration of the project as a whole (Höök, 2005; Modular Building Institute, 2011). Nonetheless, pre-project planning can be extensive for IC and can possibly require more engineers, high-skilled workers and controllers. The time and costs will be higher in this phase compared to traditional construction, but even so the duration and costs on-site will be drastically reduced (Navaratnam et al., 2019).

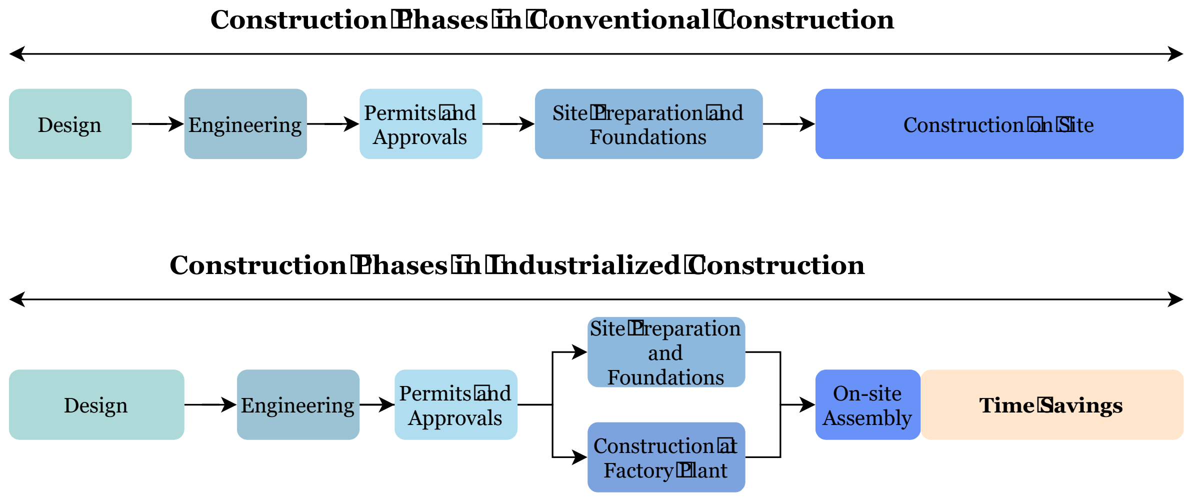

Figure 2.2. The different phases in conventional construction versus modular construction Adapted from (Kamali & Hewage, 2016).

Supply chain management
Shifting construction activities from onsite to an off-site facility demands a shift in managing the supply chain. It requires a more intensive collaboration among partners as labor, materials and equipment for a building project have to remain coordinated (Čuš-Babič et al., 2013). Current project delivery is largely fragmented involving various independent parties (Gerhard Girmscheid, 2005). Moreover, the construction industry has a nature of a single project focus and combined with the presence of competitive tendering procedures, this does not contribute to the integration of the supply chain (Doran & Giannakis, 2011).

Currently, poor communication is widely recognized within the construction sector (Mohd Nawi et al., 2014). Generally, issues arise between contractor – subcontractor – architect design interfaces, for which the exchange of information is very slow. This has to do with the aforementioned fragmented nature of the construction industry and the differences in information and language used or the communicating culture itself. A partnership culture should be created in which relationships between actors stretch beyond one individual project (Lessing, 2006). This enhances communication, which in turn, will improve logistic work, a key factor to industrialize construction. In the early stages of a project, strategic logistic works should commence. This includes determining the supply of materials and components, the involvement of suppliers and methods for the storing of elements (Lessing, 2006). Vrijhoef and Koskela (2000) identify the integration of management between the supply chain and on-site activities construction as key. In this practice, the aim is to replace the construction's usual temporary chains with permanent stable supply chains. Participants engage in mutual relations for the long-term, achieving common goals and able to create value for the client (Lessing, 2006). A new project can start faster, as the structure for co-operation has been established. Experience from previous projects serves as input for further development and this promotes greater efficiency and reliability.

To facilitate such efficiency, the use of consistent, unified IT-tools with more accurate information is required and additionally, this will promote faster transfer of knowledge and information. Finally, comprehensive continuous performance measurements and follow-ups are needed to identify areas for improvements. All participating parties should feel a sense of responsibility to contribute to the process of improvement.

2.1.6. The IC Market

The construction industry is one of the largest in the world economy, with total annual revenues of approximately $10 trillion accounting for 6% of the global GDP (McKinsey & Company, 2017; World Economic Forum, 2016). In the coming years, the sector is forecasted to grow, up to estimated revenues of $15 trillion in 2025. For the industrialized construction market, an annual growth rate (CAGR) of 5.54% during the forecast period of 2018 until 2023 is expected (Reuters, 2019). McKinsey & Company (2019) states that the adoption of modular construction methods in Europe and the United States could potentially save $22 billion by the year 2030. Concerning the American market, modular techniques account for 3 - 5% of the total construction industry, and this number is still growing (Wozniak-Szpakiewicz & Zhao, 2018). Japan and Sweden are regarded to be world leaders of prefabrication with a high penetration of IC in the industry, but the growth in Japan has experienced a slowdown due to its shrinking population (J. S. Goulding & Rahimian, 2020; Roland Berger, 2018).

Considering the European Market, Roland Berger (2018) states that absolute volume growth for prefabricate housing is expected to be boosted by the U.K. (3.8% per year between 2017 and 2022), Scandinavia (3.5% per year) and Germany (3.1% per year). Switzerland shows the highest prices per average prefabricated house with an average of €360k, followed by Scandinavia (circa €330k) and the U.K. (circa €250k).

Switzerland's situation

Residential housing dominates the Swiss building stock, namely 75% of all buildings (Camarasa et al., 2017). Single-family houses represent 40% of the residential floor area and one fourth of all the dwellings in Switzerland. The number of construction enterprises amount to approximately 3.5 thousands, employing 82.9 thousand workers (Eurostat, 2016).

Figure 2.3 exhibits that Switzerland has a significant lower market share for prefabricated one- and two-family housing, compared to other European countries. However, within the prefabrication segment, Switzerland has one of the highest shares of "turnkey" solutions. A turnkey property is a home that can be purchased or rented out immediately with finishing, fixtures and fittings completely readily available.

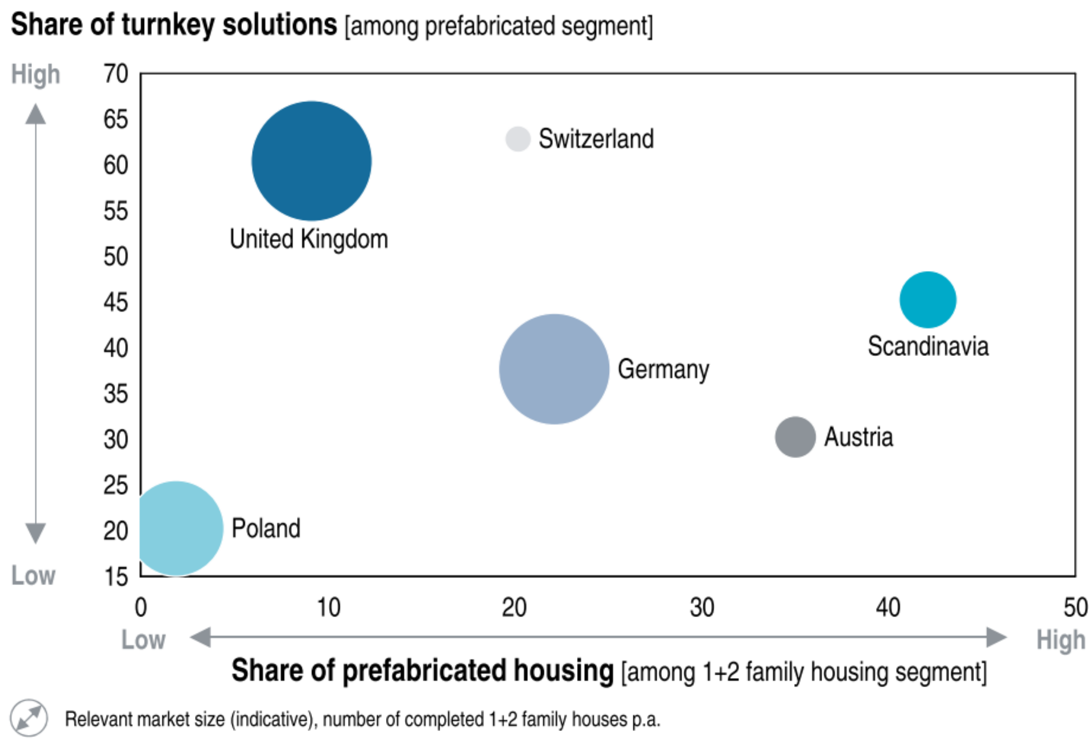

Figure 2.3. Share of turnkey solutions and share of prefabricated housing for different European countries (Roland Berger, 2018).

There is still a lot of potential for market expansion for IC in Switzerland (Rinas & Girmscheid, 2010a). The construction industry and in particular the prefabrication sector is characterized by small players where local architects dominate the decision-making for a building project. This can hinder the adoption of IC as architects and engineers might lack knowledge of planning prefabricated elements and systems (Rinas & Girmscheid, 2010b). Moreover, smaller IC companies are not able to cover the large initial investment costs required to move away from manually manufacturing a different range of products.

In 2007, the share of prefabricate concrete elements manufactured in Switzerland is one of the lowest in Europe as measured by total cement consumption (Figure 2.4 in dark blue). This is despite total volume of concrete consumption measured as twice the amount of cement per inhabitant compared to Germany and the Netherlands (G Girmscheid & Kröcher, 2007). It should be noted the presented data concentrates on the use of *concrete* in IC methods; statistical data for different materials specifically for Switzerland could not be found.

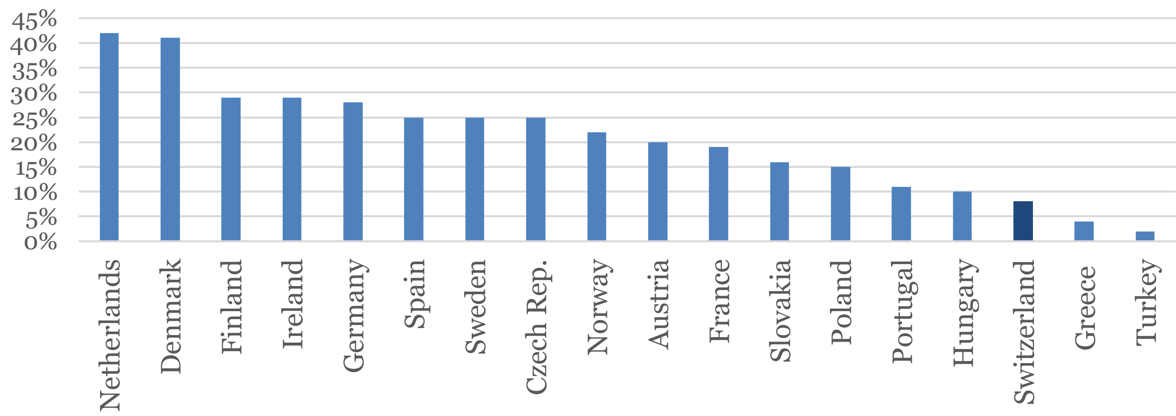

Figure 2.4. Proportion of prefabrication of concrete elements in the total cement construction industry per European country. Adapted from Girmscheid & Kröcher (2007).

2.2. The Circular Economy

As for the concept of IC, understanding the concept of the Circular Economy is key in order to conduct research on the combination of IC and CE. Here, the question "What does the Circular Economy (in the built environment) encompass?" is explored.

An overview is presented starting with the development of the idea of CE (2.2.1). Next, the definition and concept of the Circular Economy is presented (2.2.2). The chapter is completed by highlighting the enablers and barriers enhancing or hindering the development of CE in the built environment (2.2.3).

2.2.1. The History of CE

The origin of the circular economy (CE) term was made real and tangible in a short essay written by the ecological economist Kenneth Boulding in 1966 with the title of "The economics of the coming Spaceship Earth" (Cardoso, 2018). Boulding stated that: "Man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy" (Boulding, 1966). This was in stark contrast to the so-called "cowboy economy" at that time - an open economy in which the natural environment was perceived as being limitless: no limit was set on the capacity of humans to supply and receive energy and material flows (Wautelet, 2018). The "Limits to Growth" thesis written in the 1970s by the Club of Rome shared the key message that the global economy will probably suffer beyond the year 2100 if the combination of resource depletion and pollution strengthened by population growth remained untackled (Meadows et al., 1972; Wijkman et al., 2017). In other words, there is an urgent need for decoupling, which refers to the transition to a circular economy.

It was only until the nineties that environmental economists David Pearce and Robert Turner were the first to introduce the term circular economy in their book "Economics of Natural Resources and the Environment" (Pearce & Turner, 1990). Based on Boulding's ideas, they argued that the traditional linear economy excluding a recycling perspective cannot be sustainable and must be replaced by a circular system (Geisendorf & Pietrulla, 2018). Pearce and Turner developed conceptual frameworks shifting from the traditional economic model of the one-way flow of resource - product - pollution emission to a circular process of resource - product - (renewable) - resource, thus creating a whole economic system and production and consumption processes enabling integrated supply chain management and waste prevention (Winans et al., 2017).

Despite all this, it is only since recently that the concept of the circular economy has gained ground due to the propagation of works published by the Ellen MacArthur Foundation (EMF). EMF is an institution that has been publishing papers since 2012 on the opportunities of a circular economy (Ellen MacArthur Foundation, n.d.-b). The timing of the actions taken by EMF seems to be close to the 30-year update and review of the Club of Rome's reporting that the changes in policies have been insufficient for foster sustainable development (Kok et al., 2013; Meadows et al., 2004). This, in combination with the current financial crisis that is suffering from a linear production model characterized as 'take make and waste', has resulted in the need to break the strong bond between prosperity and material consumption (Lacy & Rutqvist, 2015).

To delink economic growth from increasing environmental problems, the importance of the process of decoupling is stressed (Lonca et al., 2019). In Figure 2.5, the different forms of decoupling are illustrated. It should be pointed out that this is a hypothetical representation as a means to explain the concept of decoupling and thus, not related to any scenario. Here, human well-being grows faster than the economic activity (GDP) while relatively less resources are consumed. The resource use is still increasing, albeit at a slower pace of growth than in GDP. This type of decoupling is defined as *relative decoupling*. Meanwhile, the economic activity and the environmental impact are completely decoupled: over the course of time the economic activities increase and the environmental impact decreases. This form is considered *absolute decoupling*.

There are two alternative paths to achieve decoupling:

- ⇒ Resource decoupling: maintaining economic outputs (GDP) independent from resource use and impact decoupling – achieving economic success while reducing the environmental impact of resource usage.
- ⇒ Welfare decoupling: reorientation from the production of goods (GDP) to other measures of well-being.

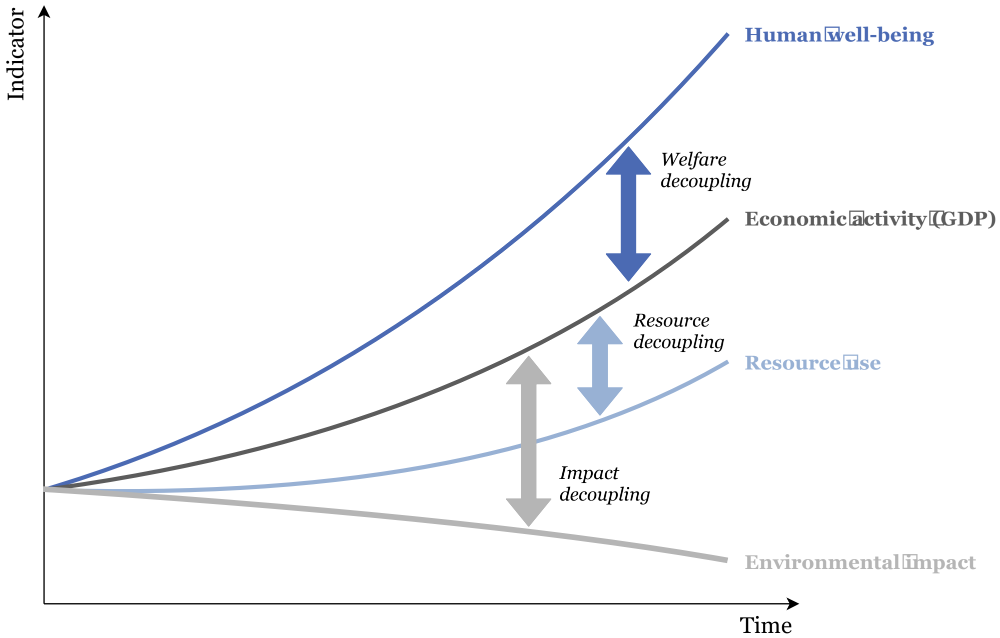

Figure 2.5. The notion of decoupling. Adapted from UNEP (2011).

Decoupling is a central concept present in different schools of thoughts that constitute CE (Ghisellini et al., 2016). As the circular economy is rooted in various theoretical backgrounds (ecological economics, environmental economics and industrial ecology), the concept has been redefined and developed by different schools of thoughts. The Ellen MacArthur Foundation (2013) states that the following recent developments have contributed to the establishment of the CE concept: Cradle to Cradle, performance economy, biomimicry, industrial ecology, natural capitalism, blue economy and regenerative design. The different schools of thoughts are examined, looking at how they prioritize different aspects and outcomes linked to the concept of CE in Appendix B (Wautelet, 2018).

2.2.2. The Definition and Concept of CE

Systematic analysis by Kirchherr, Reike & Hekkert (2017) illustrates that there are many definitions to describe the concept of the circular economy. The CE is one of the most discussed topics among environmental economic and industrial ecology scientists nowadays and its interest is receiving increasing attention worldwide by scholars and practitioners (Ghisellini et al., 2016; Lieder & Rashid, 2016). As a result, the rapid growth of publications of scientific articles and propositions on CE research mirror different understandings of what a circular economy entails.

However, the definition provided by the Ellen MacArthur Foundation is one of the most prominent and recognized references (Geissdoerfer et al., 2017; Leising, 2016). The perspective has been widely used by scholars and the industry. EMF defines the concept as: "A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles." (Ellen MacArthur Foundation, 2015). 'Restorative' use of resources is considered to be a core defining element ensuring virgin materials do not end up as discarded waste (Geisendorf & Pietrulla, 2018). This interpretation is based on the Cradle to Cradle and systems thinking concept. Additionally, it involves the distinction of two different type of materials: biological materials that can return to the biosphere as feedstock (e.g. wood) and technical materials, which cannot biodegrade and enter the biosphere (e.g. metals and plastics) (Rizos & Tuokko, 2017).

The most common conceptualization of the 'how-to' of circular economy is the 3R framework, a generic term employed by the Chinese CE Promotion Laws to define all activities related to reducing, reusing and recycling conducted in the process of production, circulation and consumption (Circular Economy Promotion Law of China, 2008; Yang et al., 2014; Yong, 2007). Many scholars regard this framework as the core principle of CE, yet there are alternations made to this exact framework. For example, the European Union Waste Framework Directive introduced an additional 'R' to include recover dimension (Waste and Repealing Certain Directives, 2008). All varieties do share the common principle of having a hierarchy in the different R's. Another core principle shared by scholars is related to taking a systems perspective. Those who describe the concept, highlight the fundamental shift needed to transition to a circular economy instead of reaching such a 'state' by incremental improvements (Lehmann et al., 2014; Velenturf et al., 2019). The definition of CE used in Leising's work (2016) will be restated in this thesis: "A circular economy is an economic and industrial system where material loops are closed and value creation is aimed for at every chain in the system".

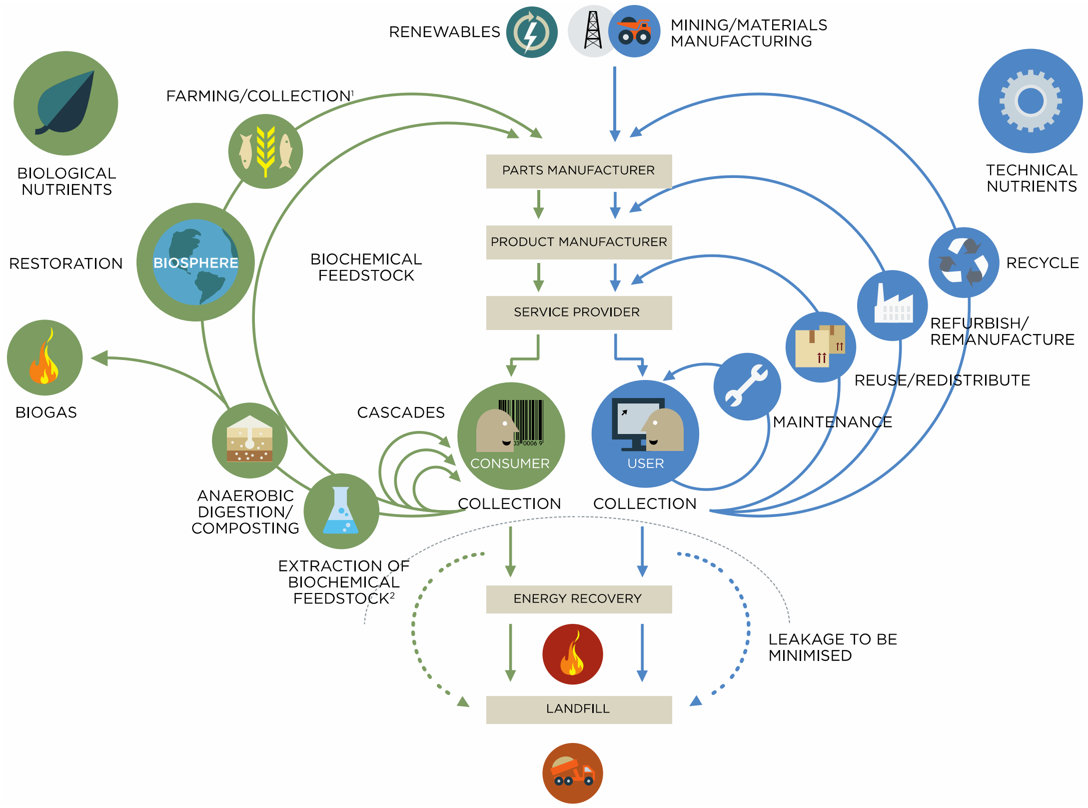

Figure 2.6. The Butterfly diagram illustrating the technical and biological cycles through the economic system each with their own set of activities (Ellen MacArthur Foundation, 2013).

The so-called Butterfly diagram displayed in Figure 2.6, presents a circular economy. It relies on three key principles:

1. Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows.
2. Optimize resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles.
3. Foster system effectiveness by revealing and designing out negative externalities.

Drawing on these principles, five fundamental CE characteristics are identified:

1. Waste is designed out by intention
2. Value diversity as a means of building strength
3. Renewable energy required to fuel CE
4. Apply systems-thinking
5. Full costs of negative externalities are taken into account

Closed material loops are visualized, such as recycling, cascading and maintaining (Mentink, 2014). The cascades of cycles featuring the consecutive use of materials in the different economic activities and processes before being restored to its official source are essential to the 'butterfly structure' (Leising, 2016). The rule of thumb here is that the inner circles are preferred to outer circles as these require less energy, material, labor and processing to be restored again, and thus the more valuable (Ellen MacArthur Foundation, 2015). The hierarchy for technical materials can be described as follows (Damen, 2012; Mentink, 2014):

1. Maintenance

Extend lifetime of a product or material by preventing faults or breakdowns. Generally conducted as a scheduled activity.

2. Repair

Restore a broken or faulty material or component to its original state (Parlikad et al., 2003).

3. Refurbish

Bring quality of a used product up to specified level that is satisfactory or repair major components that are close to failure.

4. Redistribute

Reuse without treatment to capitalize product's value longer. Occurs when a product has reached an end-of-need phase. (Mentink, 2014).

5. Upgrade

Replace outdated modules or components with technologically superior elements (Parlikad et al., 2003).

6. Remanufacture

Bring used products up to quality standards that are equivalent or even superior to the original product by complete disassembly and extensive inspection (Damen, 2012).

7. Recycle

Reuse materials from used products and parts by different separation processes in the production of the original or other products (Parlikad et al., 2003).

8. Energy recovery

Win back part of the energy content of the used products in the form of heat, electricity or fuel prior to disposal (Mentink, 2014).

9. Disposal

Last resort of a material flow if components and materials cannot be recovered by any of the steps mentioned above.

2.2.3. Enablers and Barriers to the Development of CE in the Built Environment

The concept of CE is very broad, combining various schools of thoughts and a systems thinking approach addressing multiple fields of studies (van Eijk, 2015). Research on the application of CE principles in the built environment remains limited, largely focusing on the recycling of construction and demolition waste (Hart et al., 2019). Within a whole-systems context, it is important to consider different factors for the adoption of CE in construction. In Table 2.1, the main enablers and challenges are categorized according to the following factors: economic, technical, cultural and regulatory. The challenges revealed highlight the situation as it is as of this moment, whereas the enablers present the developments required to facilitate a circular economy in buildings.

Table 2.1. Enablers and barriers for adoption of a circular economy in the built environment according to different factors (Adams et al., 2017; Cruz Rios & Grau, 2019; Hart et al., 2019).

	Enabler	**Barrier**
Economic	▪ Inclusion residual value – life cycle costing ▪ Clear business case	▪ Investors with short-term mindset ▪ High upfront investment costs ▪ Supporting infrastructure ▪ R&D ▪ Certification processes ▪ Limited funding – long-term finance needed ▪ Lack of economies of scale
Technical	▪ Design tools and guidance ▪ Availability of higher value secondary markets	▪ Complexity of building ▪ Material recovery challenges ▪ Long product lifecycles ▪ Lack of standardization ▪ Lack of data on environmental footprint, tracking and technical performance ▪ Insufficient use of collaboration tools and information e.g. building integrated modelling
Cultural	▪ Buy-in from the top ▪ Long-term relationships and partnerships ▪ Systems-thinking ▪ Build and communicate case studies	▪ Industry is conservative, risk-averted and has a silo mentality ▪ Fragmented supply chain ▪ Negative consumer perception
Regulatory	▪ Commitment to circular green public procurement ▪ Producers responsibility ▪ Incentives	▪ Lack of consistent framework ▪ Lack of incentive to design for EOL

2.3. The Circular Economy and Industrialized Construction

In this thesis, the focus is on the building sector. The building sector is one of the three sectors that comprise the construction industry - the other sectors are the infrastructure and industrial sectors. The building sector contributes to resource scarcity and the combination of applying circular economy principles and IC methods can potentially provide a solution to this issue. Chapter 2.3 provides an answer to the first sub question "What are the main developments of integrating the Circular Economy in Industrialized Construction?".

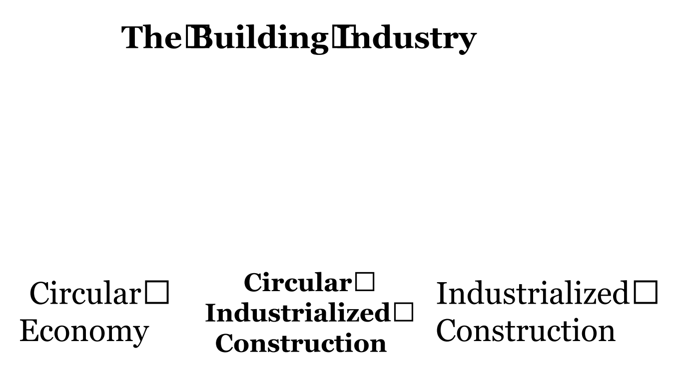

Figure 2.7. The scope of the thesis (own illustration).

Therefore, the relevance of CE and IC for the building sector should be discussed (see Figure 2.7). This is done in accordance with the following elements:

- ⇒ Why the concepts CE and IC are complementary
- ⇒ The recent construction market developments in Switzerland
- ⇒ CE business models
- ⇒ CE potential in IC buildings

2.3.1. Complementary Concepts

In the previous Subchapters, the concepts of the Circular Economy and Industrialized Construction were discussed separately. However, it is important to acknowledge that both approaches can support each other. Based on the literature review, three opportunities have been identified why IC is favorable for a circular economy:

1. **Supply chain integration**: The traditional construction industry consists of a fragmented supply chain faced by a silo mentality. To employ industrialized construction methods, a partnership culture has to be created with a higher level of integration among partners since resources, materials and labor have to remain coordinated (Čuš-Babič et al., 2013). Such long term partnerships are a defining principle of IC (Lessing, 2006). Moreover, shift from a single project focus to a multi-project environment with long-term relationships promoting information sharing and transparency in the supply chain is required. For CE business, multiple different stakeholders are generally involved. There is a need for a shared responsibility among parties, relating to long-term relationships as is the case for IC business (Ghisellini et al., 2016). This is because a CE building's design incorporates the End-of-Use and End-of-Life phase. Materials are directed back into the supply chain and thus relationships persist during the different lifecycle phases of a building (Minunno et al., 2018). As construction takes place in one location and requires a more centralized collaboration, traceability of materials and components can be improved. Material waste at the source of production can be better controlled enabling the possibility of waste returned back into the cycle to form closed-loop supply chains (Jaillon et al., 2009). It also

enhances value reclamation at disassembly, favoring CE. To conclude, the nature of supply chain integration in industrialized construction techniques supports the realization of CE in buildings.

2. **Improved planning for disassembly**: Conventionally, a building project follows a linear process where each individual step (e.g. framings placed after concrete pour) is completed before moving on to the next phase – obstructing disassembly (Höök, 2005). To coordinate all activities including assembly on-site, industrialized construction requires a longer pre-project planning phase compared to the former method (Navaratnam et al., 2019). However, this creates an opportunity to consider design for disassembly during pre-assembly planning directly, maximizing the value of material than can be retained (Aye et al., 2012).
3. **Standardization for adaptability**: By standardizing components, an aspect of IC, elements can more easily be used elsewhere within a building. In turn, this contributes to adaptability, anticipating future modifications (Albinson, n.d.). This is an important requirement for CE as the lifetime of a component can now be extended. Likewise, traditional building are built on-site to be permanent and therefore are not considered to be adaptable (Minunno et al., 2018).

2.3.2. Market Developments

The Swiss building sector has experienced several trends that could possibly facilitate the development of integrating CE principles and/or IC methods. In 2018, the construction sector accounted for 9.02% of the Swiss GDP – CHF 62 billion (Federal Statistics Office, 2019). This number is relatively high compared to other European countries and changes in construction investments are more likely to affect the Swiss economy than variations in other sectors. In Figure 2.8, the total building construction expenditure is highlighted in red. In the years 2007 and 2008, there was a decline in spending due to the global economic crisis at that time. However, the industry has managed to recover, jumping by +15.75% between 2005 and 2015. Moreover, the employed population in the construction of buildings sector has gradually increased as employment in real estate and architectural and engineering activities has increased sharply. This is the result of a trend towards smaller households and an overall demand for more personal space (Camarasa et al., 2017). It entails a promising future for the building industry and circular IC, creating opportunities for building more homes rapidly while keeping the environmental impact to a minimum. Additionally, as employment has and still is increasing, people can be schooled or retrained in order to adopt circular IC methods.

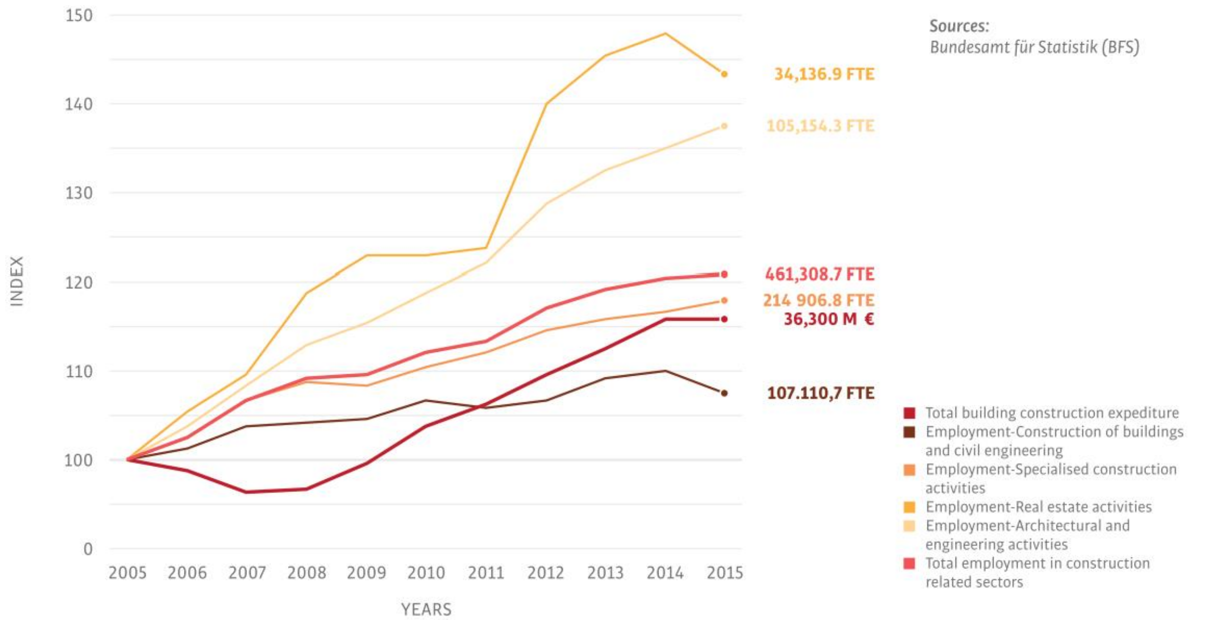

Figure 2.8. Total construction investments and total employment related to construction (Camarasa et al., 2017).

The total Swiss construction sector consumes approximately 60 to 70 tons of building material on an annual basis (Swiss Federal Council, 2018). Since the mid-1980s, a majority of the raw material is reintroduced into the material cycle as secondary material. In 2018, about three-fourths of a total of 17.5 million tons of demolition material was recycled (Federal Office for the Environment, n.d.). This includes the primary waste stream concrete as well as gravel, sand, tarmac and masonry.

It is forecasted that in the near future, construction waste originating from buildings above terrain level (The German word "Hochbau") will be significantly higher. By 2025, an increase of 20% of construction waste compared to 2015 is forecasted (see Figure 2.9) (Wüest & Partner, 2015). In other words, this indicates an increase from 7.5 million tons to approximately 9.0 million tons of construction waste. Circular IC can facilitate in minimizing this stream by retaining its value through reintroducing the waste back into the cycle.

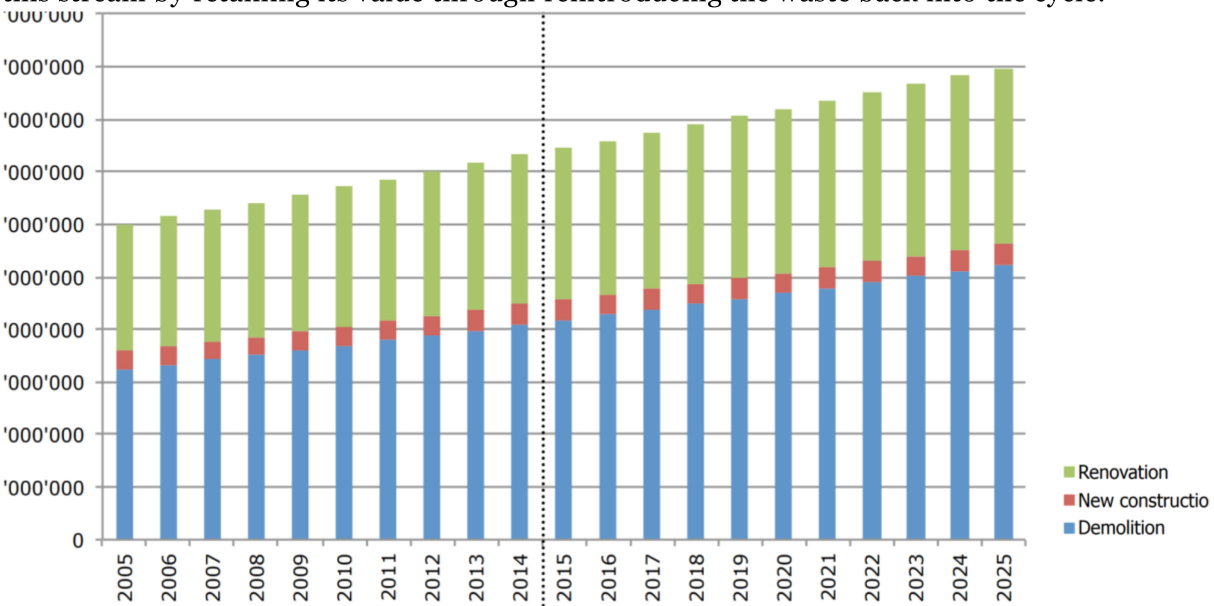

Figure 2.9. Forecast Switzerland construction waste in tons according to construction processes (Wüest & Partner, 2015).

In Figure 2.10, it can be seen that the building expenditure for conversion, extension and demolition works has increased substantially compared to the year 1980. This trend is expected to continue as 1.5 million buildings (of the 3.8 million in total) are in need of refurbishment to transition the existing stock towards a low-carbon path (Camarasa et al., 2017). This implies that this specific industry has grown resulting in more waste streams as is depicted in Figure 2.9. CE can unlock this potential by retaining value of the used materials and components (Thelen et al., 2018). Likewise, by applying circular IC through designing for disassembly, the costs for demolition can potentially be diminished, as it will be easier to separate waste streams during deconstruction on a building.

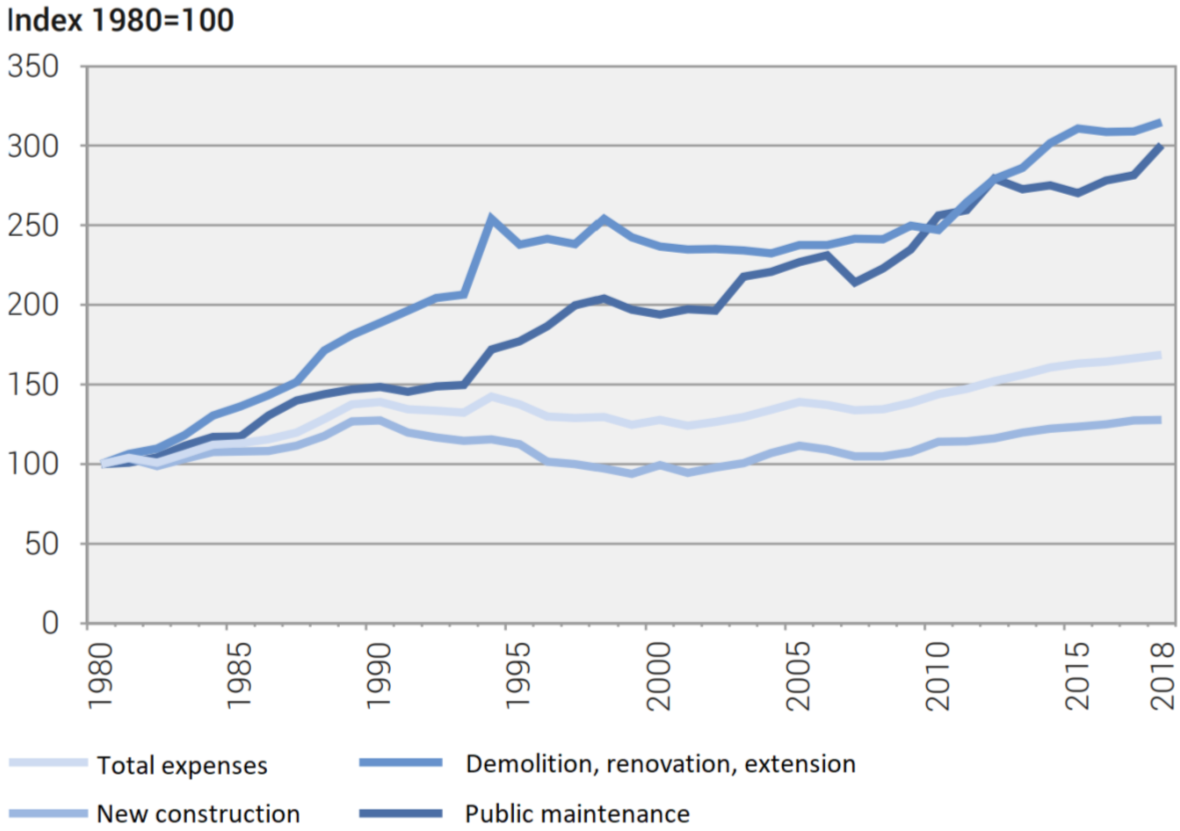

Figure 2.10. Expenses per type of construction works (Bundesamt für Statistik, 2019).

2.3.3. Circular IC Strategies

New strategies are emerging as a means to scale up the global circular built environment (Thelen et al., 2018). Five recurring strategies have been identified through desk research and include several CE characteristics that be applied to off-site fabrication practices (Agrawala & Börkey, 2018; Carra & Magdani, 2017; Lacy et al., 2015, 2020). This subchapter sketches the five specific strategies (see Figure 2.11).

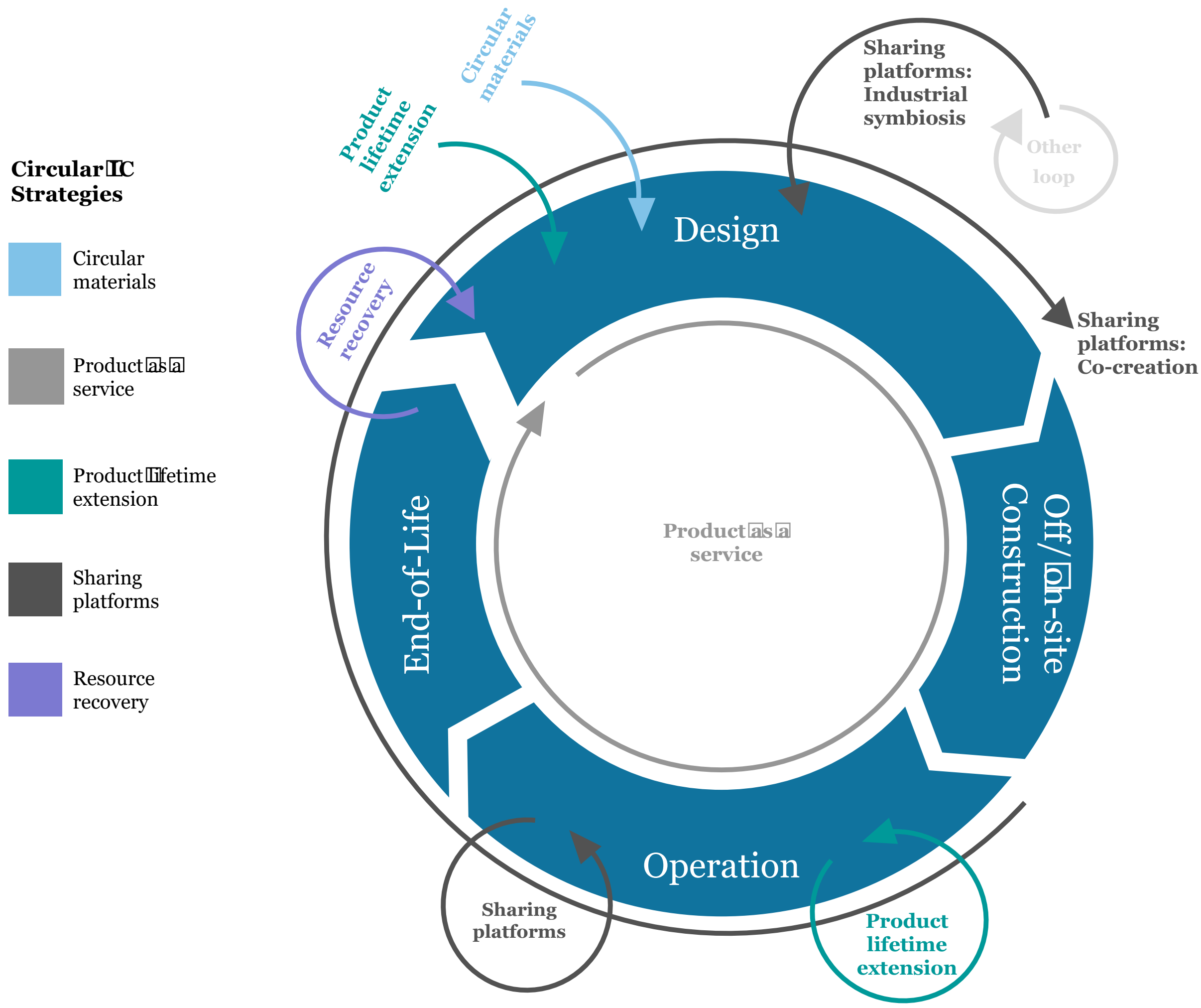

Figure 2.11. Circular strategies that can be applied to industrialized construction methods. Adapted from Lacy et al. (2020).

1. Circular materials

Circular materials focus on minimizing raw material consumption considering non-toxic, high-quality materials that can be easily recycled, reused or biodegraded or only in essential cases, use new renewable raw materials (EEA, 2019). To ensure minimal resource use, compact and lightweight constructions should be selected (Thelen et al., 2018). To illustrate, Switzerland IC players built with lightweight prefabricated timber constructions instead of concrete or steel. Wood has many advantages over the latter two - it functions as CO_2 storage, positively impacting the environment and at its EOL phase the material can still be of valuable through a cascading system (Martin & Perry, 2019). In addition, design should be flexible and modular with each layer of a building having the ability to be renewed without adversely affecting other layers. Avoidance of surplus material for non-essential functions is key as well.

2. Product as a service (PAAS)

PAAS exemplifies the concept of paying for a service rather than for a product. The manufacturer remains owner of the product or material, securing its residual value while stimulating easily repairable and long-lasting design. This business model has been vastly applied to lighting, floor carpeting and lifts (Bukowski & Fabrycka, 2019). Companies that shift from a sales-based model to service-base model start to include construction and maintenance services (EEA, 2019). New companies are established that will play an intermediary role, for example, providing contract management for a series of service providers within a single building (Thelen et al., 2018). Similar to industrialized construction, there is a demand for building long-term relationships involving the service provider and customer over the course of the service lifetime. Furthermore, the approach of construction services as a product can also be applied. A building could ultimately constitute of a basic design and a selection of various components and finishing parts that can be fitted according to a customer's preferences (Gerhard Girmscheid, 2005). This leads to a shift from constantly constructing a new unique building to an industrialized (standardized) planned and designed building project.

3. Product lifetime extension

Extending the life of a product or material used in construction is key here (Bukowski & Fabrycka, 2019). Bearing in mind a design that is flexible and adaptive enables cheaper and more resource-efficient modifications, repairs and upgrading in the future. Materials should be selected that focus on durability and a low CO_2 impact (Thelen et al., 2018). This is where IC comes into play using flexible modular components and building techniques that will not form a barrier for later reuse possibilities when disassembled. The degree of pre-assembly for disassembly has to be consider as well. To maximize the use of a product, a manufacturer must start from the very beginning at the design phase and purposefully extend through repairs, reconditioning and upgrades (Lacy et al., 2020).

4. Sharing platforms

The goal of a sharing platform is to combat underutilization of products and materials through shared ownership and optimizing their use (Lacy et al., 2020). Achieving this strategy typically requires a major transformation in business model targeting the relationship between the product and the consumer similar to PAAS models. Shared ownership can be demonstrated through the use of exchange platforms of construction equipment and machinery and unaccustomed surfaces and spaces for multifunctional purposes (Bukowski & Fabrycka, 2019). Such opportunities may be found during the different phases of IC. For example, at the EOL phase, prefabricated building modules can be disassembled and its corresponding elements and materials can be used by another party or industry (Navaratnam et al., 2019).

Furthermore, industrial symbiosis (IS) can plays a role in optimizing the use of materials and products and thus plays a role in sharing platforms. Opportunities for IS are generally found within an eco-industrial park where two or more companies often from different sectors collaborate by exchanging resources (Thelen et al., 2018). Waste materials from one party can be used as inputs for construction. For example, gypsum waste originating from the chemical industry is used to produce plaster boards.

In order to establish industrial symbiosis, co-creation in the supply chain is required whereby stakeholders work and design solutions together. To illustrate, architects and contractors can collaborate with recycling companies to develop effective measures to achieve maximization of resources. Users should be involved in co-creation as well, when designing a module for example, to align their demands, and thus increase the utilization rate. At the same time, it is beneficial for the material supplier who wishes to retrieve their materials in optimal state.

5. Resource recovery

Resource recovery is reusing materials and products that have already undergone a complete life cycle in one building in another building project (Thelen et al., 2018). It is of paramount importance to exclude hazardous, toxic materials and select materials that remain valuable without being downcycled into a low-grade product – facilitating circularity in material use.

To shift to such a model, business relationships and responsibilities need to be altered, creating new contract structures. For off-site construction, prefabricated elements should be designed to be easily disassembled giving it new purposes. This could be in the form of reusing the element as a whole or separating and recovering its materials for a new IC project. A policy approach that could support this strategy is called *Extended Producer Responsibility* (EPR). This scheme ensures that the polluter pays for the environmental impact that a material or component causes (Acree Guggemos & Horvath, 2003). It entails an extension of the producer's responsibility by placing the end of life burden on the manufacture. As such, it is expected that a producer will look into the possibilities of design such as disassembly or recyclability to reduce EOL costs. EPR may be set up as a reuse, take back or recycling program. To achieve this, business relations and responsibilities need to be extended beyond the date of purchase with new contract structures (Thelen et al., 2018).

2.3.4. CE Potential in IC Buildings

Buildings are inherently complex due to the uniqueness of each individual building project, various inputs of a great number of stakeholders and the use of many different materials that have specific characteristics, usages and life cycles (Eberhardt et al., 2019; Pomponi & Moncaster, 2017). Brand (1994) identified six levels of a building, named the Shearing Layers, and their corresponding lifespan, stipulated in Figure 2.12. Different stakeholders are involved in each separate layer (Thelen et al., 2018). Users and owners primarily have an influence on the 'stuff' and 'space plan' layers and as such have a say in the circularity of these two layers. Installation companies deal with the 'service' layer and architects, engineers and construction companies generally determine the 'skin' and 'structure' layers. Building in layers entails that each element may easily be separated or removed (Lemmens & Luebkeman, 2016). Likewise, each layer has a different timespan, allowing repairs, replacements and modifications to happen at different times without affecting other layers. To demonstrate, heating and cooling systems (part of services layers) should be designed to fit as separate entities while integrated with other services. However, they should not be intertwined within the skin of a building so that, in the event of maintenance, there will be no obstacles. Industrialized construction can play a role here as prefabricated components can be designed to be movable. As a result, the adaptability and longevity of a building is increased – a fundamental characteristic for circular buildings.

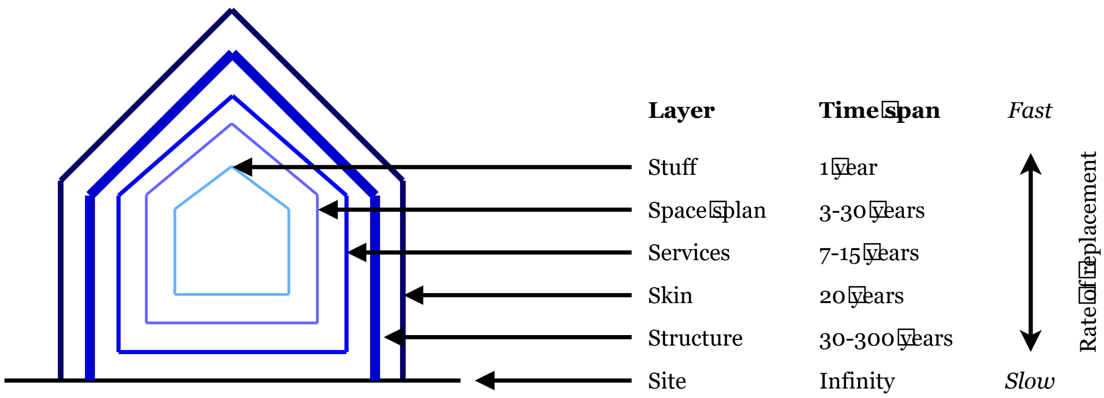

Figure 2.12. Shearing layers model with six material layers. Adapted from Brand (1994).

At a building level, there is a direct relationship between the amount of material recovered and the economic and environmental benefits. In other words, increasing circularity will require less energy consumption and material resources. This is clearly depicted in Figure 2.13. Reusing an entire building is believed to be the best-case scenario, albeit in many cases, projects are not designed in this way.

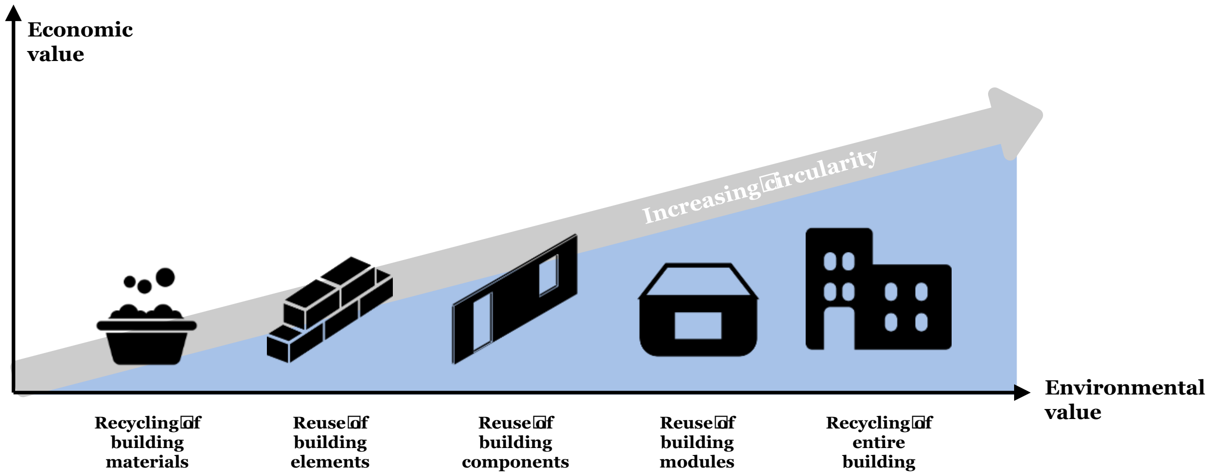

Figure 2.13. The degree of economic and environmental value is related to the degree of reuse of material recoverability. Adapted from Eberhardt et al (2019).

A higher degree of reuse material recoverability can be achieved by Design for Disassembly (DfD). It entails the future of deconstructing a building with the aim of reusing components or products (Cruz Rios & Grau, 2019; Tingley & Davison, 2011). IC methods can be complementary to DfD as prefabrication enables improved planning for the EOL phase (see 2.3.2). This in contrast with conventional construction and deconstruction, in which at the end of life phase, the building is completely demolished, recycling only construction and demolition waste, which is considered down cycling. Guy and Ciarimboli (2005) argue that, when designing for DfD, the following key principles should be considered:

- Proper documentation of materials and methods for deconstruction
- Design of accessible connections for easy dismantling, such as using bolts and screws as opposed to chemical jointing
- Design for production and assembly techniques that support deconstruction, such as prefabrication or modularization
- Separate non-recyclable/reusable/disposal components, such as electrical equipment
- Standardize components, assemblies and dimensions
- Design that reflects labor practices, productivity and safety regulations making renovations and disassembly more economical and reducing risk

There are various disadvantages related to design for disassembly. During the phase of deconstruction, dismounted components have to be stored, quality-checked and certified, costing time and money (Minunno et al., 2018). Moreover, the market for reused materials and components has not yet been fully established and matured, thus lowering the economic benefits. Finally, planning for deconstruction may delay the project's schedule and budget (Cruz Rios & Grau, 2019). Rios and colleagues (2015) state in their paper however that established partnerships and collaborations between stakeholders (e.g. governments and private sectors) can increase deconstruction's cost effectiveness and its overall success. The importance of stakeholders and network formation is discussed later on.

Through prefabrication of building components, barriers of design for disassembly can be overcome. The use of tracking technology, such as BIM, is very much related to DfD and can allow for material tracking, identification and cataloging (Minunno et al., 2018). BIM stores information about components and their relationship to the building. To ensure DfD, disassembly processes should be part of the project manual after completion of a building project and stored as a working document for the building. The use of so-called materials passports (MP) can serve this purpose by collecting and handling all the relevant information required (Heinrich & Lang, 2019). MP are digital sets of data describing characteristics and properties of materials and components in products and systems that give them value throughout its life cycling, including present use, recovery and reuse. Such passports can be coordinated with BIM, since BIM is being used more and more and thus the scope of the application of MP may increase (Waal, 2018). Furthermore, the placement of RFID tags or QR codes containing MP data in a building could foster the fast identification of each element and material (Ness et al., 2018). The scope of a MP is characterized by different hierarchy levels, including material, component, product, system and building level (Heinrich & Lang, 2019). For a material, the value of recovery can be determined whilst for a product or system it can determine specific characteristics that enable DfD. Additionally, how a product is linked to a building has to be acknowledged in order to indicate how value can be recovered during disassembly. This information stored in a MP is truly of importance for promoting a circular economy as it will increase and retain the value of materials, products and components over time. It should be noted that not all information is relevant to each stakeholder involved and might only be necessary during a certain phase of its life cycle.

Finally, there are various certifications and benchmarks to audit the sustainability and circularity degree of a building, integrating IC methods and concepts in its design. In Appendix C, the most prominent and widely used schemes are discussed.

2.4. Summary and Discussion

In Chapter 2, an answer is given to the first sub question "What are the main developments of integrating the Circular Economy into Industrialized Construction*?*". Research on the merging of the Circular Economy and Industrialized Construction methods remains very limited. Nevertheless, IC developments are complementary to a circular economy due to the nature of supply chain integration, ability to plan for disassembly and standardization for adaptability purposes. Likewise, the Swiss building sector is expected to show a promising future for circular IC. There is a greater need for new housing due to demographic changes and investments in the construction industry are rapidly increasing because of the negative interest rates, which in turn triggers the interest of investors. Additionally, an increase in construction waste is forecasted and by retaining value through circular IC, this stream can be minimized.

Both the transition of industrializing the building industry as well as the shift from a linear to a circular economy, entail a complete systems change with completely different designed supply chains. Herewith, multiple challenges need to be overcome to successfully adopt this emerging niche. High upfront costs, time-related problems and ensuring full supply chain integration are key issues circular IC will face. Moreover, the niche demonstrates unique characteristics that have never before been studied. There is a need to analyze these changes taking place:

(1) A building is a unique entity with several layers comprising different materials and components. To ensure that an element can be easily removed or replaced, it is important to separate building layers as each layer corresponds to a different timespan for maintenance or removal requirements. However, which and how the layers incorporate CE principles in IC building is currently not clear. The building layers are as follows:

- Stuff
- Space plan
- Services
- Skin
- Structure
- Site

(2) To increase the degree of material recoverability, design for disassembly principles during prefabrication have to be in place. This implies that there must be proper documentation of materials and components (e.g. MP/ BIM), easy dismantling and use of mechanical joints instead of chemical fixtures. Nevertheless, the practices applied to enable reusing recovered material in IC has not sufficiently been researched. The levels of reuse of material recoverability are shown:

- Recycling of building materials
- Reuse of building elements
- Reuse of building components
- Reuse of building modules
- Reuse of entire building

(3) Likewise, there are different levels of pre-assembling a building. A higher degree of off-site fabrication could potentially lead to improved control of construction and presumably a higher level of achieved circular economy, yet this is not clear. Below, the pre-assembly categories are listed:

- Component manufacturing & sub-assembly
- Non-volumetric pre-assembly
- Volumetric pre-assembly
- Modular building

(4) Five circular strategies have been identified that can be applied to industrialized construction methods, yet in what ways the strategies are put in place lacks clarity. The following design principles are:

1. Circular materials
2. Product as a service
3. Product lifetime extension
4. Sharing platforms
5. Resource recovery

3. Innovation and Transition Frameworks

The construction industry is characterized by a very low degree of innovation with a preference to continue using traditional building methods, leaving technological opportunities underutilized (van Egmond - de Wilde de Ligny, 2009). Hence, the evolution of new technologies within this sector progresses very slowly. As described before, the diffusion of circular IC is complex and challenging. A comprehensive analysis should be conducted to study the different levels of the multifaceted landscape the niche is embedded in to obtain a complete picture of the development of circular IC.

For this research, two different frameworks originating from innovation and transition frameworks are applied, namely the Strategic Niche Management and Multi-level Perspective frameworks. Various scholars have used these frameworks to study the development of sustainable niches, and more importantly, sustainable niches in the construction industry (Thuesen & Koch, 2011; van Egmond - de Wilde de Ligny, 2009). In the first place, it is essential to examine the niche separately to understand which processes can facilitate the adoption of this new technology. However, external factors can have a great influence on the successfulness of such an adoption, and thus the wider context should be analyzed as well. Different sources of information are needed for each framework contributing to a comprehensive and reliable analysis. In Subchapter 3.1, the Strategic Niche Management framework is introduced and in the consecutive Subchapter, the Multi-level Perspective framework is described. Subchapter 3.3 concludes the findings of the latter two, which will support the development of the conceptual framework in the Chapter 4.

3.1. Strategic Niche Management

As mentioned, circular industrialized construction has been identified as a 'niche'. Niches comprise a whole series of primarily loosely coupled experiments with a focus of creating lobbying platforms for a new solution (Kemp et al., 1998). A niche situation provides space for new ideas, practices and products to be developed while being protected against mainstream competition (Schot & Geels, 2008; A. Smith, 2007). The idea behind creating a sheltered space is that innovations are given a chance to evolve from an idea or prototype into a technology that can actually be used (Kemp et al., 2001). Hence, niches act a 'incubation rooms' for radical technologies that are in practice often facilitated through governmental interventions (F. W. Geels, 2002; Kemp et al., 1998; Loorbach et al., 2017). Such spaces are called technological niches, born by networks of organizations and people with an interest in the development of a specific application. Novel technologies, embedded in niches, are produced based on knowledge and capabilities and introduced against the backdrop of existing regimes – a concept that is explained later on in this chapter (Rip et al., 1998). When incubation is successful, a technological niche can transform into a market niche, in which the corresponding innovation can have applications in specific markets (van Eijck & Romijn, 2008). Success can be defined as the transformation of a technological niche into a market niche and ultimately the presence of a regime shift (see Figure 3.1).

However, the development of market niches will not automatically lead to regime shift (Hoogma et al., 2002). Such a wide transition cannot solely occur through niche development. It is the result of a combination of successful Strategic Niche Management, niche development, changes taking place on a broader scale within society and the further development of more mature technologies. For example, taking advantage of technological opportunities, a drastic change in energy prices or governmental policies favoring sustainability are factors that are important to consider. Strategic Niche Management plays a crucial role in this complex process, providing a clear roadmap through the different transition levels and communicating the potential of technological breakthrough (Browning, 2018).

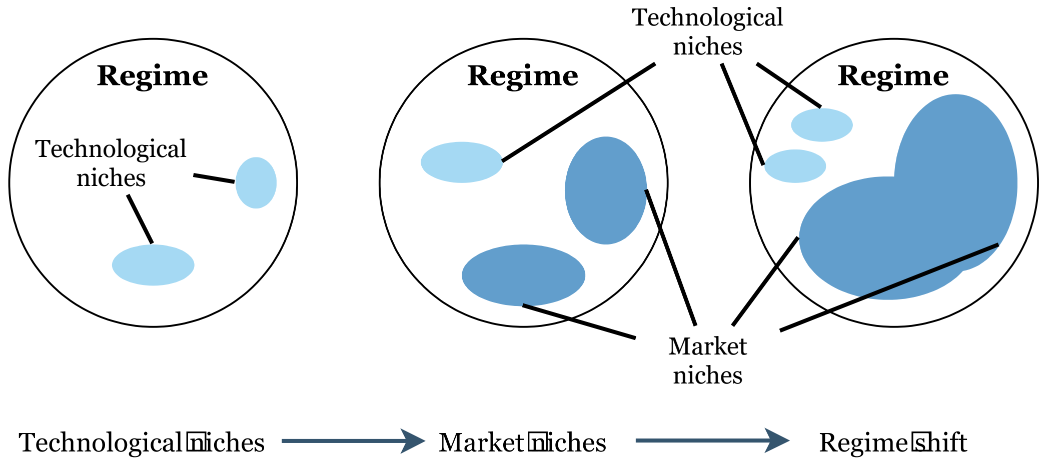

Figure 3.1 The evolution of a technological niche into a regime shift. Adapted from Schot & Geels (2008).

Strategic Niche Management (SNM) is an analytical approach that has been designed to specifically assist in the introduction and diffusion of what may be called new sustainable technologies through societal experiments (Caniëls & Romijn, 2006; Kemp et al., 1998). The SNM framework has proved useful in analyzing the potential of sustainable radical innovations, such as biofuels, public transport systems and electric vehicles (Hoogma et al., 2002; van Eijck & Romijn, 2008; Xue et al., 2016). The official definition of Strategic Niche Management originates from an article published by Rip, Kemp & Kemp (1998) and has been adopted by many SNM researchers. The following definition for SNM, based on the aforementioned authors' work, is used in this thesis: "The creation, development and controlled break-down of test-beds for promising new technologies and concepts with the aim of learning about the desirability of the new technology and enhancing the further development and the rate of diffusion of the new technology." (Kemp et al., 1998).

Central to the concept of SNM is the notion that the establishment of radical innovations that are economically, socially and environmentally sustainable is a complex and long process with a high degree of failure even if a technology seems to be very promising (van Eijck & Romijn, 2008). This is because technologies are always embedded in a socio-technical regime. Such as regime is defined as follows: "The whole complex of scientific knowledges, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructures that make up the totality of a technology." (Kemp et al., 1998). In turn, a regime is part of the wider context, namely the landscape. Niches are strongly affected by existing regimes and landscape (F. W. Geels, 2002). However, this perspective will be discussed more in-depth in Subchapter 3.2. With respect to the emergence and stabilization of a niche level, it can be concluded that a long trajectory of experiments is required to make this happen (Raven, 2005).

SNM has been used for analyzing retrospective case studies in order to develop policy and formulate governance suggestions (Raven, 2005). SNM can thus be useful as a research model for understanding technological change as well as a policy tool for influencing such technological change. Without the latter instrument, the usefulness will remain limited to analyzing cases and managing isolated learning experiments (Caniëls & Romijn, 2006). With the introduction of sustainable technologies, there is often a lack of clear advantage for an individual user or producer as an existing and clear market is yet to be developed (Raven, 2005). Governmental incentives could facilitate the creation of markets, yet only when they have a drastic impact, as they must compete with dominating existing technologies. Accordingly, Strategic Niche Management as a policy tool is based on improving the innovation process through learning and articulation, rather than on defining the destination and suggesting incentives that must be implemented to reach that state (Caniëls & Romijn, 2006, 2008b).

Within technological niches, three internal processes are critical for successful development (Rip et al., 1998; Schot & Geels, 2008). Experiments set up as part of a SNM approach must contribute in a certain way to these processes (Jansma et al., 2014; Kemp et al., 1998):
Network formation – build broad social networks
Learning - learning about problems, need and potentials / articulation process
Expectations – voicing and coupling of expectations

In the following sections, the three elements are discussed in-depth, followed by an evaluation of the interactions between the processes.

3.1.1. Network Formation

Niche creation requires an extensive and diverse co-operating actor network in order to succeed (Caniëls & Romijn, 2008a; Kemp et al., 1998). Specific actors must be involved that can facilitate the development of a niche and the activities of existing actors and their relationships ought to be changed. Certain actors with a special interest in particular technologies might not be willing to invest in innovative, competing technologies (Hoogma et al., 2002). Such stakeholders might hinder or even prevent the niche from developing. A supportive network of actors is of paramount importance composed of producers, users, regulators and societal groups that continue development, carry expectations and express new needs and demands (Raven, 2005). In the initial phase, the size of an actor network is small - there are only a few investors that are speeding up the development, the number of users is limited, and regulators might not be aware of the existence of the technology. This creates an unstable network, accompanied with the limited commitment of actors. They do not have a vested interest yet and withdrawal does not have many consequences attached to it. As time progresses, networks grow and relations between stakeholders and their roles are improved and strengthened. Hence, the network is stabilized.

Hoogma (2000) argues that the *composition of a network* is important for a niche to develop steadily. As mentioned before, there is a need for actors that are willing to invest in maintaining and expanding a niche. Large firms can take on this role as they possess capacities and (financial) resources. Yet, it is important to acknowledge if these established firms truly want to participate or if they have different reasons to join, perhaps trying to impede the development (Hoogma et al., 2002). Furthermore, big organizations might lean towards incremental improvement instead of radical change as they are heavily connected to the dominant regime. However, Hoogma (2000) explains that the more radical the niche is, the more actors involved are *not* strongly linked to the present regime. Thus, involving new firms that do not maintain strong ties with this current regime are favored, albeit they are able to provide resources and ensure the niche development will not be interrupted. When analyzing technical development, the industrial network theory by Håkansson (1987) is a promising tool to use. Three variables have been defined: (1) **actors** who perform activities and/ or control resources; (2) **activities** that are performed by actors to develop, create, combine or exchange resources and (3) **resources** that consist of physical (e.g. materials), financial and human assets (e.g. labor).

Another characteristic of network formation is the *alignment of actor's activities and resources*. Alignment makes a reference to the degree that actor's strategies, expectations, beliefs, visions and practices are heading in the same direction (Raven, 2005). Visions might not be shared between big businesses and new businesses. Big firms may want to focus on advancing current technologies whilst newer firms are fixated on increasing the market share of novel technologies (Hoogma, 2000). Therefore, there is a clash between the strategies of both parties to realize their visions and goals. Network alignment is high when relations are **stable** and perceived to be **complex**, including cross-relationships. The presence of macro actors can achieve this stage commitment and effort required in the network (L.M. Kamp, 2010; van der Laak et al., 2007). Macro actors play an essential role in increasing alignment, bringing together the necessary political and/or financials means and are typically large technology producers, government bodies or independent actors such as platforms and consortia (Raven, 2005). As alignment grows, visions and expectations are more in line due to active participation of actors. Effective exchanges of experiences and information enable rapid development of a niche, which in turn will ensure a smooth transition into the regime level (Browning, 2018).

Hoogma (2000) states that the history of a network is also important to consider. Generally, there are already existing networks prior to the setup of a (pilot) project. Such a project will benefit from a structure that includes stability and expertise of different actors and will be able to contribute to maintaining or extending the established networks. It is crucial to understand how well connected the network is and how long the actors will remain within the network to determine the network alignment. For example, this can be enhanced by organizing regular meetings to increase **connectivity** and **communicate** well and by all signing a contract stating how long the **collaboration** will last. Nonetheless, an established network can also be counterproductive as essential stakeholders such as users might be missing, which could lead to incremental improvements to a technology.

3.1.2. Learning

Many barriers hindering the development of a niche are related to uncertainty and perceptions. Hence, it is important to learn about the needs and problems to be able to overcome them, also referred to as *first-order learning* (Hoogma et al., 2002). Within the learning process about a niche introduction, actors must focus on the following five elements:

- **Technical aspects** – learning about the design specifications and complementary technology required
- **Marker and user developments** – learning about users' needs and perceptions toward the new technology
- **Industry developments** – learning about production and maintenances processes in order to market and expand the new technology
- **Societal and environmental impacts** – learning about the impact on society and the environment of the new technology
- **Government policy and regulation** – learning about the fiscal policies and regulations necessary to stimulate adoption of the new technology

Unsuccessful niche developments are often associated with minimum participation of outsiders and/or regime actors providing resources and institutional support and a lack of second order learning (Schot & Geels, 2008). *Second-order learning*, or higher order learning, entails the processes of participants re-examining and changing the fundamental norms and cognitive frames and possibly taking it one-step further by changing the rules (Vergragt & Brown, 2004). First-order learning answers the question 'are we doing things right?', whereas second-order learning relates to asking 'are we doing the right things?'

(Schilpzand et al., 2010). This degree of learning results in a radical change in approaches to interpreting observations and solving problems, moving forward to achieving desired objectives. It requires self-evaluation and deep reflection and thus Vergragt and Brown (2004) stress that such processes demand a lot of time and effort. Nevertheless, higher order learning in combination with involvement of users and outsiders in the network enhance the development of a technological niche transitioning into a market niche or even entering and taking part of the regime (Schot & Geels, 2008). This is in contrast with the limitations towards first order learning, directed at accumulation of data and facts within a given problem and given context (Quist, 2007). To illustrate, within first order learning, actors learn about improving the design, user acceptance and establishing incentive policies to accommodate adoption (Hoogma et al., 2002; Quist, 2007). In contrast, within higher order learning, these conceptions are not tested but explored and questioned, leading to mutual articulation and interaction of the technology, user demands and regulatory frameworks.

Brown and his colleagues (2003) state that there are two types of second order learning. Firstly, learning can arise within an experiment involving participants within the immediate professional networks. The second type of learning looks at learning embedded in the wider context, diffusing new ideas into society. This diffusion is enhanced when different members of society start adopting a new technology leading eventually to a collective change in their perceptions. In the same article, it is discussed that a sense of urgency that can be created by e.g. (negative) media attention, unanticipated events, failures or possibly a threat, is an important driver for second order learning as it forces a trial and error procedure, fundamental to the concept of learning (H. S. Brown et al., 2003; Leising, 2016).

The five aforementioned elements solely describe the learning processes (first-order), yet the quality of learning has to be assessed as well (Browning, 2018). The frameworks by Brown and colleagues (2003) and Brown and Vergragt (2008) propose ways to identify if there is indeed second-order actor learning taking place and using which approach. As mentioned by Leising and colleagues (2018), both articles address bounded sustainable technologies in projects, limited to a certain space and time. This also applies to the circular IC projects, discussed further on in the thesis. The three different ways, in the form of interrelated shifts among the actors are:

- A shift in **framing or defining the problem** – re-framing a problem to solve controversies arisen by the different interpretive frames of stakeholders involved.
- A shift in the approaches to **solving problems and the priorities of problems** – finding new solutions to solve problems together e.g. collaborative approach.
- A shift towards **mutual convergence** of goals and problem definitions among participants – despite partaking in different interpretive frames, stakeholder can still share or at least accept each other's problem definitions.

3.1.3. Expectations

Expectations and visions play an important role in transition studies and in the development of a niche (Leising et al., 2018). This is especially true for a CE in IC focusing particularly on the beginning phase with the introduction of experimental approaches (Hart et al., 2019; Raven, 2005). Importantly, expectations and visions give grounds for actors to invest time and money in new technologies (Raven, 2005). Raven and colleagues (2010) argue that it attracts attention, resources and actors, especially at the early development stage of an innovation, where functionality and performance of the technology are yet to be defined. Direction is given, acting as cognitive frames during decision-making in the design process of a technology. Furthermore, actors must translate their own expectations to other involved actors and engage in co-operation in order to couple expectations of technologies to societal problems (Hoogma et al., 2002). In turn, the voicing of expectations enable stakeholders to create a shared vision, facilitating the realization of a niche development (Browning, 2018). For expectations, the same dimensions as applied to learning processes are considered according to Hoogma and colleagues (2002). This include the **technical aspects**, **market and user needs/preferences**, **industry developments**, **regulations/ government policy**, and **societal and environmental effects**.

Raven (2005) argues that the addition of the dynamics between actor expectations and visions as part of the SNM model is essential. At the micro-level, expectations are highly specific regarding promising routes for solving a particular problem. At the meso-level, expectations and visions are created about the performance and functionalities of a technologies. Visions are made about the niche as a whole whereas expectations consider more specifically the performance and functionalities of technological innovations.

Leising and colleagues (2018) builds on the concepts issued by van der Helm (2009) and Quist (2007), summarizing three methods as a means to study visions. The first element, *vision image*, concerns expressing the contrast between the present time and the idealized future. Such statements are often verbalized using **metaphors** and **communicating** the vision **in text and figures** (van der Helm, 2009). Secondly, *vision guidance* considers three characteristics. It has to do with the direction and creation of clear **shared goals**, synchronizing interaction and learning processes among individuals and the group as a whole (Quist, 2007). In addition, there is room to amend current institutional setups and test **alternative rules**. Finally, as radical and innovative technologies emerge, different actors from different disciplines need to be linked to share knowledge from different fields. This results in **leadership potential** that can be utilized. The third element is *vision orientation*. A vision needs to make a statement for a radical transformation, and consequently a strong vision will lead to **inspiration**, **motivation** and **direction** providing the mental framework by which potential actions can be evaluated (van der Helm, 2009). In general, the likelihood of success for niche development will increase if the three vision elements are strengthened. However, visions should not be confused with goals. A vision creates tension between the 'what is' and 'what could be' and is supposed to provide a cognitive model that can analyze potential actions judging them by approval or rejection. On the other hand, goals are set in place to realize those visions by following rational pathways.

3.1.4. Interactions between the internal processes

It is crucial to understand the interactions between the three internal niche processes and how this leads the way to niche development. Figure 3.2 illustrates the dynamics between network formation, learning processes and voicing of expectations/ visions, transitioning a local practice into the emerging field (F. Geels & Raven, 2006). The local level is defined as the field that is comprised of local projects and the global level focusses on a state where rules and agendas are shared between stakeholders (Turnheim & Geels, 2019).

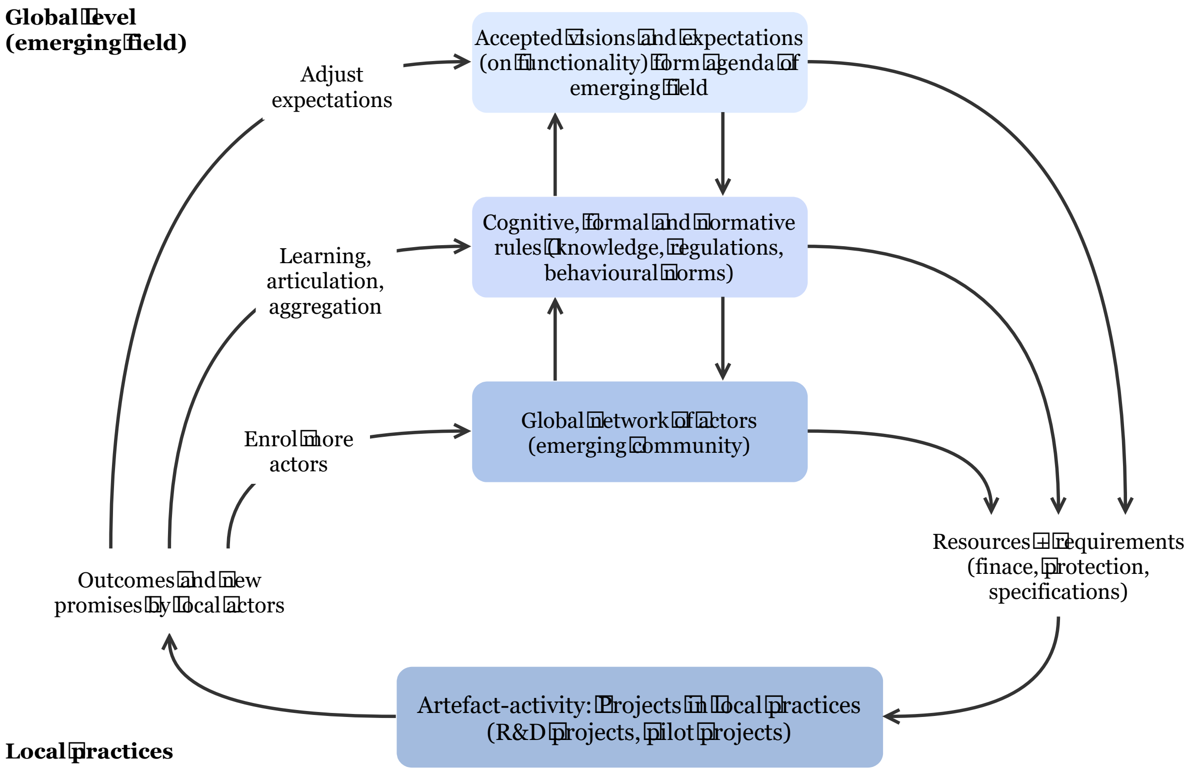

Figure 3.2. Dynamics between the three internal niche processes. Adapted from F. Geels & Raven (2006).

Niche development is facilitated by sequences of projects that encourage constant rounds of visioning, learning and network building. Projects in local practices such as demonstration and pilot projects result in more outcomes and an increase involvement of actors (F. Geels & Raven, 2006). Stakeholders will lean towards investing more resources and requirements if there is a collective positive expectation of a new technology and this is in line with shared cognitive rules, which will be able to guide the project. More projects attract actors to expand the network. This will boost learning processes as actors start to share ideas among similar initiatives, adjusting previous set expectations. It is important to stress that the stability of expectations and visions depends on the interactions with learning processes and network formation. In the event that outcomes of local projects are much below expectations, perceptions about a new technology initiative can quickly change, resulting in a shrinking network and decreasing resource availability. In turn, actors start to shift towards other technologies that have more potential driving another innovation trajectory.

As all elements are interlinked, excluding one of the niche processes will result in the obstruction of development. This also reflects the idea that a niche is entrenched in the wider context and in order for it to diffuse successfully into society, these specific layers must be identified and explored.

3.2. Multi-Level Perspective

Strategic Niche Management focusses solely on niche development and its corresponding internal processes. Nonetheless, it is essential to identify overarching factors that could hinder or enhance the diffusion of a niche. It is too simplistic to argue that as long as the internal niche dynamics occur, a technological niche is able to evolve into a market niche or even emerge into the regime (see Figure 3.1) (Raven, 2005).

Multi-level Perspective (MLP) is an appropriate framework to analyze the wider context, which can provide windows of opportunity for niche expansion (Turnheim & Geels, 2019). Moreover, recent work on adopting MLP in combination with SNM has emerged as a trend within innovation and transition research (Linda Manon Kamp & Bermúdez Forn, 2016; To et al., 2018; Turnheim & Geels, 2019). The notion of a multi-level perspective describes the interactions between three sociotechnical levels – the landscape, regimes and niches, also named the macro-, meso- and micro- levels, respectively (F. W. Geels & Schot, 2007; Grin et al., 2010). The broadest level is the landscape, comprised of social and physical factors supporting a macro-level structuring context (Grin et al., 2010). Regimes consider high levels of institutionalization with a focus on mainstream innovation journeys undergoing incremental improvements. Hence, the existence of radical change does not occur in regimes. Activities taking place in the niche spaces are capable of producing breakthrough technologies.

Figure 3.3 is one of the most commonly used illustrations to demonstrate the dynamics taking place. A transition comes about by the introduction of new innovative technologies emerging in niches, stabilizing and entering small market niches (F. W. Geels, 2018). For a market niche to break through into the regime, two developments must take place. First, drivers such a price improvement due to economies of scale, the existence of complementary technologies, supporting infrastructures, positive attitudes toward a technology or an engaging actor network are required. Secondly, landscape developments destabilizing a regime will create windows of opportunities for new configurations (F. W. Geels, 2002). Subsequently, a regime shift will appear altering the dimension framework until stability is once again secured. Adjustments will include changes in lifestyles, policies and regulations and what is perceived as 'normal'. The new regime will ultimately have an influence on the current landscape. The three levels are discussed below.

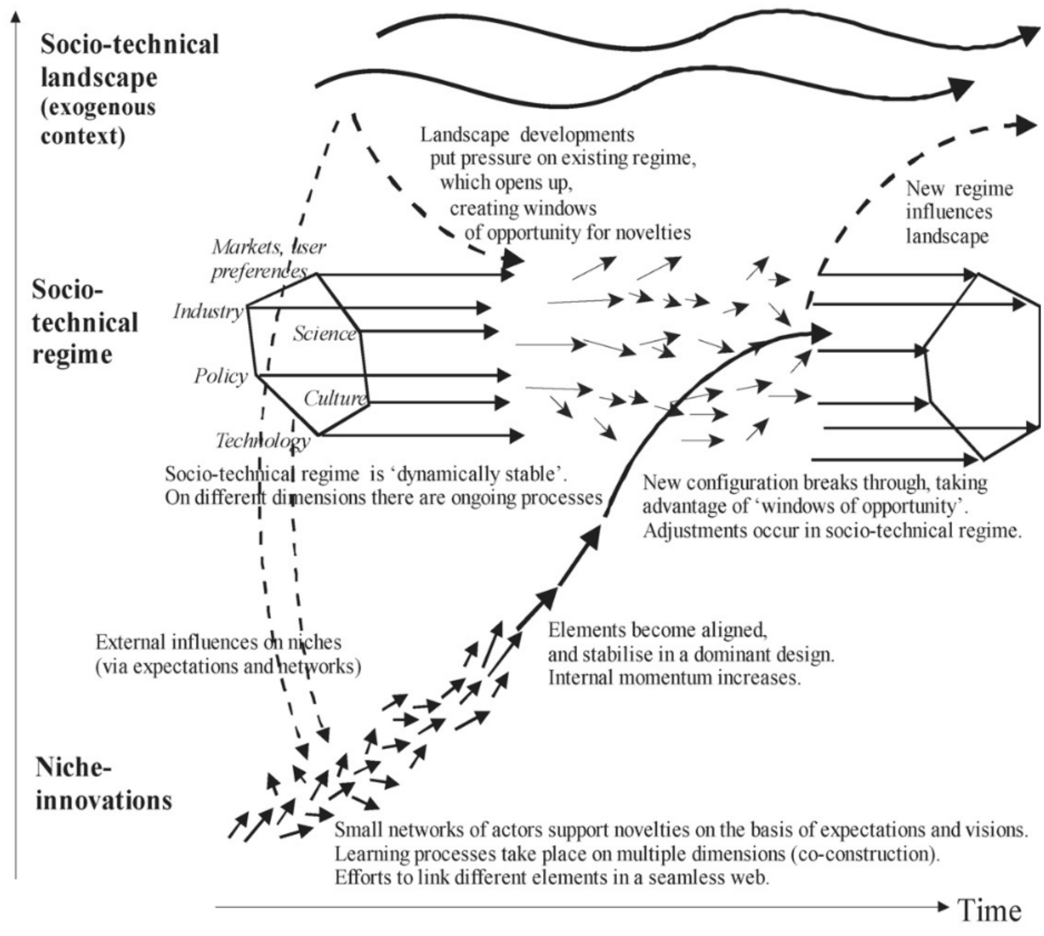

Figure 3.3. A multi-level perspective transition (F. W. Geels & Schot, 2007).

Socio-technical landscape

Processes taking place in the macro environment develop very slowly. Such developments include demographic and political changes, emerging environmental concerns, cultural developments and movements advocating for social change (F. W. Geels, 2018; Grin et al., 2010). The landscape is conceptualized as a background variable, able to influence a transition but mainly influences independently without being affected by the consequence of a new innovation journey on a short- and medium-term (Markard & Truffer, 2008). From time to time, landscape developments are a source of pressure on the meso-level, leading to new opportunities for regimes (A. Smith et al., 2010). Occasionally, it can also contribute to the stability of a regime, toughening the potential for niches to break through. Critiques argue that the landscape layer is considered a type of 'garbage can' concept that account for numerous external influences (F. W. Geels, 2011). To narrow down the scope, three landscape dynamics have been identified: slowly changing or unchanging factors (1), rapidly changing factors (2) and long-term changes in a certain direction.

Socio-technical regimes

Regimes constitute of established practices characterized by a lower level of stability in contrast to the landscape level (F. W. Geels, 2011; Raven, 2006). Nevertheless, they provide more structure to local niche practices as it is more difficult to alter the current set of regulations within this level as opposed to the niche level. As mentioned before, regimes are capable of destabilizing due to a series of events. The regime consists of six dimensions that are interrelated with one another (*technology*, *policy*, *industry*, *user preferences*, *science* and *culture*) as indicated in Figure 3.3 (F. W. Geels, 2002). The long arrows represent dynamically stable situations as opposed to shorter deviating arrows representing unstable circumstances. This is the result of tensions between the dynamics of the dimension, caused by conflict in opinions and uncertainty (F. W. Geels & Schot, 2007). A situation may arise for which there are no more opportunities available to improve the previously existing technology (Menanteau & Lefebvre, 2000). It is also possible that external factors break open the regime. One of the most urgent global issues, the impact of climate change, has a significant influence on the regime at present time.

Socio-technical niches

The niche level has previously been discussed in-depth. Yet, it is still important to explain how the niche level interacts with the other two levels within the Multi-level Perspective. Destabilization of the regime creates windows of opportunities for stabilized niches to break through. Throughout time, niche innovations build up internal momentum (Levidow & Upham, 2017). Elements are started to be linked within a network, enhanced by the three internal processes taking place. Social networks are created, standing on expectations and visions. Simultaneously, learning processes take place to value such alternative trajectories and reflect on their desirability and feasibility (Raven, 2006). The moment that such niches enter established markets, the actors in the regime level will start protecting themselves. This manifests itself by regime actors improving and preserving the dominant design (F. W. Geels & Schot, 2007). If the innovation manages to substitute the current design, bigger regime changes will occur. This pathway is characterized by a technology-push strategy.

3.3. Conclusions

The Strategic Niche Management framework identifies three key internal processes taking place within a niche – network formation, learning processes and voicing expectations. The development of a niche to breakthrough, in this case circular IC, is explored by studying the interactions of the processes. SNM can be used both as a research and as a policy tool; the latter is applicable to present the final recommendations to policy makers for transitioning to a circular industrialized construction in Switzerland.

To provide a clear roadmap through the different transition levels, a broader perspective is required. Raven (2005) argues that for a niche to interact with the regime, solely adopting a SNM perspective is considered oversimplifying. Recently, numerous scholars have conducted research integrating the SNM with the Multi-level Perspective to provide a comprehensive analysis of the development of a specific niche. MLP looks at two additional levels in the socio-technical environment, namely the landscape and regime. An unstable regime, as a result of pressures exerted by the landscape level, will create windows of opportunities for a niche to emerge ultimately leading to a new configuration of the regime.

This argument implies that to examine the development of circular IC effectively, the SNM and MLP framework must be coupled. In the following Chapter, the interactions between these two frameworks will be discussed extensively. Ultimately, this will lead to the design of the conceptual framework that will be applied to evaluate the case studies.

4. Conceptual Framework and Methodology

Based on the conclusions of the literature review and theory chapters, Chapter 4 will synthesize the information into a conceptual framework (4.1). The research methodology is subsequently developed and presented (4.2). Subchapter 4.3 concludes this section answering the second sub research question.

4.1. Conceptual framework

To obtain data on the current situation of circular industrialized construction in Switzerland and explore the opportunities for niche expansion, qualitative methods will be used. By integrating the two aforementioned frameworks, namely SNM and MLP, a comprehensive picture of the situation is obtained. The objective is to provide insights into the potential for the circular IC niche to grow in Switzerland.

For this purpose, it is essential to determine the current state of practice of circular IC, the current developments taking place within these so-called emerging niche practices as well as the external factors that can play a role. Based on these outcomes, enablers and barriers are explored to facilitate in the adoption of circular IC.

SNM is a very suitable approach for this thesis. The framework specifically focusses on the introduction and expansion of radical new sustainable technologies and circular IC can certainly be classified accordingly (Caniëls & Romijn, 2008b). The niche is in a very-early development phase, and thus considered a technological niche (Raven, 2005). There is a low degree of niche practices taking place and this must expand further to transform into a market niche and ultimately evolve into a regime shift. SNM will be used as a research tool to identify the changes taking place as well as a policy tool to provide recommendations and actions for scaling up. SNM will be applied to three different case studies, described further in Subchapter 4.2. For each case study, the three niche elements will be addressed. To gather information, a group of actors directly involved in the case studies (Case Study Actors Group) will be interviewed structured in accordance with the three processes.

In order to determine the current state of circular IC practices, additional characteristics will be reviewed. The selection, based on the final section (2.4) in the literature review, emphasizes the technical aspect of circular industrialized construction. The identified parameters are evaluated for each case study and presented as 'Understanding Circular IC' in Chapter 6 – the cross-case comparison.

The Multi-level Perspective framework is applied to analyze the wider context and contextualize SNM by developing transition pathways (Schot & Geels, 2008). The primary aim is to transition to circular IC in Switzerland, yet in order to do so; a regime shift must take place. Nonetheless, this is challenging as the existing regime is stabilized and entrenched in various ways. This is where MLP feeds right into, linking the regime with the niche level. Without studying the external factors occurring in the landscape and regime level that influence the niche, potential opportunities or barriers could be neglected, leading to a less successful expansion process into society. Hence, an additional group of actors (External Actors Group) will be interviewed. This group consists of experts of the (industrialized) construction industry, actors working in the governmental sector or associated with a research institution. The participants might not be directly involved but have industry knowledge and experiences vital to understanding the wider context influencing the niche. As such, the structure of the interviews will differ from the Case Study Actors Group interviews.

Ultimately, combining SNM and MLP will lead to a complete picture of the developments taking place within circular IC, its potential and corresponding pathways for future expansion. Alignments of processes at multiple levels are emphasized with the notion that changes occur through developments of co-evolution and mutual adaption between but also within different levels (Schot & Geels, 2008). In Figure 4.1, the grey-colored rectangles depict the layers that form the Multi-level Perspective framework. The overarching layer is defined as the landscape where main developments take place. Next, the regime constitutes of the construction industry, followed by the IC niche layer. The MLP framework considers the landscape and regime level. Here, IC is considered an additional part of the regime, comprising of various regime industry players. The circular IC 'sub niche' and corresponding case studies are enclosed within the IC niche layer. In this thesis, the Strategic Niche Management is applied to the most inner layer, highlighted in various blue shades.

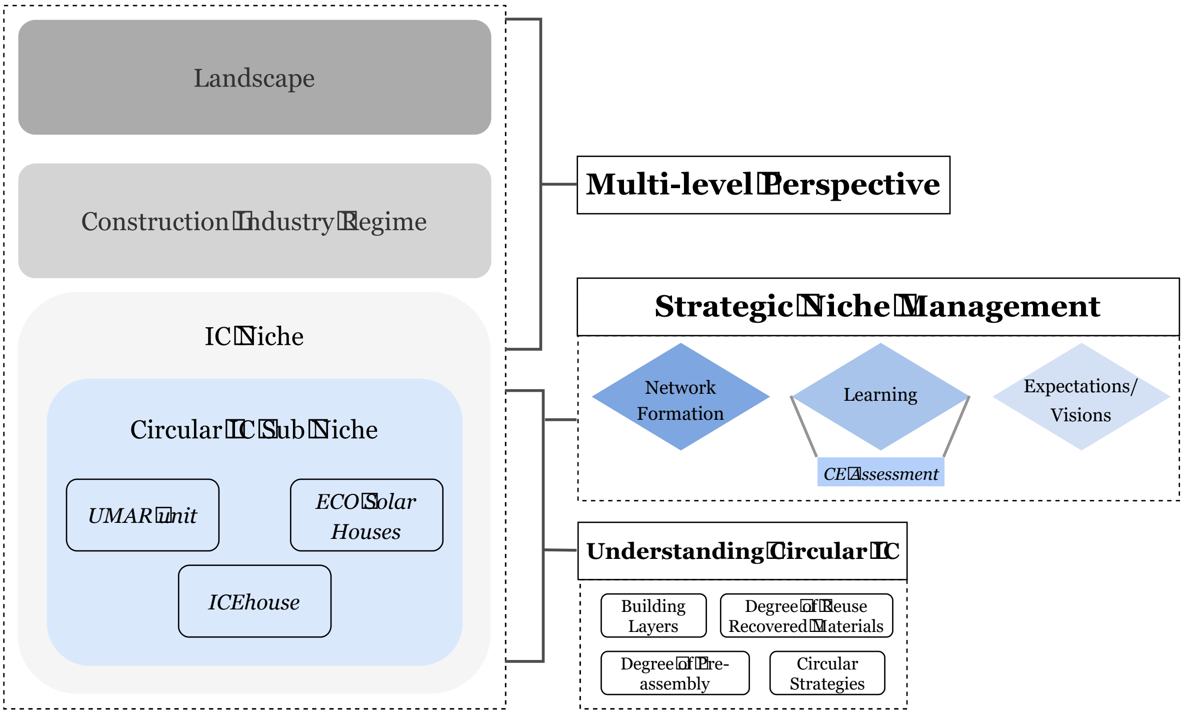

Figure 4.1. The conceptual framework for this thesis (own illustration).

4.1.1. SNM for Circular IC

The SNM block in Figure 4.1 highlights three elements that interact with one another, ultimately leading the way to niche development. Creating and pursuing expectations and visions fosters learning processes amongst stakeholder. In turn, this adjusts previous perceived expectations, attracting new actors to become involved. For each of the three processes taking place at the case study level, the various characteristics and indicators are described below.

Network Formation

Network formation is assessed at the case study level. Two characteristics are key in order to build broad social networks: composition and alignment (see Table 4.1 and Figure 4.2). First, the composition of a network including the involved stakeholders, their resources and activities are analyzed. Secondly, the alignment within a network is considered. Here, stability and complexity of relationships between actors and the type of collaboration, connectivity and communication is analyzed. Through analyzing the history of relations as well as the presence of a network builder, the complexity and stability of actor's relationships within the network is determined. Regarding the type of collaboration, the management of the project is analyzed considering factors such as the frequency of meetings and the possibility of a drafted agreement between involved parties.

Table 4.1. Network Formation characteristics and corresponding indicators (Leising et al., 2018).

Characteristics	Indicators
Network Composition	○ Participating actors, desired actors involved ○ Activities performed and resources supplied of actors
Network Alignment	○ Stability and complexity of relationships between actors ○ Type of collaboration/ connectivity / communication

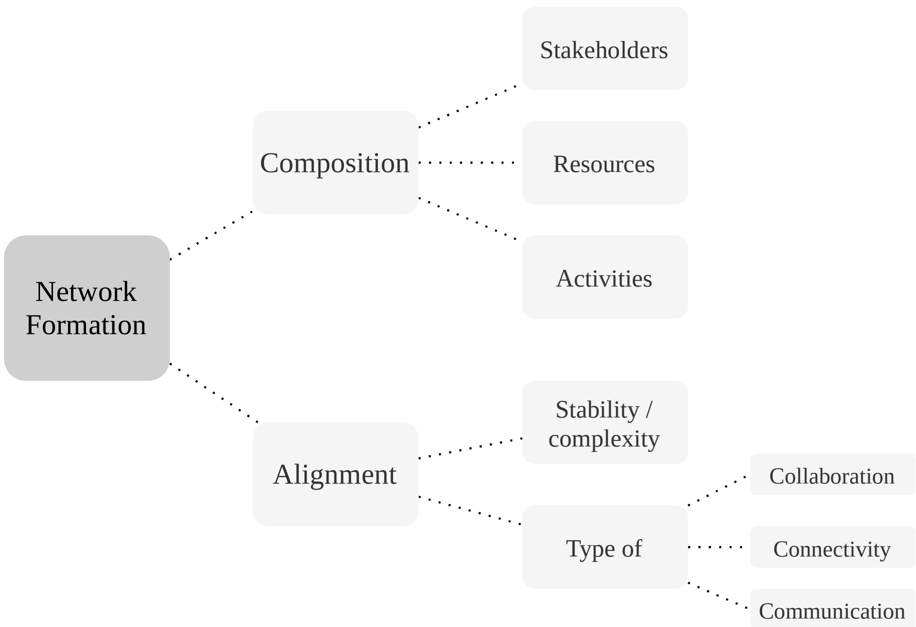

Figure 4.2. The different elements of network formation integrated in the conceptual framework (own illustration).

Learning Processes

In the beginning phase of a niche, there are many uncertainties and therefore it important to learn about the specific problems and needs in order to resolve them and further facilitate the development. As part of the learning, first order learning processes have to be determined, providing information for a given problem within a given context. Here, learning applies to the case study as well as the circular IC level. Both levels are discussed in-depth for each case in the results Chapter. According to the five dimension's framework established by Hoogma and colleagues (2002), a checklist in Table 4.2 has been created to identify the different learning processes.

Table 4.2. First order learning process characteristics and corresponding descriptions (Hoogma et al., 2002).

Learning Processes	Description
Technical Aspects	○ What was learned about the design specifications and complementary technology required?
Market and User Needs	○ What was learned about the market and users' needs/ perception?
Industry Developments	○ What was learned about the production and maintenances processes in order to market and expand further?
Societal and Environmental	○ What was learned about the impact on society and the

Impacts	environment?
Policy and Regulations	○ What was learned about the fiscal policies, regulations and incentives necessary to stimulate expansion?

Table 4.2 serves as a descriptive checklist for what has already been learned on both levels. However, second learning processes (see Table 4.3) are also important to consider in order to evaluate the learning processes further, exploring new terrain. Such learning entails change processes that can result in radical change of approaches – a key driver of niche transitions. Three elements comprise second-order learning. The first characteristic is shifting in problem framing and coupling to technology or society. Subsequently, problem solving approaches and shifts in priorities are analyzed. Thirdly, shifts in learning mutually together are considered. The establishment of a case study is the result of second-order learning and thus the questions posed to examine the three elements are related to understanding past developments.

Table 4.3. Second order learning process characteristics and corresponding indicators (H. S. Brown et al., 2003; H. S. Brown & Vergragt, 2008; Leising et al., 2018).

Characteristics	**Indicators**
Problem Framing Shift	○ Reframing a problem to accommodate different interpretive frames of actors
Problem Solving and Priorities Shift	○ Searching for new solutions to solve a problem together
Joint Learning Shift	○ Sharing or accepting other actor's problem definitions

Figure 4.3 presents an overview of the first- and second order learning indicators that will be evaluated.

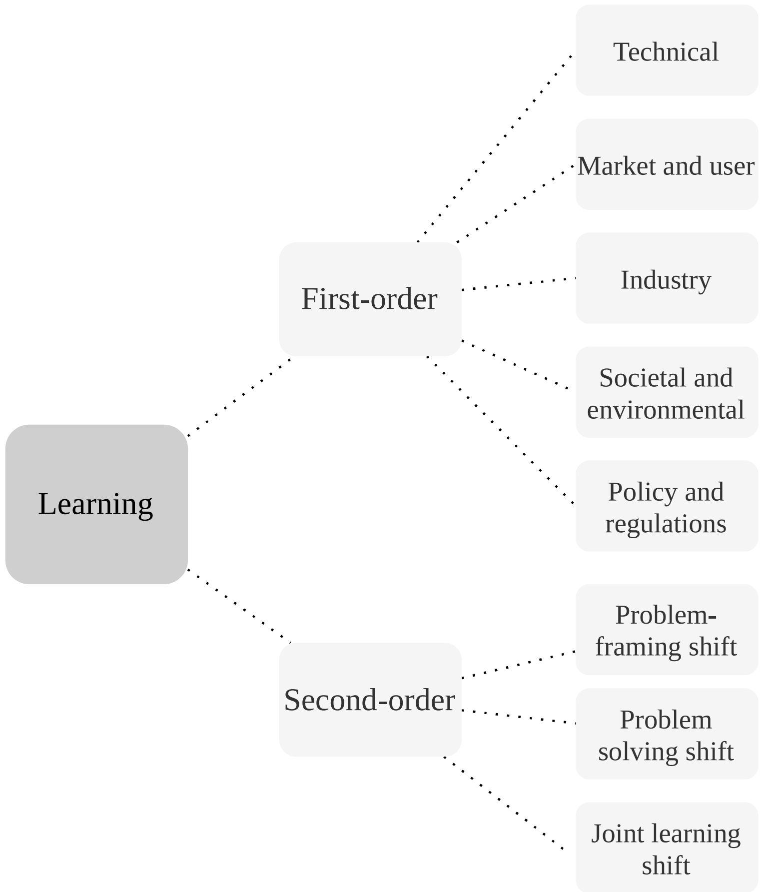

Figure 4.3. The different elements of learning processes integrated in the conceptual framework (own illustration).

Expectations

For voicing expectations, different levels of the system can be considered, stretching beyond network formation and learning processes. This means that an expectation interacts with not only the circular IC level, but also with IC, the construction industry and the established landscape. Thus, expectations are identified for both the case study and circular IC. Based on the five-dimension framework explained in the learning processes section, a checklist has been created to determine the expectations for the various perspectives (see Table 4.4).

Table 4.4. Dimensions of expectations and corresponding descriptions (Hoogma et al., 2002; Schot & Geels, 2008).

Characteristics	Description
Technical Aspects	○ What are the expectations for technology advancements/ specifications and complementary technology developed?
Market and User Needs	○ What are the expectations towards the needs/ perceptions/ preferences for the market and users?
Industry Developments	○ What are the expectations for changes in production/maintenance processes?
Societal and Environmental Impacts	○ What are the expectations for the impact on society and the environment?
Policy and Regulations	○ What are the expectations regarding policy, regulation frameworks and incentives that will stimulate expansion?

Voicing expectations offers support for the creation of future visions. Visions are analyzed in-depth at a case study level and circular IC level. Visions are analyzed based on three pillars, illustrated in Table 4.5. For vision image, metaphors that have been used are identified as well as their explicitness in words of figures. The second element, vision guidance, looks at the presence of clear collaborative goals, changes in the rules that occur and leadership potential that is realized to guide the vision. Vision orientation is expressed through motivation, inspiration and direction.

Table 4.5. Vision characteristics and corresponding indicators (Leising et al., 2018).

Characteristics	Indicators
Vision Image	○ Verbalized using metaphors ○ Clarity by expressing vision in text and numbers
Vision Guidance	○ Setting of clear shared goals ○ Presence of alternating rule set ○ Identification of leadership
Vision Orientation	○ Presence of motivation ○ Presence of inspiration ○ Presence of direction

Figure 4.4 presents the breakdown of both indicators for expectations and visions, which will be analyzed according to the three case studies.

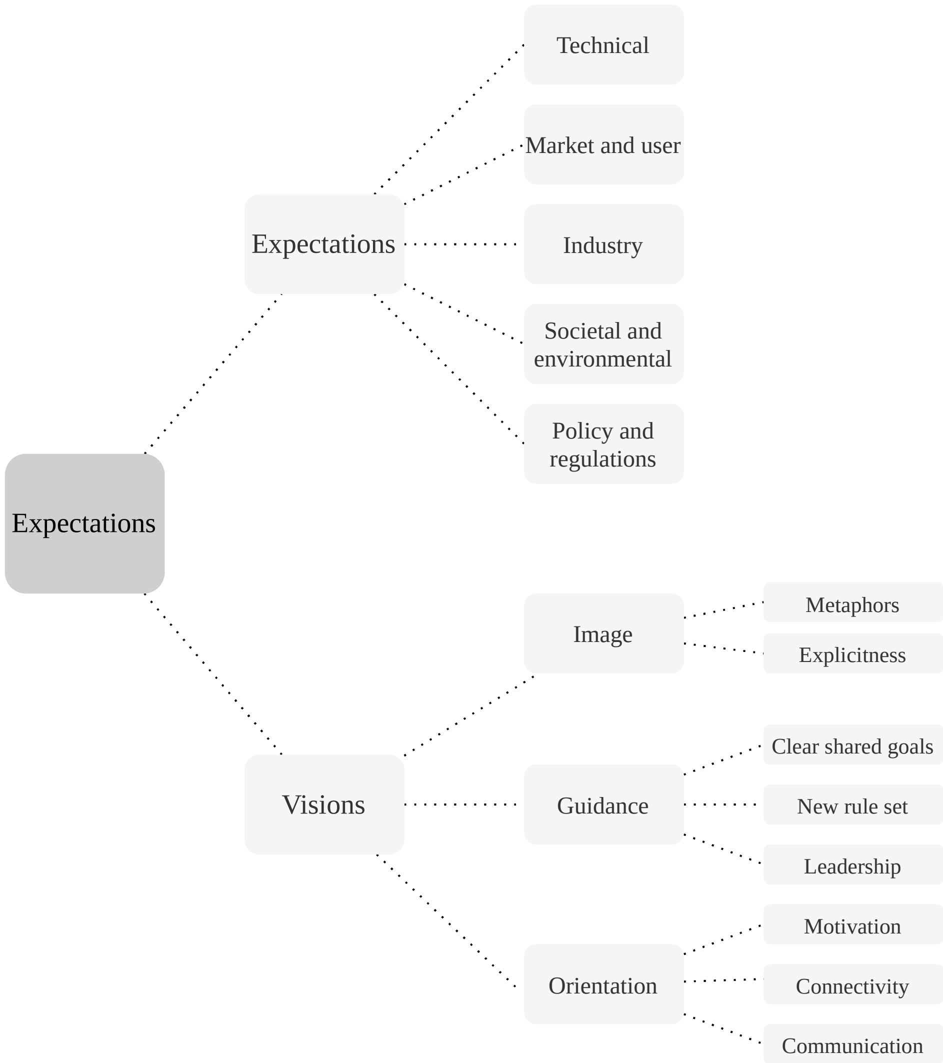

Figure 4.4. The different elements of expectations and visions integrated in the conceptual framework (own illustration).

The final part of analyzing the case studies consists of a technical comparison, also referred to as 'Understanding Circular IC'. The following indicators are evaluated and compared: Buildings Layers, Degree of Reuse Recovered Materials, Degree of Pre-assembly and the five Circular Strategies. The outcomes will be presented in Subchapter 6.1.

4.1.2. MLP for Circular IC

The second part of the conceptual framework studies the two remaining layers of the socio-technical environment focusing on the landscape and regime levels. Here, two different processes taking place are examined: (1) the macro-level developments taking place that (de)stabilize a regime and (2) the stability of the meso-level that could hinder of foster breakthrough of niche developments.

The socio-technical landscape

The socio-technical landscape signifies the main developments occurring in Switzerland according to three types of changes (A. Smith et al., 2010). This includes slowly changing factors, such as the physical climate or law and regulation framework. Rapidly changing influences, such as a financial crisis leading to possible lower investments in construction can play an important role as well. Finally, long-term changes, e.g. climate change and corresponding emerging concerns shifting the public opinion into a certain direction are considered. A balanced analysis is conducted looking at the different types of developments within this level.

The socio-technical regime

The locus of a socio-technical regime is the presence of established practices and associated rules and regulations that stabilize existing structures (F. W. Geels, 2011). In this framework, the regime level signifies the current Swiss construction industry. An additional layer has been created between the regime level and the (sub) niche level to cover the niche of industrialized construction. The reason for this is that IC is considered part of the regime, comprising of large industry players in the sector, even though the share remains limited. Along with that, circular IC is defined as the niche level that will be studied using the SNM framework, and thus IC is considered an extra layer of the socio-technical regime.

As mentioned in Chapter 3, there are six dimensions that comprise the regime level (F. W. Geels, 2002). These dimensions are linked with each other but due to changing factors, the framework can destabilize creating windows of opportunities for niches to breakthrough. A selection of four dimensions is examined based on the assumption that inadequate information is available for the remaining two dimensions. The following dimensions, looking at tangible elements, will be discussed in the analysis:

- **Public policy** via taxes, subsidies, regulations and standards that incentivize niche practices, clients and other involved actors to engage in circular IC (F. W. Geels, 2018). The policy framework for the circular economy and the (industrialized) construction industry in Switzerland is studied.
- **Science** is distributed through discovering new technologies and instruments developed by a wide range of actors, including universities, laboratories, consultancies and R&D departments at organizations (F. W. Geels, 2004). In view of this, the different stakeholders that play a prominent in the advancement of science and technology in Switzerland are determined.
- **Industry structure** entails the networks of suppliers, producers and distributors (F. W. Geels, 2001). Here, the prominent industry players in the construction and industrialized construction industry in Switzerland are identified.
- **Market/ user preference** considers the market and user's perceptions, norms, values and ideologies in Switzerland. Changing user and market preferences may lead to new markets in which new technologies become successful (F. W. Geels, 2006).

The remaining two dimensions – technology and culture, will not be analyzed. As circular IC is such a novel topic with a prior literature review expressing the limitations in terms of information about technology, it is assumed that a comprehensive overview for the technology dimension cannot be provided. The latter perspective concentrates principally on intangible elements such as certain beliefs, social practices and knowledge. This is rather difficult to study, especially as a foreign researcher with lacking experience and knowledge of the Swiss (construction industry) culture.

4.2. Methodology

In this thesis, a case study research design is selected. A case study approach is conducted as the method to understand the dynamics present within single settings (Eisenhardt, 1989). The different types of case studies and applied methodology are explained in Appendix D.

4.2.1. Case Study Selection Criteria

Key criteria for selecting the case studies include the presence of an individual project located in Switzerland that has not been applied on a commercial scale - either a pilot/ demonstration project or a reference project. In addition, the adoption of IC methods and CE principles is different for each project and thus the selected case studies must demonstrate this contrast as well. The case studies were selected through an online search and through the network of the Chair of Innovative and Industrial Construction at ETH Zürich. Several potential projects seemed to be interesting but did not meet the requirements. The Ustinov Hoffmann Construction System is a Swiss patented modular construction system made entirely of recycled PET (Ustinov & Hoffman, 2019). However, the company has not demonstrated its proof of concept yet. The ON Mountain Hut, situated in the Swiss mountains, is made from sustainable materials and completely self-sufficient (ON Running, n.d.). Nevertheless, the use of industrialized construction methods was not clearly present here. Finally, the swisswoodhouse, a prefabricated wooden apartment building, seemed very promising but the ambition to achieve circularity was not evident here (Renggli & Barmettler, n.d.).

Preliminary research demonstrated that the UMAR unit, ICEhouse and the ECO Solar Houses meet all key criteria and thus it was decided to form this group of projects. The three projects are all located in different Cantons in Switzerland, as shown in Figure 4.5.

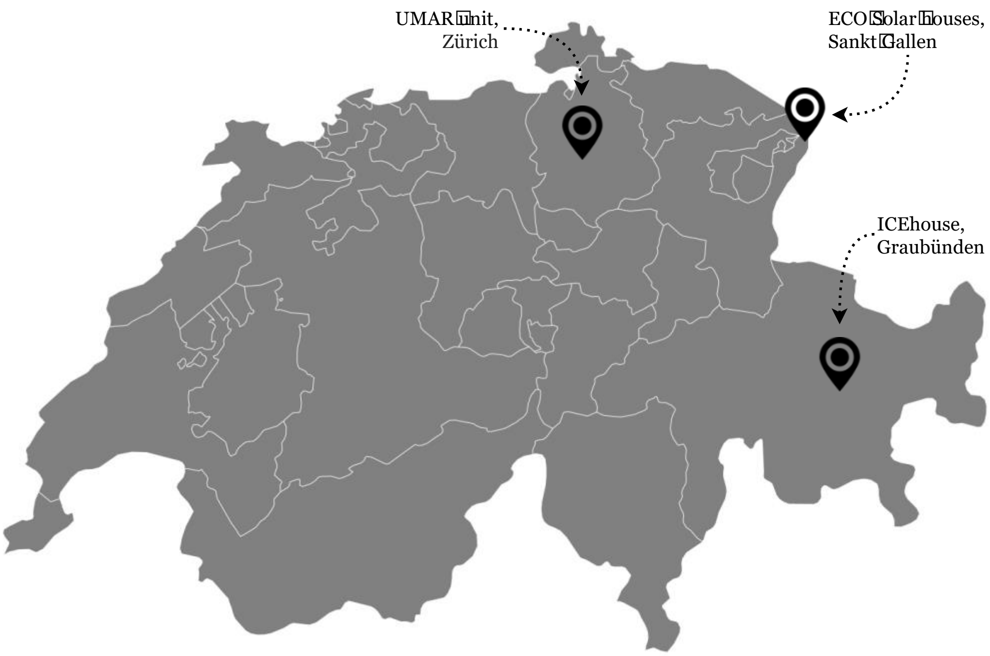

Figure 4.5. The location of the three case studies in Switzerland.

4.2.2. Data Collection and Reporting

For this thesis, data is collected through three different sources – literature review, desk research and interviews. For the previous three chapters, academic literature and reports published by governmental institutions and organizations was very useful to provide a comprehensive overview. To store and manage the sources safely, the reference management software tool Mendeley is used (Mendeley, n.d.). Desk research supports the evaluation of the landscape and regime analysis and related factors, gaining insights into the policy framework in terms of circular economy and industrialized construction in Switzerland.

Regarding the interviews, there are two groups of interviewees – the Case Study Actors Group and the External Actors Group. All interviews followed a semi-structured interview leaving room for a discussion with the interviewee. For the former group, stakeholders were chosen that are directly involved in one of the case studies, see Table 4.6. These interviews primarily supported the SNM analysis. The External Actors Group were asked questions to accommodate the MLP framework, focusing on the wider context. For this specific group, information was collected through interviews and email communication, see Table 4.7.

For both actor groups, candidates were found through online searching and snowball sampling. Separate interview protocols for the Case Study Actors Group and External Actors Group were designed (see Appendix E). The interviews were recorded and their files were uploaded on otter.ai (Otter.ai, n.d.). This AI-powered tool converts a voice recording into text, which assist in speeding up the process of transcribing. However, manual editing was still required to ensure that the program did not misinterpret a word or text. Occasionally, an interviewee was asked a number of follow-up questions for further clarification. This correspondence is included in the interview transcriptions. Finally, the empirical findings were structured using the conceptual framework and presented in Chapter 5.

Table 4.6. Case Study Actors Group

Case Study	Organization	Job Title	Date
UMAR unit	Empa	Tour Guide NEST / UMAR unit	26th Nov 2019
UMAR unit	Karlsruher Institut für Technologie	Professor of Sustainable Construction – Initiator 1	4th Dec 2019
		Researcher at the Chair of Sustainable Construction – Initiator 2	
UMAR unit	Empa	Innovation manager NEST/ UMAR unit	13th Dec 2019
ICEhouse	SABIC	General Manager Sustainability - Client	16th Dec 2019
ICEhouse	William McDonough + Partners	Executive Director WonderFrame - Initiator	18th Dec 2019
ECO Solar Houses	ECOCELL	CEO/ Founder - Initiator	16th Jan 2020
		Employee	
ICEhouse	WEF - Davos	N/A	22nd Jan 2020

Table 4.7. External Actors Group

#	Organization	Job Title	Expertise	Type	Date
1	TACLE project at ETH Zurich	PhD student	Resource perspective on CE in Switzerland	E-mail	5th Dec 2019
2	Group for Sustainability and Technology at ETH Zurich	Senior researcher	CE in the built environment in Switzerland	Interview	12th Dec 2019
3	The Federal Office of Environment	Scientific collaborator	Legal aspects CE in the built environment in Switzerland	E-mail	20th Dec 2019
4	Swiss Association of Engineers and Architects	Board member	Process optimization/ BIM/ lean construction	Interview	20th Dec 2019
5	Losinger Marassi	Project director	CE in the built environment and IC methods	Interview	16th Jan 2020

		Technical director – sustainable buildings	Sustainability in construction		
		Innovation manager	Construction industry in Switzerland		
6	Madaster Switzerland	CEO / Founder	CE in the built environment in Switzerland	E-mail	24th Jan 2020

Research Ethics

Because the research design is based on collecting data through interviews, different ethical guidelines were put into place for the research period. Prior to the recording of the interview, each interviewee was asked for their consent to participate in the research by signing a consent form (see Appendix F). It was ensured that participants took part voluntarily and any harm to the participants was avoided. After a transcription was complete, the text was shared with an interviewee for confirmation. If an interviewee did not agree, the specific passages were redacted to refrain from sharing confidential information the participant might wish to conceal.

Data Processing

To interpret the raw data, transcriptions were imported into the application Dedoose (Dedoose, n.d.). This platform is used for excerpting and coding text. A code list was created prior to coding according to the different elements of the SNM and MLP framework. The SNM framework codes were solely used to code the Case Study Actors group interviews, whereas the MLP framework codes were used primarily for the External Actors group but could be identified in the former group of actors as well. Line-by-line coding was adopted, scanning the data thoroughly and underlying excerpts that were applicable for a certain code. Moreover, some excerpts were also coded as an enabler or barrier. A second round of analyzing was performed to confirm that the excerpts were coded correctly. The coded transcriptions have been attached separately.

Reporting

With regards to the following Chapter, the case studies are reported, in accordance with the SNM framework, using the following procedure:

1. An introduction and background of the case study
2. An analysis of the actor network and composition
3. An analysis of the learning processes
4. An analysis of the expectations and visions

4.3. Conclusions

In this Chapter, the second sub question "How can niche initiatives in circular industrialized construction be researched from a niche transition perspective?" has been answered. Based on the theory of innovation and transition frameworks, the SNM and MLP framework are selected and applied to design a conceptual framework. Using this structure, the niche initiatives can be analyzed by studying the three internal processes and the technical characteristics whilst investigating the corresponding regime and landscape level. In turn, this analysis will lead to better understanding the niche and its potential for further expansion and diffusion in society. Chapter 5 will now apply this conceptual framework to report the case results of the UMAR unit, the ICEhouse and the ECO Solar Houses.

5. Developments in Circular IC in Switzerland: Case Study Results

In Chapter 5, the three selected case studies are discussed and analyzed. Part 5.1 discusses the UMAR unit, 5.2 relates to the ICEhouse and Section 5.3 concerns the ECO Solar Houses.

5.1. UMAR unit

Figure 5.1. The UMAR unit located on the second floor of the NEST building © Zooey Braun, Stuttgart (Sobek et al., 2018).

Figure 5.2. The interior of the UMAR unit © Zooey Braun, Stuttgart (Sobek et al., 2018).

5.1.1. Introduction

The Urban Mining and Recycling unit (henceforth: the UMAR unit) is a project located in Dübendorf, Switzerland. It was installed into the NEST (Next Evolution in Sustainable Building Technologies) building in 2017 and opened the next year (Kakkos et al., 2019). NEST is a research and innovation lab of the organization Empa. Projects contributing in different ways to the living lab concept in the building industry are set up in this environment in the form of units (Richner et al., 2018). The UMAR unit is considered a prototypical two-bedroom living unit (Heisel et al., 2019). The *mission* of the UMAR unit has been integrate maximal prefabrication and modular design with the use of waste as building products and materials that can be extracted cleanly, separated and sorted (Empa, n.d.-a). The structure is made up of a modular frame with replaceable wall, roof and floor elements from materials that follow the CE principles, either reused, recycled/ recyclable or compostable.

Project timeline – how did the UMAR unit emerge?

The start of the UMAR unit goes back to the year 2014. In that year, three architects published a book named Building from Waste: Recovered Materials in Architecture and Construction. The question was prompted and further elaborated: how can we design products differently that do not become waste in the end? (Hebel, personal communication, December 4, 2019). After the book was published, the deputy CEO of Empa at that time reached out to one of the architects expressing his interest (Marchesi, personal communication, December 13, 2019). The architect asked the company Werner Sobek to join, as they knew each other before and both are working in similar fields. Thereupon, the idea was further developed by the team of Werner Sobek and two of the three architects regarding planning and the partners to collaborate with. The company Kaufmann Zimmerei und Tischlerei was asked to build the unit in 2015(Hebel, personal communication, December 4, 2019). The next two years involved the further planning of the project. In 2017, the unit was constructed and in November 2017, installation took place. The following year on February 8, 2018 the project was opened for public tours and events. Two months later, two PhD students moved in as tenants.

Industrialized Construction

The unit is comprised of seven modules that were prefabricated and completely equipped in a factory by the company Kaufmann in Reuthe, Austria (Hebel, personal communication, December 4, 2019). The construction relies on diagonal cladding from untreated timber put into place by tongue and groove connections to meet the requirements for the necessary air tightness (Heisel et al., 2019). Regarding the degree of pre-assembly, this unit consist of pre-assembled volumetric units (*modules*) that form the real structure and fabric of the building.

The units were shipped using three large trucks to Dübendorf and were lifted in between the two concrete slaps with the help of two mobile cranes within one day (Figure 5.3). The different modules were moved into the right position using heavy-duty wheels on rails (Figure 5.4). Once set, on-site work was minimal – the modules had to be connected simply by placing fitted boards, connecting all the pipes (plugs and screw caps) and the placement of the façade. In total, it took roughly four days for the building to be ready for use. The design considers disassembly as the modules that are resting on wheels can easily be taken out again.

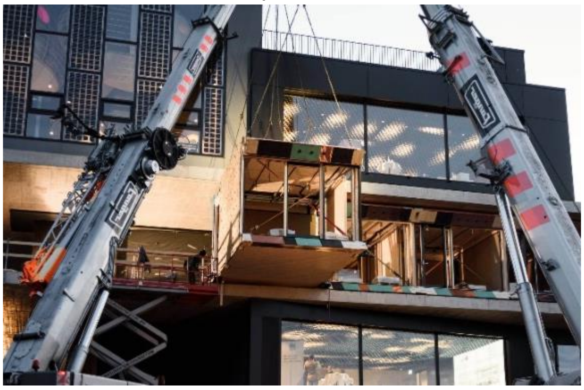

Figure 5.3. On-site assembly of the modules with two mobile cranes (Kaufmann, 2017).

Figure 5.4. Installation of the modules using wheels running on rails (Sobek et al., 2018).

Circular Economy Principles

In terms of CE, different strategies have been identified (Heisel et al., 2019). Figure 5.5 demonstrates the intersection of the different insulation layers using *circular materials*. Windows were used to display how the wall was constructed (Heisel & Hebel, personal communication, December 4, 2019). The brown layer on the outer left represents the hemp flex insulation boards (UMAR, 2018b). As bound material, cornstarch is used to ensure the sheets are biodegradable. The middle blue layer is made up of cotton fabric from denim waste, signifying the strategy *resource recovery*. The denim has been shredded, saturated with Boron salt fire retardant and baked in a large oven before being pressed into sheets (UMAR, 2018a). Ultimately, this insulation material can be recycled after its use phase. Additionally, so-called MycoFoam insulation boards placed in the bedrooms have been made of a type of fungi called Mycelium. The mushrooms are grown and mixed with recycled waste wood chips binding the substrate into a composite (Weinmann, tour visit, November 26, 2019).

Furthermore, a turning wall has been installed to divide the kitchen and dining area from the living area (see Figure 5.6). Bricks made from mineral construction waste are used for building up the wall (UMAR, 2018c). There are holes in the bricks to thread them onto the steel rods, offering the possibility to remove the bricks by simply pulling them up the rods. As a result, no mortar is used to bind the building bricks. This example demonstrates *resource recovery* as well as the product has undergone already a life cycle as well as the use of circular materials due to the non-toxicity and ease of taking the bricks out to reuse of recycle them.

Figure 5.5. Wall intersection showing different layers of insulation (own photo).

Figure 5.6. A dry-stacked turning wall created using wasted based bricks (own photo).

The strategy *product-as-a-service* has also been incorporated in the design. The carpets, made from regenerated nylon yarn, have been leased, retaining ownership of the product by the manufacturer Desso (Heisel et al., 2019). After the EOL phase of the carpets, the material will return to the factory where it will be recycled into new carpets.

Design for disassembly or *product lifetime extension* is clearly present. The prefabricated units are interconnected using mechanical instead of chemical joints. This entails reversible connections including screws and interlocking joints. No glues, emitters or lacquers have been used (Heisel & Hebel, personal communication, December 4, 2019). The timber is also left untreated. All materials have been fully documented allowing for proper sorting at the EOL phase.

5.1.2. Network Formation

As is illustrated in Figure 5.7, a *large* network of *different* types of stakeholders is involved in the UMAR unit. The different group of actors and their corresponding responsibilities have been categorized using various colors (see Legend). The actors that are considered part of the core team regarding the development of the project are highlighted with a blue star. This includes the *initiators* comprised of a professor and researcher from Karlsruhe Institute of Technology (KIT) and the team of the architecture company named Werner Sobek. Additionally, Empa including the innovation manager of the UMAR unit/ NEST building, plays an important role in the development of the unit, having two roles in this process, namely as the client as well as the main investor.

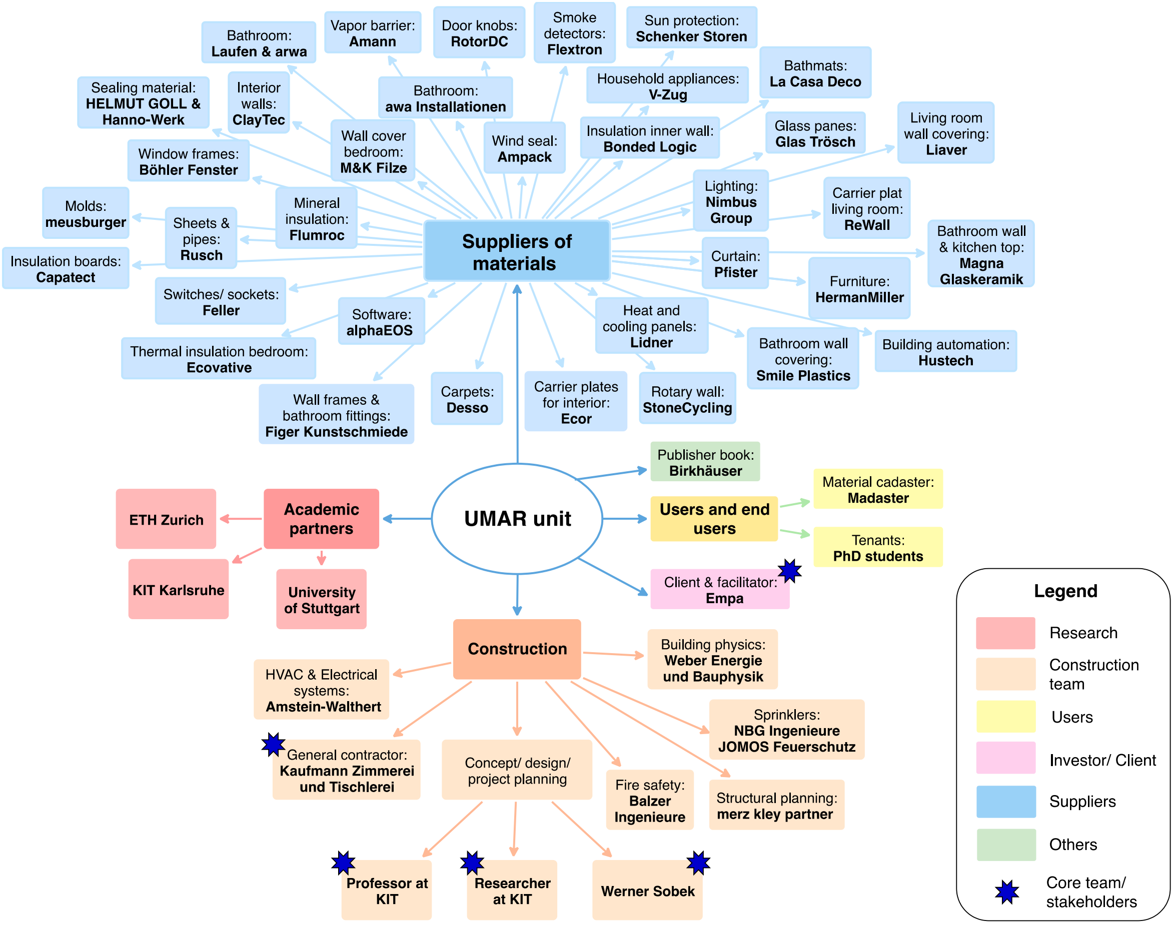

Figure 5.7. Stakeholder map of the UMAR unit.

Regarding the **composition** of the network, *Empa* is considered a *key stakeholder* to the successful delivery of the UMAR unit. Not only did they represent the building owner/ client, they also *financed* the whole project and supplied a *network of partners*. The architects were given the *freedom to design* a building provided that they would develop a strong research concept behind it (Hebel, personal communication, December 4, 2019). This entailed that the designers of the unit could push the limits of urban mining and recycling without financial and design requirements impeding the innovation possible within circular IC. The organization asked the two architects and the team of Werner Sobek to decide which suppliers to involve, asking for sponsorship to reduce the costs for themselves. Empa also took over the liability for the material used in the UMAR unit, which ultimately did not cost them a lot, but diminished the risk for the team of initiators developing the project. Additionally, Empa let PhD students live in the unit to provide feedback on the right methods of application of the products and materials. Every three months, two new students moved in to keep a regular feedback cycle in place, signifying the strategy *co-creation*.

Little governmental involvement was present in the UMAR unit in means of providing support or financial benefits. Still, the NEST building from Empa is an investment of the Swiss Federation with the purpose of funding research and knowledge regarding sustainability and the living concept in the built environment (Marchesi, personal communication, December 13, 2019). This entails that the government does have a stake in the UMAR project indirectly as the investment is not exclusively dedicated to the development of a circular IC case.

Multiple parties were involved in *supplying* the UMAR unit with materials and products. NEST holds an established network of partners that were involved since the start of the research lab (Empa, n.d.-b). Partners could test out their products examining any failures, covering the costs for materials in the unit. For example, a tour guide was explaining that the kitchen cabinets from one supplier showed signs of discoloration and deteriorations (Weinmann, Tour visit, November 26, 2019). This valuable information could then be translated in improving and optimizing their products. In general, the material suppliers had an *open mindset*, willing to collaborate and align their innovations with the *initators' mission statement*, an activity which will be explained further in 5.1.3. As the team of UMAR unit could utilize this network, it made it easier to select the most suitable materials. Furthermore, the initators *shared history* with some of the suppliers, which in turn increase stability within the network.

Most companies and partners were based in German speaking areas. Only Empa and the initators, working at ETH Zurich at that time, were situated in Switzerland. The company Werner Sobek is based in Stuttgart, Germany and the builder Kaufmann is located in Reuthe, Austria. As the innovation manager of the UMAR unit mentions, "… the *focus* for NEST is on Switzerland or Central Europe. … However, we live in a globalized economy so it doesn't make sense to say what's outside the Swiss border is not considered." (Marchesi, personal communication, December 13, 2019). To illustrate, the American company Bonded Logic provided insulation material and the Dutch company StoneCycling built the rotary wall in the living room.

Academic partners are key in this network. Both the professor and researcher were conducting extensive research on the possibilities of 'circular' building materials based on their backgrounds at ETH Zurich and the Future Cities Laboratory in Singapore. This led to the publication of the book Building from Waste: Recovered Materials in Architecture and Construction, which formed the basis for the idea of the UMAR unit. Without academia involved, important research would not have been available to utilize for developing the project.

Alignment in terms of *stability* is perceived to be very high in this network. Empa, *a macro-actor*, was described to function as a *safety net* – "You can screw up without negative consequences, which means you can go farther in decisions, what technology to use, how risky you want to build." (Marchesi, personal communication, December 13, 2019). Likewise, the presence of a *cross-relationship* is emphasized here. Empa had a supporting role but the organization was also considered the client. The organization of the project was similar to a regular building project, yet slightly more support and detail in terms of project management was needed due to the higher risks for Empa.

In terms of *communication*, regular meetings were held to exchange information with *professionalism* within the team contributing to the success of the UMAR project. The innovation manager had to intervene to a minimum in running everything smoothly.

Moreover, the team of Werner Sobek and the two initators both worked together as the architects and engineers of the UMAR unit. The innovation manager at NEST named the former team the architects and the latter team the material scientists and urban mining/ circular economy experts. However, as both teams have an architectural profession; it created an interesting way of *complexity* and *collaboration*. This is discussed in further detail in 5.1.3.

One of the architects points out that "Trust is also key in building such an innovative building." (Hebel, personal communication, December 4, 2019). However, the innovation manager mentions that *trust* is due to the fact of a successful project management, not necessarily a requirement for engaging in urban mining in general (Marchesi, personal communication, December 13, 2019). This translates in the establishment of close relationships between the direct stakeholders. For a *later project* named the Mehr.WERT.Pavilion in Heilbronn, Germany, the professor, researcher and the firm Kaufmann worked together. One of the initiators said that the core team has stayed together since the opening of the UMAR unit (see quote 1, Table 5.1). As a result, there was less of a barrier to ‘pick up the phone’ and ask to work on a new project together.

To conclude, the network has grown in terms of the number of actors involved. The initiators brought in different stakeholders that formed the core team. Moreover, a large organization of suppliers was established to provide the materials for the UMAR unit. The relationships were strengthened over the course of the project by working together. This is illustrated in the continued collaboration in new projects between the direct stakeholders.

5.1.3. Learning

This analysis starts with the five-perspective framework (technical, market/user, industry, social/ environmental and policy/ regulation) of first-order learning, established by Schot & Geels (2008). Subsequently, the three characteristics of second-order learning developed by Brown and colleagues (2003) and Brown and Vergragt (2008) are examined.

First-order Learning

Technical

Crucial in the process of the UMAR unit was to design everything in a way that it could be disassembled at the EOL phase. This entailed that many products had to re-examined and altered. For example, a coating of aluminum on the LED lighting was omitted due to the inability to recycle the components otherwise (Weinmann, personal communication, November 26, 2019). However, this exact product was not sold on the market but was specifically requested. Another example considers the mirrors, which were not allowed to be attached to the wall with glue. As a result, the mirrors started bending and ended up replicating fun mirrors. The team of the UMAR unit learned from these deficiencies improving the design in the future. The sprinkler system had to be altered as well as the connections with the system were generally welded with plastic, which implies an irreversible process. As an alternative, screws were used. One of the architects mentioned that this technology was maybe the state-of-the-art twenty years ago (see quote 2, Table 5.1).

Not only the initiators went through a learning process, also the suppliers experienced a learning curve. A prime example is Lindner, a German company manufacturing cooling and heating ceiling panels. The panels were re-developed in order to accommodate the circular design. At the same time, it was an experiment for Lindner to take one of their standard products and examine what must be done to achieve circularity. The systems consisted of three subsystems - the panels themselves made from uncoated aluminum ensuring complete recyclability, the pipes from pure copper that were screwed on instead of glued and the felt strips serving the acoustics, were held in place by the same screws (UMAR, n.d.). The panels were mounted in the prefabricated units prior to assembly of the modules on-site. As of now, the company has included this product in their standard product portfolio and the system has been tested and classified as Cradle to Cradle level Silver (Lindner, 2018).

A complementary technology for circular IC that was highlighted by the initators was the use of the platform Madaster (see Appendix B). For the selection of the materials in the UMAR unit, indicators were used including characteristics such as the origin and chemical data of the material and the possibility for recycling or compositing (Heisel, personal communication, December 4, 2019). Data was collected in a very detailed manner and the materials that fulfilled the criteria were used for the project. However, only after the UMAR unit was completed, the researcher implemented the data in Madaster. It was learned that the circularity assessment of a building could be calculated using this tool, identifying possibilities for further enhancement such as providing insight into the residual value of materials. Comprehensive documentation was required and fortunately, the UMAR unit was well documented in the first place making the data readily available.

Market and Users
The users of the UMAR unit involve paid and unpaid guided tour visitors, partners of NEST and the tenants. The tour visitors are generally people from the building industry, yet other interested parties from different fields have registered. The tenants are comprised of PhD students from Empa staying for a period of three months and have shared general positive experiences so far (Weinmann, personal communication, November 26, 2019). There have been signs of wear and tear of the materials and components but aside from that, the students are content and new enthusiastic people are easily found that want to live in the unit.

The innovation manager mentioned that by showcasing the UMAR unit, people experienced a tangible example of the circular economy (Marchesi, personal communication, December 13, 2019). A pretty-looking PowerPoint slideshow can be presented to an audience, but only by seeing the unit, the manager believes people will understand the concept and recognize how well it functions as a building. More importantly, the UMAR unit has proved circular IC to be economically viable. Werner Sobek calculated the project to be 20% more expensive compared to a regular building of similar size. Despite the concept of circular IC being clear for initiators, it was learned that by demonstrating this project, the idea of circular IC was not regarded as too theoretical or virtual any longer. The innovation manager also stated that when the unit was launched, the popular media named it: a house made out of garbage. This implies that the market's perception towards circular industrialized construction is not positive in terms of aesthetics. The message suggested that the 'house' stinks and smells because CE principles were applied, whilst quite the opposite is true. Therefore, it was important for the core team to design a building that is aesthetically pleasing for the customers.

Finally, it was learned that most building professionals who visit the UMAR unit are unaware of the concept of urban mining (see quote 3, Table 5.1). In the event that a person was acquainted with the topic, there was the impression that circular IC is challenging, expensive and completely novel due to lack of knowledge.

Industry Developments
On the circular IC level, it was learned that the application of industrial manufacturing has a significant advantage over traditional construction when building in a circular manner (see quote 4, Table 5.1). The researchers explains that with industrialized construction, the planning phase for construction tends to be longer compared to the conventional way, but planning for the final stage of deconstruction of the building will in turn become more direct (Heisel, personal communication, December 4, 2019). The initiators learned that there is a higher level of control present by applying IC methods, leading to the generation of less waste. The NEST innovation manger stressed the potential of IC facilitating urban mining and building in the CE (Marchesi, personal communication, December 13, 2019). Currently, construction has extremely fragmented sequential processes with many different stakeholders involved. He explains that by streamlining these processes through the use of a 3D printer, several tasks can be performed at once, reducing the time and costs whilst achieving higher quality. As an example, he says that a 3D printer can produce a ceiling slab with a hole integrated, instead of having one worker pour the concrete in the ceiling slab followed by another working making a hole in the concrete.

It was learned that companies have to rethink their production processes and create new business models. For example, the carpets used adopt a product-as-a-service model, defining it as a resource instead of solely a product. It ensured that the resource can be returned because of its value to the company manufacturing the carpet. Additional value is also created for professional building operators that need to replace carpets every five years. With such a business model in mind, new investments and a new decision process were avoided. Notably, the innovation manager reported that it does not have to be difficult for suppliers to transform in manufacturing a circular product (see quote 5, Table 5.1). The design might have to be altered slightly but it does not imply that the element or material will have to cost more.

The UMAR unit is a research unit; hence, it is not considered a static object. The innovation manager of the unit explains that retrofitting and adjustments to the building should take place. In addition, there are plans to dismantle individual modules and replace them for new modules to study the use of different connections and differences in terms of operation of the unit. It is found that it is crucial to examine if any physical faults might occur, in order to optimize the design. Furthermore, the professor mentioned that in order to truly achieve a circular economy, it is important to disassemble the structure proving its design.

Societal and Environmental Impacts
The materials used in the UMAR unit have been carefully selected ensuring a minimal impact on the environment. However, one part of the lifecycle assessment was evaluated as extremely unfavorable. The researcher explained that the prefabricated modules were built in Austria and transported with three large trucks to Switzerland. It was discovered that this process emitted the largest amount of CO_2 (Heisel, personal communication, December 4, 2019). Thus, in order to deliver a circular IC system that is sustainable, it was learned to consider the whole life cycle.

Regarding the impact on society, the professor discovered that the UMAR unit is the most request unit to visit in the whole NEST building (Hebel, personal communication, December 4, 2019). From the 1000 visitors a month, 700 people visit the UMAR unit. This entails that many people are drawn in by the project and thus become more aware of urban mining, the circular economy and industrialized construction, increasing the awareness of circular IC. Moreover, the designers learned that in order for the UMAR unit to evolve into a mass market product, its prices must decrease. The professor at KIT believes that through a representable CO_2 tax agreement, conventional products will become too expensive and the mid-level of society will start to rethink their choice of materials.

Policy and Regulations
One of the initators learned from the project that if the Swiss government would supply safety nets, innovation in the building industry would grow, enhancing experimentation in the field of circular IC. He explains that taking over liability of the materials would be an effective measure, mentioning two additional policies that could be conducive to the development of the UMAR unit (Hebel, personal communication, December 4, 2019). First, a higher CO_2 tax is needed to account for the negative externalities of construction materials. Secondly, an adjustment to the value added tax (VAT) system could play a role. As of now, the same VAT is applied to each material. However, by applying a reduced fee on a material that has already undergone one or more lifecycles, an incentive is created for utilizing reused materials.

For the project, a number of materials were implemented that had not been certified yet, complying with national regulations. Empa gave consent regardless of this matter. Still, no exemptions in safety-regulated regulations were made, hence the reason sprinklers were installed. Nevertheless, it was learned that because of this given freedom, more could be accomplished compared to a status quo construction.

Second-order Learning

Problem Framing Shift
A shift in problem framing is not clearly visible partly because the beginning of the project development has not comprehensively been outlined. Nevertheless, one example is present.

Two architectural companies worked together on this individual project with both different ideas and cultures. The company Werner Sobek focused on creating prototypes that enabled dismantling at the EOL phase, a way of construction that the team at KIT valued. Accordingly, the latter two believed that materials originating from a second or third lifecycle also had to be integrated in the building. This ultimately led to conflicting views. To tackle such issues, the professor explained that occasional meetings were setup to move towards a common understanding (Hebel, personal communication, December 4, 2019). It was successful, as both parties started to understand each other's way of thinking. Even so, it demanded time and patience to make it work.

Problem Solving and Priorities Shift

The lead architect of Werner Sobek Köhler was a key player in finding a solution to build the UMAR unit in a circular way. The designers of KIT had developed a research concept for the building but were pondering how to construct with the idea of building for disassembly. This is where Köhler stepped in, with a proposed sketch to create 'small little units' that can be easily assembled and taken out using a crane (Hebel, personal communication, December 4, 2019). Dividing the UMAR unit into seven units, created clarity and direction, making the situation digestible. At the same time, Kaufmann was introduced as the party to complete the job. The CEO of the company convinced his team to engage is this innovative project, developing solutions such as minimal solid wood drilling and the use of screws to ensure that the wooden parts of the modules could be used later on elsewhere. Together with the lead architect and the team from KIT, the project began to take shape. It was learned that by having a multidisciplinary design team with actors from different backgrounds, the creation of better solutions to tackle the problem followed (see quote 6, Table 5.1).

Joint-learning Shift

One instance has been identified concerning a shift in joint learning. The KIT researcher explains that all the individual experts such as the structural planners, sanitary planners or fire safety specialist were asked to attend all meetings despite the sessions not always being directly relevant to them (see quote 7, Table 5.1). The partners had an open interpretive frame and carefully listened to the concept of circular construction during the course of the conceptualizing the UMAR unit. The moment when this group of people was asked to present their plan, they did not show their detail in a conventional way but drew it in a circular manner. This is something that was jointly learned between these actors. However, it took a lot of effort and convince to get everyone to sit around the table. Involving actors earlier on in the process created a shared circular mindset amongst the construction team, which in turn helped in achieving the goals for the UMAR unit.

5.1.4. Expectations and Visions

This section is subdivided into two parts. First, expectations for the project itself and circular IC are studied summarized according to the five-perspective framework (Schot & Geels, 2008). The different factors are highlighted in **bold**. Secondly, the visions are analyzed based on the following three characteristics: image, guidance and orientation (Leising et al., 2018).

Expectations

The professor at KIT explains that the UMAR unit was not created to promote a product into the mass market, but 'its thinking' into the mass market (Hebel, personal communication, December 4, 2019). He believes that it should not be the **technology** which should be incorporate in construction design, but the idea of planning in a circular manner in every building built. In the future, architects and engineers entering their professional life will understand and follow such principles, 'throwing out the old books'. The professor thinks that this is key in the transition to a more circular way of construction. The researcher adds to this statement that the accessibility of a comprehensive database system on construction materials is crucial for selecting products that have the lowest environmental impact (Heisel, personal communication, December 4, 2019). He continues by saying that the Madaster platform is planning to collaborate with certified material databases such as buildup and ecoinvent in Switzerland to collect information on thousands of materials and products. Their corresponding values are then used for calculating the circularity index of a building. Instead of reinventing the wheel, the researcher expects that by working together, data will become accurate and accessible, helping stakeholders in making informed decisions.

The innovation manager expects that transitional process of circular IC could go extremely fast, however it remains very unpredictable (Marchesi, personal communication, December 13, 2019). He believes circular IC is at the first stage and that what the (Swiss) **market** needs is to reduce the costs. To survive market adoption the UMAR unit should be able to compete with conventional building units, providing a better solution at a lower cost (see quote 8, Table 5.1). As mentioned earlier, the unit is 20% more expensive compared to the status quo, which forms a barrier. Generally, technologies are more costly in the beginning phase as economies of scale have not yet been realized. Moreover, the residual value of the UMAR unit was not taking into account. The innovation manager expects that once the market considers this aspect of circular economy and understands the building's true value, the transition can move very fast. To enhance this shift, the expectations are that the UMAR unit will start to function more as an information point providing knowledge and insights into the marketplace. The main focus from actual work performed in the unit starts to change to dissipating information through seminars and lectures. As a result, awareness is created as people's perceptions change, increasing the **social** acceptance of the circular economy in general.

The architects of the UMAR unit are unsure if the UMAR unit can be fully categorized as industrialized construction. Certainly, it has applied the concepts of prefabrication, pre-assembly and modular construction, but one of the initators mentions that many unique decisions were made to develop the project (Heisel, personal communication, December 4, 2019). This has to do with the fact that the UMAR unit is part of a niche; standardized **production processes** are not clearly present yet. The expectations are that in order to adopt circular IC processes, standardization is required to speed up the process. Moreover, the UMAR unit should not serve as a static object. Building maintenance, e.g. discoloration and deterioration of materials should be addressed. The modules should be taken out after five or six years for research purposes, however, the initators do not expect this to happen.

One of the initators mentions that the UMAR unit is much cheaper than a regular building if the **environmental impacts** were considered. The expectations are that new instruments will be developed to show the positive environmental impact of circular IC. An LCA concluded that the UMAR unit performs better in comparison to a concrete building of similar size. The analysis showed a reduction of 18% in cumulative energy demand and a 40% lower global warming potential (Kakkos et al., 2019). If this method of construction would be extrapolated to the mass market, it is expected to have a great positive impact on the environment.

It is expected that the public realm needs a **political framework**. The architectural team explains that building norms are hindering certain innovations (Heisel, personal communication, December 4, 2019). The building codes would have to be altered to allow the use of new construction materials. In Switzerland, the public and the government look upon the engineer and the architect with a level of trust, which implies that it could be less challenging to pass a law in favor of circular IC. For the UMAR unit, Empa tolerated certain circumstances that would be inconceivable in a regular building. As this project is a research project, failures can occur, providing the design team with a great extent of freedom.

Visions

Vision Image

The vision of the UMAR unit was verbalized using the following metaphors: functioning as a materials laboratory and a temporary material storage (Sobek et al., 2018). The first statement refers to the experimentation of exemplary product groups originating from waste streams, revealing its potential to be used as a suitable building material. The second metaphor implies a shift in the value chain of construction. Instead of disposing and demolishing the building, the UMAR unit has been designed for full re-use. The vision of the architects was made explicit based on the book Building from Waste: Recovered Materials in Architecture and Construction that was published at the same time that the NEST was accepting the first research units. The team was approached by Empa with the request to challenge the examples illustrated in the book and prove it works in real-life. They explained that they were keen on proving the materials successfully in construction applications (Heisel, personal communication, December 4, 2019).

Vision Guidance

The setting of a clear shared goal is present. The UMAR unit innovation manager mentioned four questions that were important for the UMAR unit: How far can we go? How expensive is it? How difficult is it? And what does it look like? (see quote 9, Table 5.1). This meant that the unit should achieve a high degree of innovation, not be too costly and difficult to develop and should be aesthetically pleasing. The first goal is in line with the vision of 'functioning as a materials laboratory'. The aim of testing new materials that are suitable on a larger scale was shared amongst NEST and the initiators, guiding the core team in the collaboration process. The firm Werner Sobek also stretched that the UMAR unit has to be aesthetically pleasing. Both Empa and Sobek believed that the moment people visit the unit and dislike the design; they will not be interested in buying such a concept. This also offered guidance to the core team in making it a high priority.

The vision of Empa contains various alternating rule sets. In a few cases, the ownership of building materials shifted and transferred back to the supplier of the materials. Companies who employed the strategy of product as service will retrieve their products at the end of life phase, referring to the temporary material storage metaphor. Moreover, the reuse of waste materials in modular construction is regarded a new rule set. Novel materials suitable for industrialized construction were tested, presenting an example of the functioning of a materials laboratory. Finally, the risk and time pressure for the initiators was eliminated in this building project. At NEST, the dedicated building space for the UMAR unit could have been kept empty for a while before it was installed, and in the future it can even been closed down for a longer period to perform a retrofit. This environment enables the laboratory setting as expressed in the first vision. The vision was co-created by the team of KIT and Empa. As such, no individual leader for establishing the vision is defined. The book laid out the possibilities for circular design, but without encouragement from Empa, the UMAR unit would not have evolved into a research concept.

Vision Orientation
Inspiration was provided by the aforementioned book. It introduced an inventory of materials and examples, which in turn formed the guideline and direction for selecting the materials that were to be integrated in the building. The prefabricated modular design enabled and simplified the temporary storage of materials in the unit and as such the vision provided direction in view of this as well. Moreover, it gradually inspired suppliers to rethink their products and propose a new circular design. The vision of creating a laboratory setting to test out new materials and components, being able to fail, served as motivation. The innovation manager explained that he did not expect the initiators to pay anything in order to conceptualize their plan. However, he did expected them to innovate in the NEST building and use that innovation, in this case the UMAR unit, in bringing the construction industry one step further in terms of sustainable development (Marchesi, personal communication, December 13, 2019) (see quote 10, Table 5.1). This relieved the core team from having to worry about the consequences of failing and rather let them focus on innovating. Moreover, team members showed enthusiasm and professionalism. Consequently, the project ran smoothly by having regular meetings to discuss process.

Table 5.1 Interview quotes related to the UMAR unit.

#	Quote	Interviewee
1	"We keep the team together and keep on pushing ourselves towards new ideas."	Initiator 2
2	"So we also realized we had to go a couple of steps backwards because saying that we can take anything out … also meant sometimes going back in time."	Initiator 1
3	"Because when building professionals come here, most of them have no clue what urban mining is all about."	Innovation manager
4	"If you prefabricate and then assembled on site, the step towards a planned disassembly is much more direct than if you cast on-site."	Initiator 2
5	"That was it. That does not make the product more expensive. That does not require a change in your manufacture process it all. "	Innovation manager
6	"I think in the end, [Kaufmann] together with the project architect from Werner Sobek Bernd Köhler, they and us developed fantastic ideas constantly on how to fulfill our promise."	Initiator 1
7	"All the planners, the individual experts, fire safety, sanitary planning etc. had to be present for a joint meeting, even if it wasn't directly relevant to them. But in the end, they listened to concepts of circular construction for weeks and when they were asked for their plan or detail, they drew this in a circular manner."	Initiator 2
8	"I am pragmatic when it comes to market spread. I say its market decisions. So the costs need to be at the right point. It is nice to be idealistic and provide ideas and try to push them. But at the end of the day it needs to survive in the market … You need to compete with it and you need to be better at lower cost. Baseline."	Innovation manager
9	"It was important to show that it's feasible. To show that it's not rocket science. To show that it's not ultra-expensive and to show that you can produce very beautiful results."	Innovation manager
10	"Very often I have potential partners and they ask what you expect from us because they think they are kind of tied into something where they need to pay. And then I say, actually, I don't expect anything, I expect that you innovate here in NEST."	Innovation manager

5.2. ICEhouse

Figure 5.8. The exterior of the ICEhouse in Davos (Hakvoort, 2019).

Figure 5.9. The interior of the ICEhouse in Davos (Hakvoort, 2019).

5.2.1. Introduction

The Innovation for the Circular Economy house (henceforth: ICEhouse) is a structure showcased during the World Economic Forum in Davos, Switzerland each year starting from 2016. The ICEhouse is an adaptable and reusable building inspired by the Cradle to Cradle framework (William McDonough + Partners, 2018). The *mission* of the project was to demonstrate the C2C design framework, the sustainable development goals of the UN and the reuse of resources implicit in CE. It employs the Wonderframe, an open source frame system that can be easily assembled and disassembled and insulated with reusable polymer cladding. In 2020, the ICEhouse was assembled for the fifth time in Davos.

Project timeline – how did the ICEhouse emerge?

The beginning of the ICEhouse dates back to 2014. The two co-founders of the Wonderframe developed an idea to create a lightweight, easily constructed building system for housing (Rood, personal communication, December 18, 2019). Simultaneously, one of the Wonderframe founders had a separate connection with the CEO of Hub Culture – a company offering meeting spaces in venues across the world. At that time, they had difficulty finding additional space during the World Economic Forum. This coincided with the possibility to prove the concept of the Wonderframe structure. The first experimental pieces of the Wonderframe were made in a local metal shop in Vermont, the United States and later on the complete frame was produced in a metalworking shop in Wisconsin.

Concurrently, the same co-founder, who happens to be the founder of the architectural firm William McDonough + Partners as well, was in contact with SABIC (a plastic company). The architect and former CEO of SABIC knew each other from before, dating back to 2012/2013 (Kuijpers, personal communication, Decmber 16, 2019). The initial reason to start working with SABIC was for the team of initators to explore the possibility of making the WonderFrame structure components out of recycled plastics (Rood, personal communication, December 18, 2019). It was proven to be more difficult than anticipated and instead the designers opted for aluminum due to financial reasons. Finally, the first ICEhouse was showcased in Davos in 2016, taking nine days to assemble the whole building. Since then the ICEhouse has been assembled each year in Davos.

Industrialized Construction

The Wonderframe is an aluminum flexible, expandable, lightweight and adaptable structural frame consisting of *non-volumetric pre-assembled* parts as depicted in Figure 5.10 (Finch, 2019). It can act as a structural wall or span for roofing and flooring (Finch & Marriage, 2019). The modular structure was patented in 2017 (McDonough & Rood, 2017). It stresses the importance for a structure that can be "assembled quickly and efficiently on site to enable elegant, simple construction and post disaster recovery". In total, it takes a crew of five to erect the frame of the prefabricated elements in two days (see Figure 5.11) (Rood, personal communication, December 18, 2019).

For each module, four chords and four webs (diagonals) are needed. Five bolts are used to connect the members (with holes at the end) of one module together. A single joint accepts eight members coming from different directions in order to connect all the modules. No chemical or adhesive-based fixings are used nor are specialized tools needed for coupling the connections. Battery operated drills and bolts are currently used to speed up the assembly, yet this is not specifically required. Because of its stability properties, the frame can be disassembled from any point on site. The material retains its performance through various lifecycles as is successfully demonstrated by the multiple times of assembly and disassembly (Finch & Marriage, 2019). The total area of building is equal to 90 square meters (9m x 10m) with a 1.5 meter overhang (Rood, personal communication, December 18, 2019). It represents efficient standardization and its prefabricated frame is deliberately simplified. A dimension was selected that is universal and conducive to housing situations. If a different size of the current structure is preferred, it is just a matter of incorporating an additional module as part of the building enabling adaptability.

Insulation is added within the empty spaces (McDonough & Rood, 2017). Similarly, wiring and piping are fed through the same spaces or through additional holes that can be made in the chords and webs, concealing it from the rest of the structure. At last, ease of transportation is key. The structure and insulation sheets fit into just one container.

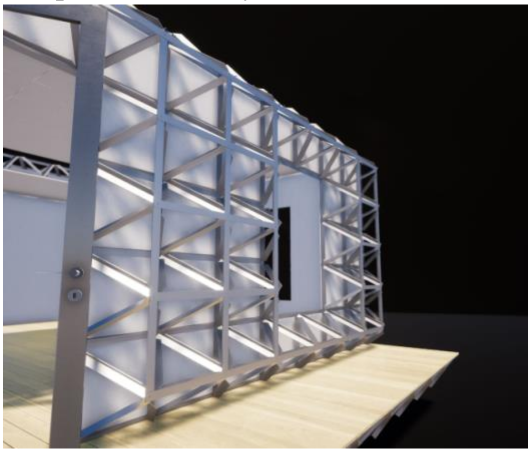

Figure 5.10. The Wonderframe with polycarbonate cladding (Finch, 2019)

Figure 5.11. On site assembly of the Wonderframe structure (C2C Centre, 2019).

Circular Economy Principles

The technical nutrient loop (Butterfly Diagram) is presented in the ICEhouse. Four technical materials were used to construct the ICEhouse: aluminum, polymers, aerogel and Nylon 6. The aluminum is used for the structural frame, the polymers for the cladding, roof and furniture, the aerogel inside the sheets to establish its insulating properties and the Nylon 6 for the carpets. All nutrients are considered *circular materials* as they can be returned to the industry and endlessly remanufactured into new products with no deterioration of material quality (Guldner, 2017). The project is designed to demonstrate the design framework of Cradle to Cradle as discussed in Appendix A (Jensen & Sommen, 2018). William McDonough + Partners (n.d.) states that all products are "either Cradle to Cradle Certified™ or in the process of becoming certified". However, up until now, only the carpets, which are leased through the *product as a service* model, have been certified.

Another important feature for CE is DfD, maximizing *product lifetime extension* (Lewis, 2018). The materials remain aesthetically desirable after disassembly. No chemical fixings are used. Instead, joints are bolted and with the help of tools that can be employed by low-skilled workers, a quick process of dismantling the building is facilitated.

Finally, the Wonderframe structure can span both horizontally and vertically (Finch & Marriage, 2019). It minimizes the amount of differently shaped components, contributing to *resource recovery*. Openings such as windows and doors can be articulated throughout the structure without the use of extra elements or larger spanning systems. As a result, this makes the structure more flexible, modular and better in terms of its circular economy potential as no other material or different dimension is required.

5.2.2. Network Formation

Figure 5.12 shows a *diverse* but *small* network for the ICEhouse. The core team of the ICEhouse is characterized with a blue star. The *initiators* comprise two actors – one is considered the founder and architect at William McDonough + Partners, whereas the other actor is the architect of the Wonderframe. Both are also the co-founder of the Wonderframe. The ICEhouse was designed by William McDonough + Partners, conceptualized through McDonough Innovation and built by WonderFrame LLC. SABIC, a Saudi Arabian plastics company, acted as a *facilitator*, financing the entire project along with supplying the cladding material. Hence, the actor is labelled with three colors, indicating the roles as investor, supplier of material and user. Hub Culture was the commissioner of the building as well as the *facilitator* assisting the involved parties and thus is labeled with two colors: client and user.

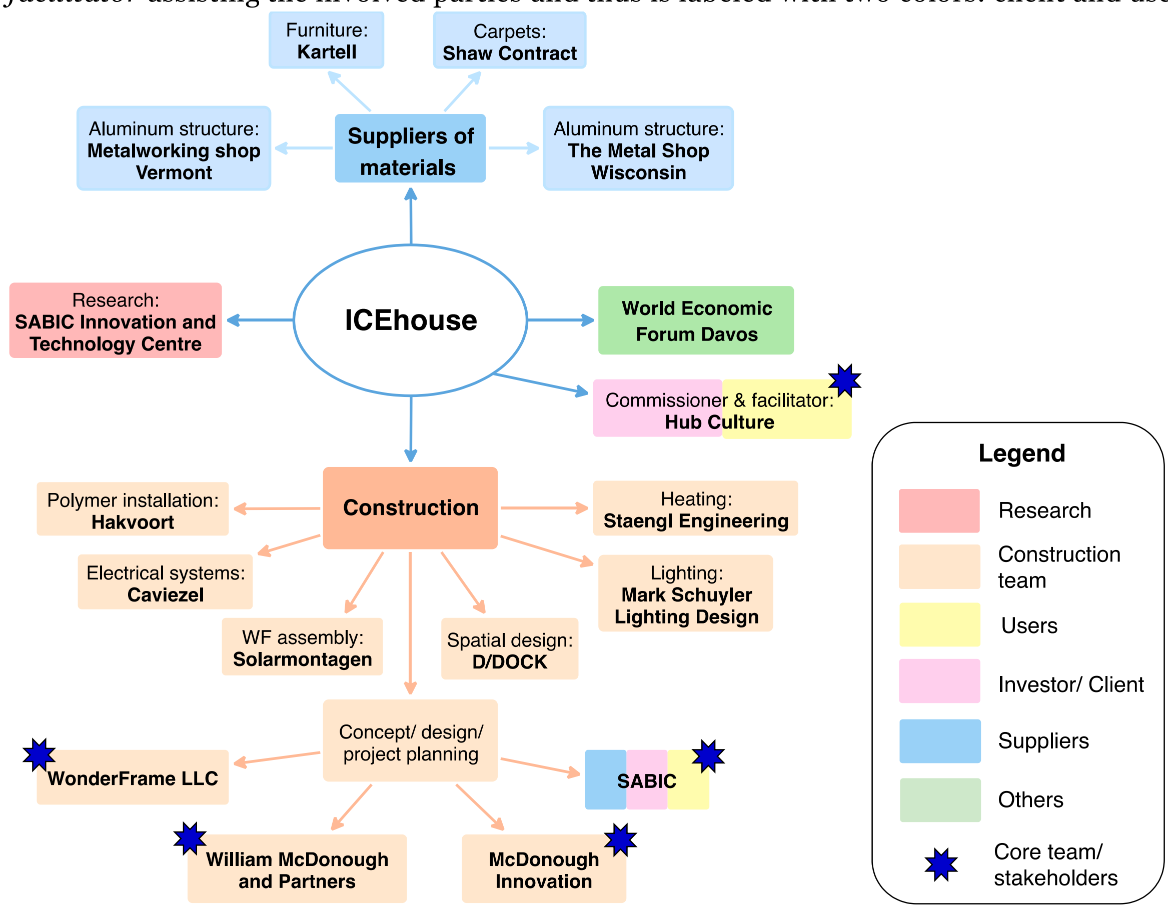

Figure 5.12. Stakeholder map of the ICEhouse.

The **composition** of the ICEhouse relies each year on William McDonough + Partners, Hub Culture and SABIC. *SABIC, a macro-actor*, plays a *crucial role* in the project. The company was interested in collaborating specifically with the founder of William McDonough + Partners to create circular products (see quote 1, Table 5.2). The Saudi Arabian company took the opportunity to apply their product portfolio of the polycarbonate LEXAN sheets to the building industry by suppling *full financial resources* and *flexibility* in terms of time in return. In terms of essential activities, it was evident that the initators *clear mission statement* attracted the interest of several parties including Hub Culture and the assembly company Solarmontagen. The latter firm was a small market player and thus was more *open toward innovation* and experimentation, which was beneficial for the success of the ICEhouse.

With the help of *SABIC's in-house research center*; the material was further developed to ensure its recyclability. Several sustainability parameters were studied, including the energy saving potential due to its high thermal insulation characteristics and weight savings, lowering the environmental impact of transportation. Furthermore, the innovation manager of SABIC stated that their intention was to utilize the ICEhouse as a platform for communication purposes during the World Economic Forum (Kuijpers, personal communication, December 16, 2019). In contrast to the UMAR unit, less suppliers are present in the network. Since, the ICEhouse functions as a meeting space instead of a living unit, the interior design was kept to a minimum. Shaw Industries donated Cradle to Cradle PAAS certified carpets and Kartell provided the polycarbonate furniture and light fixtures (McDonough Innovation, 2016).

A limited number of actors are based in Switzerland. The firm Caviezel, which installed the electrical systems in the building and Solarmontagen responsible for assembling the WonderFrame onsite are both based in Davos, Switzerland. SABIC's main office is based in Saudi Arabia and Hub Culture is headquartered in Bermuda. The company WonderFrame and William McDonough + Partners are based in the U.S. As a result, the first time the ICEhouse was showcased, the WonderFrame structure and the cladding panels had to be transported from outside Switzerland. However, following the recurring events, the elements were stored for the rest of the year in containers in Switzerland. The ICEhouse had very *little interaction* with the Swiss and American *government*. No financial support was provided, nor asked for. Governmental involvement was thus only required to ship the ICEhouse across borders from the US to Switzerland.

There is a high level of **alignment** concerning stability as well as complexity of the relationships between actors. The macro-actor SABIC was focused on advancing its current technology of the LEXAN sheets within the project. Financial support was given for the initators to develop the Wonderframe structure further, looking into the possibilities of replacing the aluminum components for recycled plastic components, yet experimentation proved to be unsuccessful (Rood, personal communication, December 18, 2019). This resulted in a *clash* between the *mission* of the initiators and SABIC. As a compromise, SABIC made the landing deck of the ICEhouse out of plastic, a product they hoped to develop further as a deck for tractor-trailers or trucks. The presence of this *cross-relationship* created complexity within the network.

The relationships are perceived to be very stable as the core actors share a *substantial history* with one another. The co-founders of the Wonderframe have known each other for more than fifty years on a personal level but have also worked together on numerous projects. This creates a strong bond and familiarity with each other's work culture. Likewise, the founder of William McDonough + Partners and past CEO at SABIC knew each other dating back 9 years ago. Moreover, the founder has known the owner of Hub Culture for fifteen years (Hub Culture, 2020b). The network has *partly continued to exist* through the two initators collaborating together on a new project. In Bogotá, Colombia, an academic building for the Universidad EAN is under construction integrating the WonderFrame structure as sun shading cladded with multi-colored perforated panels (William McDonough + Partners, 2017). This entails the versatility of the technology as well as the persistent relationship between the initiators of the ICEhouse project.

A *framework agreement* was set up between SABIC, William McDonough + Partners and the construction companies Solarmontagen and Hakvoort. In term of *communication* and *connectivity*, nine to six months before the World Economic Forum, the first coordination meetings were held. At the beginning, such gatherings take place each month, but at a certain point, the team has weekly contact through virtual meetings or phone calls. (Kuijpers, personal communication, December 16, 2019). Additionally, SABIC also has a contract with Hub Culture to make use of the space for events hosted by the company. The sustainability manager at SABIC describes that each year the composition of the parties involved can change, though this has not happened yet. Finally, *professionality* was identified as a key success factor in terms of stability in the network.

To summarize, the network has grown in terms of stability over the course of the project. The existence of prior established relationships between the core team and the set-up of framework agreements strengthened the connections between actors. The macro-actor SABIC play an important role in increasing the alignment by providing financial means to the project.

5.2.3. Learning

In this Subchapter, first-order learning is studied based on the technical, market/user, industry, social/ environmental and policy/ regulation perspective. In the second part, the analysis of second-order learning, including problem-framing shift, problem-solving shift and joint learning is given.

First-order Learning

Technical

To design for disassembly to ensure the structure can be stored away easily each year, connecting bolts that can be unfastened are used. The designers of the Wonderframe learned that the aluminum joints have to consider deflection (Rood, personal communication, December 18, 2019). This entails that every joint should accept a slight fraction of movement to accommodate the bolt going through eight holes. It is not noticeable to the eye but to ensure no problems occurred in terms of shedding water and snow a covering surface was used. During the design phase of the Wonderframe, it was also learned that the dimensions should be conducive to housing situations if the structure would ever be employed on a larger-scale. Thus, the elements were standardized and able to span a universal dimension.

The co-founder of the Wonderframe mentioned that the aluminum frame could also be replaced for bamboo or wood members. Experimentation has shown that it is not possible to make joints out bamboo. As of now, the joints are dependent of the structure. A hole is incorporated within the chords and webs and by dropping a bolt through the holes in each of these members, the joint are secured in place. If the joints can be made independent of the members, the possibilities arise for replacing the aluminum members for different material. If the ICEhouse is used as refugee housing, the joints can be made from aluminum but wood or bamboo for the structure could be used instead. These particular materials can be sourced on site, decreasing the reliance on global sources. In turn, this would be beneficial for the circular economy, minimizing the transportation impact and supporting local materials flows. Finally, it was demonstrated that recycled plastics was not suitable material for the WonderFrame. It took a lot of time to produce, and multiple steps were needed to make it a workable product. Fire retardant was added, the plastic was reinforced and made unsusceptible to degradation due to ultraviolet lighting. Consequently, the free waste plastic at the beginning turned out to be more expensive than aluminum.

Regarding the CE assessment, the goal was to make a building based on the Cradle to Cradle principle. However, as it was learned that during the development of the WonderFrame, the use of materials originating from the biological cycle were unfitting. The client from SABIC describes that biodegradability leads to different, more complex problems compared to the use of technical nutrients (see quote 2, Table 5.2). For the latter, materials can be brought back easier to its original state.

Market and User

The users who had access to the ICEhouse were people attending the World Economic Forum main events. In general, they held a senior position with an extensive network and utilized the space for meetings or presentations. Additionally, a wide range of seminars were organized with reference to the circular economy. For example, climate activists such as Greta Thunberg have presented on stage. The feedback received after visiting the ICEhouse was that guests found it a beautiful and inspiring building. In an interview given by Hub Culture, it was revealed that the former CEO of Unilever describes the place as a way to help frame your thoughts: “When you have a lofty thought and your eyes go up, there is nothing that is distracting you.” (Hub Culture, 2020b). One of the co-founders described the notion of illumination, transparency and warmth conveyed in the ICEhouse and that users perceived it in this fashion as well.

The initators learned that when you are undertaking such an innovative building project, it can be challenging to find large partners that are willing to participate (Rood, personal communication, December 18, 2019). Before the first ICEhouse was showcased in Davos, the initiators were engaging with a Dutch multinational company that would possibly be assembling the structure onsite. For months, the parties worked together trying to assess the costs of installing the structure. However, the company was hesitant to take the risk and thus proposed a very high price. One of the initators came across a very small company named Solarmontagen who was willing to perform the task for half the price. He learned that a small firm is not part of extensive bureaucracy and might be less risk adverse than a multinational company in becoming involved in innovation within construction. Furthermore, the initiator learned through experience that a commitment has to be made on the part of the client or the one initiating the building project. He explained that he discovered there is no resistance to circular economy but that people need to be given direction (see quote 3, Table 5.2).

Industry Developments

The metalworking shop located in Vermont manufactured the first components of the WonderFrame. However, the shop was not able to produce the elements on a mass production scale. It was learned that the initiators had to find another location that could make a larger volume, which led them to the metalworking shop in Wisconsin. However, to expand the production of the WonderFrame, manufacturing will have to be relocated to an even larger facility. In addition, the co-founder explained that to speed up the process it would be possible to cast the shapes of the frame instead of individual bending, drilling and shaping the members (Rood, personal communication, December 18, 2019). He also stated that economies of scale could be applied if the frame is manufactured on a large scale. Another possibility to lower the costs is by using a different material for the load bearing of the building. The main virtue of the WonderFrame is its ability to span as opposed to load bearing and thus a redundant structure considering the walls. The co-founders looked into replacing the load bearing elements with a cheaper system of bricks made from recycled plastic, which were manufactured by a company in Colombia. Nevertheless, the idea was not realized but it does imply that production processes optimization was considered to reduce the costs.

The client explains that the ICEhouse was fairly easy to develop but that it was difficult in terms of execution (Kuijpers, personal communication, December 16, 2019). He learned that is it crucial to bring together different parties and asses what the issues that might be faced are. The main problem lies with introducing new concepts in an existing industry with existing standards, laws and regulations and bringing these parties together to put forward a system solution disregarding all individual processing steps. He discovered that the establishment of new company that can create such a systems solution could be an answer. However, this organizational structure was not applied in the ICEhouse.

Societal and Environmental Impacts

The main social component learned by the initiators was that to have an impact, the structure has to be easily assembled. For ICEhouse, battery operated power tools were used to advance the process of installation. If applied as refugee housing, locals with few building skills would be able to construct the frame without the use of power tools. Regarding the impact on the environment, no learning process was directly identified. Nevertheless, it can be assumed that the impact of transportation is considerably high as manufacturing occurred in the United States in order to be shipped to Switzerland.

Policy and Regulations

Learning about fiscal policies and regulations necessary to stimulate the growth of circular IC remains limited. The core team of ICEhouse learned that is was very difficult to take the containers with the components across borders to display it during a CE event in Amsterdam one year. It implies that to create awareness of the ICEhouse outside of Switzerland is more challenging than was anticipated.

Second-order Learning

Problem Framing Shift

The direction was pre-set by the architect from William McDonough + Partners prior to acquisition of the partners (see quote 4, Table 5.2). This meant that involved actors reframed the problem to accommodate his dominant interpretive frame. There was no resistance to adopting the WonderFrame structure and assembling it that particular way. All other actors were elevated to contribute, yet there was never the opportunity to rethink if the proposed idea would have been the best solution. SABIC states that the construction industry is one element of its business' operation but emphasizes that finding applications in packaging industry is most relevant to them. However, the company persisted with the aforementioned mission for the ICEhouse and reframed the problem in finding a suitable product for the cladding material in the building.

Problem Solving and Priorities Shift

The client described that producing a product with the lowest possible carbon footprint, preferable a net zero carbon footprint is viewed upon as the aspect that brought William McDonough + Partners and SABIC together. Nevertheless, the initial goal set by SABIC in making the complete structure out of recycled plastic was not achieved. The initiator of the ICEhouse states that the evolution of the product is the learning process. Even if the initial idea could not be implemented, he believes it was still a successful result (see quote 5, Table 5.2). As such, SABIC decided to shift their priorities and focus on marketing their product, the LEXAN sheet portfolio application for the construction industry (SABIC, n.d.).

Another interesting problem-solving collaboration was identified between the designated person engineering the Wonderframe and the initiators. The engineer initially designed the components a substantial size guaranteeing the structure would withstand the forces in a worst-case scenario. However, the elements were not all stressed to the same degree, depending on their location. Ensuring the frame would be aesthetically pleasing; the sizes were manipulated without sacrificing the strength required. Consequently, the actors found a new solution in finding the right dimensions for the ICEhouse.

As mentioned earlier, SABIC's expertise did not lie in the building sector (Kuijpers, personal communication, December 16, 2019). The project faced numerous constructive challenges concerning the corresponding carrying capacity of the polycarbonate sheets. The initators performed calculations to find a solution, whereas the Saudi Arabian company had no experience or know-how in addressing this. Interestingly, SABIC learned that by bringing together all the different disciplines and expertise, a system solution is reached (see quote 6, Table 5.2). Instead of looking at one problem individually, new possibilities were created.

Joint-learning Shift

Shifts in joint-learning did not take place. However, it was learned by the core team that the circular economy aspect was an integral part of the project (see quote 7, Table 5.2). There were no conflicting views while the ICEhouse was being built. One of the initators stated that all actors had a certain awareness of circular economy; the people making the WonderFrame elements in the metalworking shops conscious of aluminum's recycling potential, SABIC's awareness for the circularity of their product and the installers at Hakvoort apprehensive of the fact that polycarbonate is a responsible material to use. Finally, Solarmontagen's core business is installing PV systems and thus they are very much involved in renewable energy.

5.2.4. Expectations and Visions

Subchapter 5.2.4 provides an answer to the expectations and visions of the ICEhouse. For the expectations section, the different perspectives based on Schot & Geels framework (2008) are listed in **bold**. Next, the visions elements have been analyzed (Leising et al., 2018).

Expectations

It is expected that the **technical** elements of the ICEhouse will be further developed, possibly made from of a different material (Rood, personal communication, December 18, 2019). The chords and webs might be comprised of recycled plastic, if continued testing demonstrates that it could be a suitable material. Moreover, one of the initators believes that in the future the joints will be 3D printed or casted as they are too complex in terms of shape to manufacture manually. The use of locally sourced products is also expected to happen, for example in the event the ICEhouse is applied as disaster relief. However, it might be decided to construct the WonderFrame using steel as the material is slightly less costly and the structure would appear more delicate. Likewise, the material is stronger and the components themselves could be engineered smaller. Nevertheless, steel is heavier having a detrimental impact on the **environment** in terms of transport. Lastly, there are plans to integrate PV on the roof (Kuijpers, personal communication, December 16, 2019). This idea is being conceptualized; however, it is questionable whether placing PV panels during winter is meaningful.

The initiators of the project expect to reach a larger audience once the structure can be applied as refugee housing benefitting **society**. The intention of the designers is to adopt the frame for other applications in the future as well such as the setup of a clinic in the aftermath of a disaster. The expectations are that the ICEhouse in Davos will be used as a platform for communicating the concept of circular IC in the coming years. The **users** will remain World Economic Forum guests attending meetings and presentations.

SABIC explains that the ICEhouse is a prime example of creating a system solution. Actors are encouraged to step out of their existing value chains and work together with other parties to explore new opportunities or **processes**. Even if the ICEhouse is one application of circular construction, it is key to introduce new concepts in an existing industry that allow for more applications in the future, enhancing the growth of the niche. Regarding manufacturing, it is important to have flexibility in terms of pre-assembly. The client explains that it is possible to assemble all the components of the ICEhouse in a factory and transport the building as a whole (see quote 8, Table 5.2). However, transportation could become more complex, which is unfavorable for the life-cycle assessment. It is expected that the level of pre-assembly might change for other applications in the **market** such as for refugee housing or displaying the project elsewhere outside Switzerland. No expectations in terms of **policy** and **regulations** stimulating the development of the ICEhouse or circular IC were identified.

Visions

Vision Image

The founder of William McDonough + Partner describes the ICEhouse as a building that is 'designed for next use'. The initiator adds that it is 'like a cherry blossom – it comes and it goes' (Hub Culture, 2020a). With this metaphor, he refers to the process of the assembly and disassembly of the ICEhouse. The structure is stored in a container and can be transported to any location. The project can be used repeatedly. The vision was made explicit through demonstrating the design framework described in Cradle to Cradle: Remaking the Way We Make Things (William McDonough + Partners, n.d.).

Visions Guidance

The presence of clear shared goals is illustrated with the clients' statement (see quote 9, Table 5.2). For SABIC, it was important to reduce the carbon footprint of the products manufactured, preferably achieving a net zero carbon footprint. The client as well as sustainability manager at SABIC described that what brought the founder of William McDonough + Partners and SABIC together is that SABIC believes their materials could support McDonough + Partners' notion of Cradle to Cradle thinking. He commented that this not imply that all SABIC's business operations contribute to this goal directly, but it does form the foundation for this collaboration. In addition, SABIC was deeply interested in ensuring their product would be considered circular.

The visions contain a few alternative rule sets. It shows a new perspective of ownership of building materials. The ICEhouse has been designed for next use and therefore materials are temporarily stored in the building. To illustrate, the furniture and finishing adopt a product-as-a-service business model and at the final stage of use are returned to the supplier. Likewise, the concept of designing for disassembly was important to create a structure that 'comes and goes'. By using a prefabricated frame with cladding sheets that could be removed easily, it was possible to achieve this vision. Additionally, the founder at William McDonough + Partners mentioned that the term 'end of life' should be replaced for 'end of use'. The ICEhouse is comprised of technical nutrients that become repetitive as materials are considered cross generational (Hub Culture, 2020c). A material never reaches an EOL phase but returns back to a new use. This is in contrast with the labelling of conventional buildings at the deconstruction and demolition phase, generally named the end of life phase.

Leadership is evident in this project. The vision as well as direction for the project was created by the founder of William McDonough + Partners and all stakeholders involved were aware of this from the start. For example, the material selection was in place before any actor was brought on board, which actively guided decision-making. It was clear to stakeholders what to expect but it could have hampered innovation. Quote 10 in Table 5.2 illustrates this clearly – the use of a different material such as acrylic was never considered.

Vision Orientation

Inspiration was certainly present in this project. The client at SABIC titled the architect at William McDonough + Partners as 'the guru in this field of circular thinking' (Kuijpers, personal communication, December 16, 2019). The concepts of Cradle to Cradle and the circular economy are evident in the ICEhouse – the architect being the founder of the principle and as such the inspiration source for the building.

SABIC had various motives for participating in the ICEhouse. The company aimed to prove its product to be circular but also regarded the ICEhouse as an icon project during the World Economic Forum to foster conceptual thinking in terms of applications for their materials as well as providing a location to host events.

For the initiators, the second metaphor provided direction to explore different applications of the WonderFrame as a structure that could be put together and be removed easily. As such, WonderFrame was established as a separate company to explore the development of a building system that is easily transportable and constructible by untrained people with limited tools (Rood, personal communication, December 18, 2019). It has now shown to be successful in Davos and therefore the time is right to prove its application outside Switzerland (see quote 11, Table 5.2). Finally, motivation was reflected in the close contact between the core parties coordinating the project (see quote 12, Table 5.2).

Table 5.2. Interview quotes related to the ICEhouse.

#	Quote	Interviewee
1	"They [SABIC] are very generous and supportive and they're very much interested in working with William to make sure their products are circular economy."	Initiator
2	"Biodegradability in the circular economy cannot easily be brought back to its original state or products. Best-case scenario, you can compost but, in the meantime, you create a bigger problem that initially wanted to solve."	Client
3	"You can go to a builder or construction company and say, I want you to use these materials, whatever they are: aluminum, steel, bamboo, polycarbonate, they are perfectly happy to use them."	Initiator
4	"The direction of the project was established before basically any of the partners were involved since you know, Bills projects and Bill is Cradle to Cradle and Circular economy, and the material selection was in place before anybody else was brought on board."	Initiator
5	"Maybe we'll get there and maybe we won't. I think that all the things that we have done have proven to be successful. "	Initiator
6	"I do think that we might be able to jointly find a solution faster than when not everyone is looking through the same lens."	Client
7	"The circular economy aspect of it is just baked into the project."	Initiator
8	"The parts can be produced for example in the Netherlands and put together as a bigger frame in Switzerland. You have all the flexibility for this. In the end, the bottom line is what it the best option regarding transportation."	Client
9	"These aspects brought both Bill McDonough and us [SABIC] together because we believe that the materials that we produce can help/support this."	Client
10	"Everybody's very excited about doing it but there was never an opportunity or a reason for anybody to come forward and say: Hey, instead of polycarbonate, why don't we use acrylic or something?"	Initiator
11	"William also tries to use it as a steppingstone to communicate that the ICEhouse can have more applications."	Client
12	"... At a certain point, you have weekly contact at minimum to coordinate. And that can be sometimes through email or through a call. That is for us a common way of approaching a project, of project execution."	Client

5.3. ECO Solar Houses

Figure 5.13. Aerial view of the ECO Solar Houses in Saint Margrethen (ECOCELL, n.d.).

Figure 5.14. Assembly of ECO Solar Houses in Saint Margrethen using the ECOCELL system (ECOCELL, n.d.).

5.3.1. Introduction

The ECO Solar Houses situated in St. Margrethen are the first buildings to be constructed with the ECOCELL building system developed by the start-up ECOCELL (ECOCELL, n.d.). The *mission* of the project was to "proof the versatility of the building system and the architectural possibilities the system offers". In 2016, four stand-alone family houses with each a net surface area of 110 m² were built, sold and inhabited the next year.

The company ECOCELL was found by an architect four years earlier. ECOCELL produces standardized elements of honeycomb from recycled corrugated fiberboard (1.0) coated with mineral cement to make it highly durable, water and fire retardant (2.0) (see Figure 5.15) (Iseli, 2018). Next, the honeycomb is sandwiched between two orientated strand board panels with glue to create robust walls (3.0). The elements are cut to customize the dimension that is preferred and provided with grooves for the connections (4.0). For the ECO Solar Houses, the panels were used to build the entire-load bearing structure including the walls, ceilings and roof elements. In addition, the roofs were fully covered with photovoltaic panels to maximize the generation of energy when the buildings were in operation.

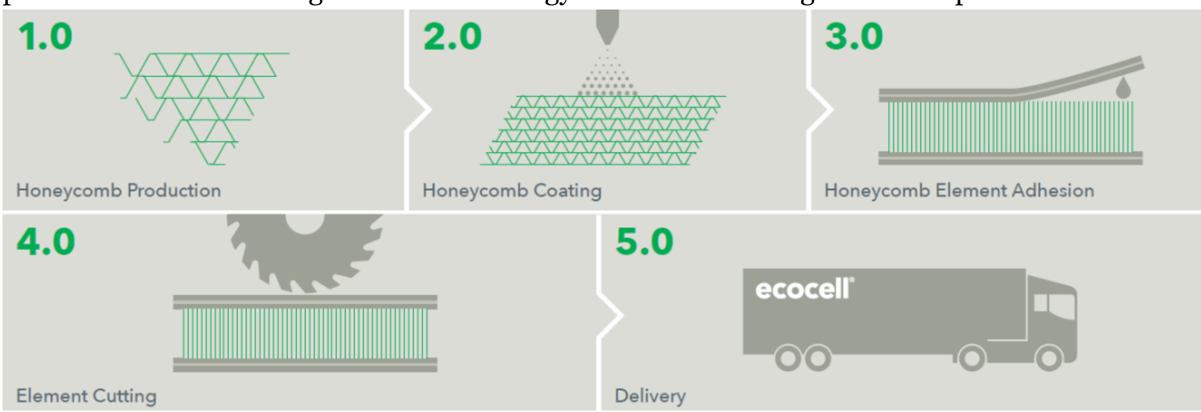

Figure 5.15. Production process of the ECOCELL panels (Iseli, 2018).

Project timeline – how did the ECO Solar Houses emerge?

The first idea of designing ECOCELL's technology started 20 years ago (Iseli, personal communciation, January 16, 2020). The founder was the owner of a cardboard factory and came up with the idea to make pallets with recycled paper. This design stood out thanks to its high load capacity and lightweight design that would prove to be suitable for multiple applications (SWISSMAG, 2016). There was a high interest from the industry at that time – the lightweight paper sheets were outselling the finished transport pallets. The founder was originally an architect, searching for a solution to provide a cheap and quick alternative to concrete and brick construction. The idea was further developed by incorporating a special treatment with cement with a team at ETH Zurich. The entire process for the industrial production of a mineral-coated honeycomb as well as a building system method was created and patented (Iseli, 2014, 2015). In the beginning of 2015, a pilot factory in Sulgen, Germany was opened to manufacture the panels on a small-scale. The following year an industrial production plant was established in Sulgen, Switzerland (ECOCELL, n.d.).

In 2016, the company received the renowned GreenTech Awards, Europe's most important environmental award. This boosted the reputation and recognition of the company in the building sector. At that time, a landowner in St. Margrethen was trying to sell the house on the initial plan but without any success (Iseli, personal communciation, January 16, 2020). The owner was familiar with the company and made an offer to ECOCELL to build their first proven houses with the technology. Sustainable operation of the ECO Solar Houses was essential and thus the generation of renewable energy was included in the design. PV panels were placed on the roof an air-to-water heat pumps were installed running on the electricity generated by the PV. After the houses were completed, a rental agency put the houses up for sale taking only three weeks to sell all the properties.

Industrialized Construction

The ECOCELL building system emphasizes the importance of industrial construction. It is based on *non-volumetric pre-assembled* individual standard components manufactured under industrial conditions and claims to reduce work on the building site by 60-80% and costs by 20-30% (ECOCELL, 2019). It consists of three components: the main elements, the finish profiles and the tongue-and-groove connections (see Figure 5.16). The main elements, in other words the panels with the coated honeycomb, follow the standard housing dimensions: two by four feet (72.5 x 248 cm) or two by eight feet (72.5 x 248 cm). Electrical wiring and plumbing has been integrated in the panels through the use of a cable canal, see Figure 5.17.

Another benefit of this technology is the simplicity of assembly. With the easy plug connection and light-weight material, the task of assembly could be performed by a single worker (ECOCELL, n.d.). At the EOL stage of the ECO Solar Houses, the buildings panels cannot be recycled as the honeycomb elements have been glued (see step 3.0, Figure 5.15) but can be *recovered by reusing the components* in a new project. To construct the wall, floor/ceiling and roof, different layers of the panels were required. For the walls, one or two layers of the elements were required, for the floor/ceiling two or three and for the roof one or two layers. For the floor underlay, the coated honeycomb excluding the OSB panels was installed on top of the floor/ceiling elements. Grooves for the underfloor heating pipes were milled into the composite material at the factory. Openings such as windows and doors however were still installed after assembly of the panels. The use of standardized components instead of modules made transportation easier and cheaper as no large specialized trucks were needed (Iseli, personal communciation, January 16, 2020).

Figure 5.16. A ceiling consisting of a three-layered panel with tongue-and-groove connection (ECOCELL, n.d.).

Figure 5.17. A cable canal for wiring integrated in a three-layered ceiling panel (ECOCELL, n.d.).

Circular Economy Principles

CE principles are clearly applied to the ECO Solar Houses. First, 100% recycled paper is used for the production of the raw honeycomb structure. ECOCELL relies on the waste streams of the paper industry demonstrating *industrial symbiosis*. It applies *resource recovery* by upcycling the corrugated fiberboard into a lightweight composite panel. To produce the mineral-coated honeycomb panels, cement is indeed required. However, a complete concrete mixture including the use of sand is avoided required (ECOCELL, 2019). Currently, sand is the second most used natural resource behind water and used in many different applications, primarily in building materials (G. Brown, 2019). As a result, this corresponding building system is not dependent on materials that are at present time considered scarce.

Moreover, the components are connected using the tongue-and-groove system. Because no adhesives or chemical jointing is used, the panels can be dismantled, rearranged and reused in the same building or in another construction. *Product lifetime extension* is present here, as the concepts of flexibility and adaptability were incorporated into the design. Finally, one of the characteristics of CE as mentioned in Subchapter 2.2 is that renewable energy is required to fuel the circular economy. In terms of operation, the houses are sustainable as well *avoiding life cycle impacts*. Energy consumption is minimized by the use of solar PV panels installed on the roofs.

5.3.2. Network Formation

Figure 5.18 reveals a *small* and *uniform* stakeholder map for the ECO Solar Houses. The different colors indicate the various roles actors have within the network (see Legend). A blue star points out if a stakeholder belongs to the core team. Here, the company ECOCELL, responsible for manufacturing and delivering the innovative building elements, is of great importance in the realization of the project. Likewise, the architectural firm Iseli Architectur is the designated partner to design the houses. The *initiator* of the ECO Solar Houses is both the lead architect at Iseli Architectur as well as the founding principal of the firm ECOCELL. Finally, the landowner of the plots in St. Margrethen as well as is regarded a decisive factor in the success of the project.

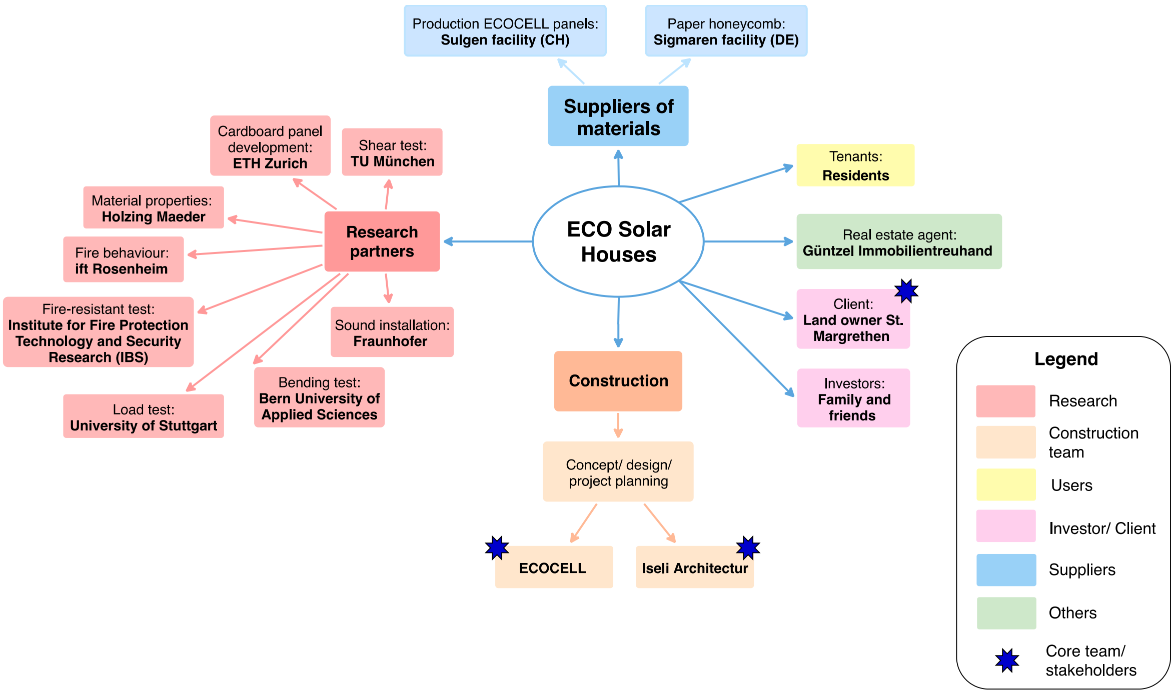

Figure 5.18. Stakeholder map of the ECO Solar Houses.

Looking at the **composition** of het network, it is noted that *numerous research partners* were involved in developing the technology behind ECOCELL's panels. The ECO Solar Houses were the first houses to showcase the technology of ECOCELL and thus extensive research was conducted prior to construction. The foundation for experimentation was laid by ETH Zurich running a project to developing lightweight, environmental-friendly structural elements that could be used for walls in residential and office buildings (Institut für Baustatik und Konstruktion, 2013). At that time, the mineral-bound coating material was created and applied to cardboard – forming the basis of ECOCELL's technology. The founder had a very *clear mission* for the project and acknowledged that the development proceeded slower than anticipated and thus it was decided to abort the research project to continue the course of conceptualization as a company individually (see quote 1, Table 5.4). Subsequently, a group of stakeholders was assembled to perform various tests on the panels ensuring the material's technical feasibility, including a shear and fire-resistant test.

The *landowner* in St. Margrethen was essential to the project. When it became apparent that the technology proved to be successful, the company ECOCELL was exploring ways to realize their building system in real life. Simultaneously, a landowner that was not able to sell his property reached out to the initiator. The landowner was aware of the novel technology playing a *facilitating* role by accepting and partly *financing* the project and *avoided* setting a tight *deadline* for the team of ECOCELL to deliver the houses.

There was little *governmental involvement* as the Kanton of St. Gallen had to intervene in this building project. The objective of energy self-sufficiency during operation was an important aspect in the design. The initiator planned to cover the entire exterior shell of all four buildings with PV panels. The proximity of a village church constrained the design. In response to this, the historical environment was retained by installing the photovoltaic elements exclusively on the roof covering the remaining shell with a horizontal wood lattice.

The paper-corrugated fiberboard were produced in Sigmaringen (Schoch, 2018). Thereafter, the material was transported to the facility in Sulgen where the subsequent production processes were carried out, including the coating of the fiberboard and adhesion to the wooden elements. Ultimately, the real estate agent played an important role in the success story of the project as well. Güntzel Immobilientreuhand took on the risky endeavor of selling the first ECO Solar Houses. The houses were marketed as 'help shape a piece of energy history!'. In three weeks' time, all four houses were sold at a price of +/- CHF 650,000.

Alignment is fairly low in this network. The intensity of *communication* and *collaboration* between the initiator and the other stakeholders remains limited. Nevertheless, complexity is still perceived to be present in the network. The initiator of the ECO Solar Houses acted as the architect as well as the founder of the technology, demonstrating a *cross-relationship*. Numerous relations between stakeholders were determined to be complex because the connections take place on a personal level. The shareholders of ECOCELL were *friends and family* (Iseli, personal communication, January 16, 2020). In total, this group invested millions in the development of the technology and the first project of the houses (Schoch, 2018). The landowner who exchanged his land against shares in the company knew about ECOCELL before and was interested in supporting his initiative, as they *shared history* on a personal level influencing the property owner is his decision-making. Therefore, the project could benefit from a structure of stability prior to the construction of the houses. The partnership between the client and initiator has ceased to exist. ECOCELL had the ambition to give out a license to the industry and was therefore not interested in developing new projects with the same core team. The initiator commented that having small team increased *connectivity* and was beneficial to achieving his vision for the company as decisions can be made easily without being hindered by a macro actor that might have a different agenda (Iseli, personal communication, January 16, 2020).

Overall, the network has not grown in size since the start of the development of the ECO Solar Houses. The landowner, family and friends are considered the only investors that contributed to speeding up the development. Additionally, there is limited commitment of the core team to the project as collaborative process has stopped, creating an unstable network.

5.3.3. Learning

In this section, first- and second-order learning is discussed. For first-order, the perspectives according the framework by Schot & Geels (2008) are discussed. Secondly, the second-order learning criteria: a shift in problem framing, problem solving, and joint learning are studied.

First-order Learning

Technical

Various design specifications and technology complementary to circular IC were learned throughout the process of construction the ECO Solar Houses. ECOCELL learned that a higher degree of pre-assembly of the panels is possible and beneficial for reducing on-site construction work. For the houses located in St. Margrethen, the windows and other openings were placed after the load boarding structure had been constructed. For a second project in Uttwil, similar family houses were constructed but within a much shorter time span. Prior to assembly of the second project, the windows with the required composite were integrated into the panels including the connections and the blinds (Iseli, personal communication, January 16, 2020). Furthermore, the founder reported that after building the first house, the construction workers onsite improved their understanding of the system (see quote 2, Table 5.4). Thus, retraining the builders was learned to be key in enhancing the speed of assembly.

Moreover, there was more freedom to experiment with other building materials. The ECO Solar Houses was the first project to test the technology of ECOCELL in a real-life situation. Of course, numerous performance tests had been conducted, however, the plaster material had not been tested before construction. In the first two houses, adobe was used to plaster the walls, but it was found that gypsum boards are a better option for the other two buildings. Adobe plaster, which requires a significant amount of water, is not complementary to ECOCELL's building system using a dry construction method. This is also reflected in the differences in construction time– the first two houses were built a couple of months apart, whereas the third and fourth house were built in the same week (ECOCELL, n.d.).

Circular economy principles were clearly present here. The honeycomb took up approximately 75% of the total volume of one ECOCELL panel and thus represents the largest portion of the composite. The honeycomb, made from 100% recycled paper, relies on existing production capacities of the global paper industry. The OSB panels and honeycomb are glued together to ensure the structure does not break apart. This does imply that the elements cannot be separated at the end of life phase of a building. However, the ECOCELL team has learned that it is better to keep the panels as a whole. In an event, the panel needs to be replaced or the building is deconstructed, the system can be taken apart as individual elements and used for a new construction (see quote 3, Table 5.4).

Market and Users

In general, the tenants in the ECO Solar Houses are content with their living situation. The houses were marketed as very innovative houses. This advertisement attracted the interest of people who were environmentally conscious. One resident commented: "I have continuously tracked the construction phase and I am very happy to have had the opportunity to buy this house" (ECOCELL, 2018). This implies that residents were closely involved in the development of the project and were happy to start living there. As a result, the user's perception towards circular IC is regarded to be positive. Another resident explained that he thought the house had a good price and performance ratio, which was a decisive factor for him to purchase the property. ECOCELL claims that the houses could be priced 20% below the regular local market prices (ECOCELL, n.d.). As such, it was learned that the ECO Solar Houses can be marketed at a lower price, encouraging people to invest in a novel technology.

Industry Developments

ECOCELL has learned that the ECO Solar Houses was successful as a proof of concept and that production could be carried out without causing any issues. However, the initiator explained that the development of the project took place on a small scale and for the technology to have a significant impact, production processes need to occur on an industrial scale (Iseli, personal communication, January 16, 2020). Thus, the initiator kept emphasizing the importance for ECOCELL to license the technology to a big industry player with more resources. Consequently, it was learned that a large production facility is required to start manufacturing a high volume of the panels. This is in line with the aim of merging the two current production facilities as a way to streamline processes, explained further in the next section. In turn, supply chain risks will be mitigated enabling a higher production volume.

As of now, the company wants to expand its operations internationally by licensing the building system in the US. To achieve this, it was learned that the system used for the ECO Solar Houses had to be altered. The founder and his team created a completely new system with different connections. The tapered roof panels used in the project were too complex for the new US building system. The design provided very limited flexibility, making it very difficult to work with. Thus, it was decided to create a simpler system without the special corners.

Social and Environmental Impact

One of the lessons from the ECO Solar Houses was that ECOCELL's technology had an impact on society. The initiator comments that most people are not aware of the strength you can reach with paper (see quote 4, Table 5.4). He believes that he has shown that composite material has a very high strength and is very much applicable for construction. Additionally, as ECOCELL's building system is cheaper than conventional construction, it can be used as a low-cost building material and offer new opportunities for social housing. The company believes that it can contribute to society by providing affordable housing.

The team of ECOCELL has learned that the ECO Solar Houses have a significant positive impact on the environment in terms of CO_2 emissions (see quote 5, Table 5.4). The cautious decision was made to use individual components instead of modules to obtain a higher capacity with transportation leading to environmental improvements. For the environmental impact assessment, the ECOCELL's team performed calculations to determine how much CO_2 emissions per square meter were saved using ECOCELL's technology during the raw material production phase. However, it is unclear if an LCA was performed to obtain the corresponding figures. In Table 5.3, this number is compared with the CO_2 emissions generated per square meter of the production of a brick wall and concrete ceiling. The founder reported that the ECOCELL technology binds CO_2 emissions, leading to a positive environmental impact of the panels. The board material, wood in this case, stores carbon dioxide from the air, reducing greenhouse gasses (ECOCELL, 2017). In fact, it leads to a reduction of 30 kilograms of CO_2 per square meter of wall, ceiling or roof construction. The company states that the emissions caused by harvesting, transportation and further processing of the wood have been taking into account as well (Iseli, 2018). For the ECO Solar Houses, ECOCELL calculated that in total 185 tons of CO_2 emissions were saved compared to traditional construction methods. Per house, this amounts to a savings of 46.25 tons CO_2 per building (ECOCELL, 2017).

Table 5.3. CO_2 emissions and savings of different materials in the raw material production. A plus sign means CO_2 is emitted. A minus sign equals CO_2 savings.

Material	*Brick wall*	*Concrete ceiling*	*ECOCELL wall/ ceiling*	*Brick wall substitution ECOCELL*	*Concrete ceiling substitution ECOCELL*
CO_2e per m^2 savings	+38 kg	+64 kg	-30 kg	-68 kg	-94 kg

Policy and Regulations

The involvement of the government before the completion of the project was regarded to be troublesome (see quote 6, Table 5.4). During construction of the ECO Solar Houses, the team of ECOCELL won the Greentech Award. Subsequently, the initiator was contacted by a private company from the Swiss government assuring them that they would give out a guarantee for the project. For this, ECOCELL had to provide a substantial amount of information and perform additional studies on the technology. In the end, the aforementioned company decided not to go into business with ECOCELL. Their reason was that too many companies were already involved. However, it resulted in a lot of wasted effort and money coming from ECOCELL's side. This forms a hinder in stimulating the adoption of circular IC, as companies involved in the niche are not motivated by the government to innovate further.

As part of the circular economy, using less energy during operation of the houses should also be considered. It was learned that as a producer of renewable energy, the Swiss government does not remunerate the excess electricity returned to the grid on the same basis as is paid for. The initiator believes that the interest for installing PV on will increase it if this is equalized through the implementation of a new fiscal incentive.

Second-order Learning

Problem Framing Shift

One event has been identified as a shift in problem framing. The initial design for the plots in St. Margrethen was drafted by a local architecture office. However, based on this particular design, the landowner could not sell his property to potential buyers. When ECOCELL was introduced to the project, it was decided to keep a similar design, making some slight adjustments and modifications in order to realize ECOCELL's building design. This example illustrates the company reframing the problem to accommodate the interpretive frame of the local architecture firm and landowner (ECOCELL, n.d.).

Problem Solving and Priorities Shift

Two events demonstrate a problem-solving shift taking place. The application of the adobe plaster was more challenging than anticipated. The workers experienced the plastering to be very challenging due to their lack of experience with the material. Likewise, the technique required large amount of water, which did not correspond to ECOCELL's dry construction method. To solve this solution, it was decided that it would be best for the construction workers to cover in the inside of the external walls with gypsum boards.

Furthermore, ECOCELL was in contact with a company that glued together OSB panels (Iseli, personal communication, January 16, 2020). Normally, ten separate boards were glued together to form one single product. This resulted in an immense strength yet made it also very heavy (see quote 7, Table 5.4). The parties discussed that when using the honeycomb for the middle part and thus replacing multiple OSB panels, the structure would become lighter while keeping its strength. Together, they searched for new solutions to solve this particular problem.

Joint-learning Shift

A shift in joint learning was not evidently present. For the building workers, it was the first time using this particular building system to construct the houses. This meant that it took longer to build the first house in contrast to the last house. The workers were not trained yet to assemble and connect the system. The initiator acknowledged this problem and accepted the fact that they needed more time to construct the houses. Ultimately, the construction workers became more experienced and learned together how to speed up the process of assembly (see quote 8, Table 5.4).

5.3.4. Expectations and Visions

The final Subchapter discusses the expectations and visions of the ECO Solar Houses. Based on the five-perspective framework, the different expectations are highlighted in **bold** (Schot & Geels, 2008). The Subchapter is concluded with a section on the visions, looking at the image, guidance and orientation characteristics.

Expectations

In the future, ECOCELL expects to have developed a special system for the total electric supply in the house. After the ECO Solar Houses were constructed, the company built duplex houses in Uttwil, which were covered completely with photovoltaic panels. Ultimately, the electricity generation of the PV's was equal to three times the total electricity demand of the houses (see quote 9, Table 5.4). As a producer, the architect commented that you are not rewarded for delivering excess energy to the grid. Thus, the initiator believes in terms **of technical specifications** that, similar to the ECO Solar Houses, the shell of a house should not be completely covered with PV panels but possibly only the façade (Iseli, personal communication, January 16, 2020). The architect predicts that the technology for batteries will advance and become cheaper. This complementary technology will reduce the operational energy demand of the houses and in turn, ensure less dependency on fossil energy sources. In addition, the initiator adds that aesthetics are key in adoption of the technology. For the second project, executed after the ECO Solar Houses, the PV panels were reviewed by the tenants as too 'technical'. In the future, simplified panels that are more visually appealing will be purchased and used for new building projects.

Furthermore, the founder pointed out that in order for ECOCELL's technology to grow within the niche, the manufacturing **processes** should take place on an industrial scale. The processes should be automated and transferred to one facility. The company also highlighted this as one of their goals for their future; to merge the two production factories in Sulgen and Sigmaringen in order to increase efficiency and productivity (Iseli, 2018).

There is some interest from the industry, particularly from big companies in the United States and Australia wanting to bring the technology to the **market**. The company has made a clever move of designing a new building system specifically for US design specifications to ensure wide adoption in the country. If this proves to be successful, the initiator claims that the system for the Swiss market will be modified to this standard as well (Iseli, personal communication, January 16, 2020). For a large adoption, the company expects that different production facilities have to be set up. He has calculated the capacity and **environmental impact** that possibly can be reduced by the use of such a facility. The performance of one individual plant would annually amount to the production of 125 x three-story buildings each with 600m2 of usable space with 450m2 of ECOCELL wall element and 1250m2 of ECOCELL ceiling element (Iseli, 2018). Based on the data represented in Table 5.3, it is expected that this capacity corresponds to a savings of 18,512 ton CO_2. Expressed differently, this number is similar to the annual emissions of 10,000 mid-sized cars.

It is expected that the **user's preference** for ECOCELL's technology will originate primarily from countries in Scandinavia. However, the type of users will remain the same as the ECO Solar Houses are specifically dedicated for housing purposes. The initiator reports that in Switzerland, the construction industry is accustomed to using bricks and concrete. In countries such as Norway and Sweden, the sector builds housing using a similar system with the same dimensions as in the United States (see quote 10, Table 5.4). The team of ECOCELL believes that the new US building system would be a good alternative to this group of users.

The team of ECOCELL foresees the impact of the building system on **society** to be high. It is reported that the technology used to construct the ECO Solar Houses could also be used for different applications, in particular disaster relief. The team clarifies this by referring to the situation of the bushfires occurring in Australia in 2020 (Iseli, personal communication, January 16, 2020). Many people have lost their homes and are in need of replacement of their houses. ECOCELL points out that the building system would be very applicable here due to its rapid assembly, use of a high quality material and protection against hurricanes or other extreme weather events. The company expects that by applying this circular IC method, it can lead to a positive societal impact. Moreover, the case study is used as a proof of concept, showcasing the success achieved with the technology, conceivably leading to increased attention for external parties to invest.

As of now, ECOCELL is waiting for approval regarding a request for a building permission in the European Union and Germany (Iseli, 2018). Because ECOCELL's technology is considered a novel composite material for the building industry, it demands a European Technical Assessment procedure (European Commission, n.d.). If the approval is accepted, it implies that ECOCELL can easily expand its business operations in Europe. It is expected that such a **regulation** will stimulate the development of new materials that can potentially be used in circular industrialized construction methods. In turn, more possibilities are created, enhancing the growth of the niche.

Visions

Vision Image

The vision has been verbalized through two metaphors. The first statement is expressed as 'LEGO for grown-ups' (ECOCELL, 2019). ECOCELL wanted to develop a fast building system based on individual standard components signifying the LEGO blocks (see quote 11, Table 5.4). The metaphor also implies that the system must not be complex signifying the use of LEGO for children. The ECO Solar Houses were assembled without specialist training for the construction workers. Likewise, LEGO pieces can be assembled and connected in many ways to construct different objectives. This is also highlighted through ECOCELL's design, providing a flexible design and multiple use of the individual 'blocks'.

The second metaphor is related to the lightweight composite panel technology: 'High-tech at low-cost". The founder of ECOCELL believes that they will *start a megatrend in environmentally friendly construction* transforming the current construction practices completely. It implies that ECOCELL regards their panel technology to be very promising for the building sector. ECOCELL stresses that it is their mission and ultimately their vision to produce their technology on a large-scale. Only then, can the construction method truly be regarded a good alternative and make an impact in the building industry. However, the circular economy aspect is not clearly evident in the metaphors.

Vision Guidance

The setting of a clear-shared goal was present during the development of the ECO Solar Houses. The houses were built as a first project to showcase ECOCELL's technology. The core actors were all aware of this strategy. There was never the intention within the team to build more ECO Solar Houses in St. Margrethen or the rest of Switzerland (Iseli, personal communication, January 16, 2020). However, the main goal had always been to sell the license to the industry and use the ECO Solar Houses as an example of a proof of concept (see quote 12, Table 5.4).

Leadership was evident during the ECO Solar Houses project as well. The founder of the panel technology, who is also the designer of the houses and coordinator of the project, created the vision. This is clearly marketed on the website of ECOCELL. He provided direction to the core stakeholders involved, defining the goal of the ECO Solar Houses. An alternative rule set is not directly present here. It can be seen that the initiator as an individual took on multiple roles in the building project as previously mentioned. This is regarded to be uncommon compared to a regular construction project where multiple stakeholders are involved.

Vision Orientation

The main direction the vision provided is in developing a successful project highlighting ECOCELL's technology (see quote 13, Table 5.4). In turn, this tangible example is used to attract the interest of investors and licensees. Moreover, the vision gave direction in reforming labor in the project largely (Iseli, personal communication, January 16, 2020). By standardizing a large part of the production process, labor-related costs are minimized, referring back to the metaphor of 'High-tech at low-cost". Inspiration was clearly present in this case study as well. The landowner was inspired by ECOCELL's technology prior to the construction of the ECO Solar Houses (see quote 14, Table 5.4). He believed in the initiator in realizing the vision and thus provided him the flexibility and time to develop the buildings. Some motivational influence can be described to the vision. The construction workers of the houses were excited to construct using the building system but had no experience. Throughout the project, they began to master the technique, building enthusiasm in the workplace (see quote 15, Table 5.4).

Table 5.4. Interview quotes related to the ECO Solar Houses.

#	Quote	Interviewee
1	"We worked together with the ETH, but everything took too long and maybe a bit too much. They worked too much on the computer, and in reality, nothing worked. So we had to make a decision to go faster and make it all on our own."	Initiator
2	"So for them [construction workers], it becomes more routine and therefore it speeds up the whole system."	Initiator
3	"And if you don't need to wall anymore ... then you can just take it away and use it for another wall. So for the whole system we always looked that we can use it multiple times. That's also something that we always have to look for."	Initiator
4	"Alone, if you fold paper, you cannot tear paper that's been folded more than seven times. And those are the strengths that you actually have in the material. But I think the average person isn't even aware of it."	Initiator
5	"The philosophy behind is that we actually want an industrial production. And we have a lot of environmental progress that we can actually solve with that system."	Initiator
6	"The government cost us more money than we hoped."	Initiator
7	"They have enormous strengths, but it is also very heavy. And with them we discussed that when they used the honeycomb, the structure will get lighter."	Initiator
8	"If it is something that you do for the first time, you often come across things that you hadn't thought of. And then the second one you really know, I can do better if I do it like that."	Initiator
9	"We showed that with the whole outside [of the houses in Uttwil] that we covered with photovoltaic we get about more than three times the energy that is needed. So in the future we will maybe only do the facade and no roof because we don't get anything back that from delivery the electricity."	Initiator
10	"We actually just invented ECOCELL in Switzerland and we also made the first house here. But we have to enter more in Scandinavian Market or the US market, because we actually don't need new carpentry here in Switzerland. "	Initiator
11	"We built with Lego stones you could say."	Initiator
12	"But we don't even want to do this because we want to sell actually the license to give it over to the industry. This [the ECO Solar Houses] was just to show how we build it, how we put the things together."	Initiator
13	"This is our main mission now: to give out license. Because we have shown that the whole thing works, and it doesn't make too much sense now to build the element by implementing a small factory. Now, this really needs a big adoption."	Initiator
14	"The owner of the land believed in the ECOCELL FAST-BUILDING-SYSTEM developed by Fredy Iseli."	Initiator
15	"Through the experience. You [the builders] try something and then you see: I can do it!"	Initiator

6. Cross-case Analysis

Chapter 6 continues the analysis by examining the emerging practices according to the similarities and differences across the case studies. Subchapter 6.1 summarizes the different characteristics and circular industrialized construction strategies for each case study. The consecutive three sections present the comparison for the three internal niche processes – network formation, learning and expectations, respectively. The Chapter is concluded in 6.5 addressing the third sub question "What practices and strategies can be observed from emerging circular industrialized construction case studies in Switzerland?". The findings will serve as input for the analysis of the potential for scaling up the niche in the next Chapter.

6.1. Understanding Circular IC

Based on the literature review in Chapter 2, different principles and their corresponding characteristics according to the case studies are analyzed. The three following tables (Table 6.1, 6.2 and 6.3) show the results for the UMAR unit, ICEhouse and ECO Solar Houses. For each individual principle, multiple characteristics can be selected.

Table 6.1. Circular strategies applied to the building layers (Brand, 1994) in the three case studies.

Principle	Characteristics	UMAR unit	ICEhouse	ECO Solar Houses
Building Layer	Stuff	☑	☑	☑
	Space plan	☑	☑	☐
	Services	☑	☐	☐
	Skin	☑	☑	☑
	Structure	☑	☑	☑
	Site	☑	☑	☐

Table 6.2. Level of reuse of recovered materials in the three case studies.

Principle	Characteristics	UMAR unit	ICEhouse	ECO Solar Houses
Degree of Reuse of Recovered Materials	Recycling of building materials	☑	☑	☐
	Reuse of building elements	☑	☑	☐
	Reuse of building components	☑	☐	☑
	Reuse of building modules	☑	☐	☐
	Reuse of entire building	☐	☑	☐

Table 6.3. Level of preassembly in the three case studies.

Principle	Characteristics	UMAR unit	ICEhouse	ECO Solar Houses
Degree of Preassembly	Component manufacturing & sub-assembly	☐	☐	☐
	Non-volumetric pre-assembly	☐	☑	☑
	Volumetric pre-assembly	☐	☐	☐
	Modular building	☑	☐	☐

Main similarities

The three cases have separated the stuff layer, defined as the furniture and movable objects placed in a building, is reusable and replaceable. Moreover, all the case studies demonstrate circularity and separation of the skin and structure building layer, such as circular insulation and surface skin materials as well as recyclable and lightweight structures. These layers have been mainly determined by architects, engineers and construction companies, responsibilities carried out by the initiators of the projects.

Regarding the degree of reuse of recovered materials, only the first two characteristics have been identified in the case studies – recycling of building materials and reuse of building elements or components. This entails that a lower degree of circularity and thus low economic and environmental value is more commonly visible. Both the ICEhouse and the ECO Solar Houses demonstrate non-volumetric pre-assembly. The former case adopted skeletal pre-assembly in the form of a structural frame whereas the latter made use of planar pre-assembly with the ECOCELL panels.

Main differences

The UMAR unit and the ICEhouse both separate the space plan and site building layer yet in different ways. The space plan of the UMAR unit is flexible due to the rotary wall that changes the floor plan of the living room and kitchen. The unit consist of 7 separate modules but each module can be taken out if necessary. For the ICEhouse, the separation of the solid internal fit-out including walls and floors is demonstrated through the integration of additional modules to increase the usable space available. Considering the site layer, the UMAR unit, which was placed with heavy-duty rails on a rails, can be moved in the event of the site having to be renewed. The surface area and environment surrounding the ICEhouse had to be carefully considered. Due to its location, the structure was made to be very lightweight, which influenced the design team to opt for certain materials. It can be easily disassembled without interfering with the site layer. Furthermore, the UMAR unit was the only project to separate the services layer, by altering the design of heating and cooling panels.

The ICEhouse is the only case that demonstrated maximum reuse of recovered materials by yearly assembly and disassembly. Additionally, the UMAR unit showed the highest level of pre-assembly, which could be an opportunity leading to improved control of construction and thus a higher CE potential as will be further discussed in Table 6.4.

Circular Strategies

Table 6.4 highlights the five circular strategies and subcategories identified in the three case studies. The subcategories are determined based on the literature review and the responses of the interviewees.

Table 6.4. Circular industrialized construction strategies in the three case studies.

	Sub-category	UMAR unit	ICEhouse	ECO Solar Houses
(1) Circular materials	*(a) Material selection (non-toxic/ recyclability/ reusability/ biodegradable/ lightweight)*	▪ Non-toxic fire retardant ▪ Untreated timber ▪ Coating lighting omitted ensuring recyclability ▪ Biodegradable insulation boards/ bound materials	▪ Reusability of entire building ▪ Recyclability of structural frame and cladding ▪ Lightweight building materials	▪ ECOCELL panels can be reused elsewhere ▪ Lightweight panels
	(b) Waste minimization	▪ Building off-site -> higher level of control and thus less waste generation	▪ Holes for joints integrated in design members	▪ Electrical wiring and pipes integrated in design panels ▪ Less water with dry plaster
	(c) Separation cycles	▪ No hybrid materials used	▪ Only technical nutrients	
	(d) Separation building layers	▪ All building layers separated	▪ All building layers, except service layer, separated	▪ Stuff, skin, structure layer are separated
	(e) Avoidance life cycle impacts			▪ Individual panels instead of modules -> higher

				carrying capacity -> less transport ▪ PV panels/ heat pump
(2) Product as a service	*(a) Ownership extension material*	▪ Carpets	▪ Carpets	
	(b) Ownership extension building	▪ Perform maintenance work and deconstruct after about five years		
(3) Product lifetime extension	*(a) Extend lifetime*	▪ Long-term solution as each element designed for disassembly ▪ Suppliers check for discoloration and deterioration of materials	▪ Considers deflection in design to address continuous disassembly	▪ Considers design for partial disassembly
	(b) Flexibility/ adaptability	▪ Tongue-and-groove connections ▪ Mechanical instead of chemical joints ▪ Rotary wall to alter living room space plan ▪ Modules placed on wheels	▪ Bolting of joints ▪ Extension or shortening of building in height, length and width by placing more or less modules	▪ Tongue-and-groove connections ▪ ECOCELL panels are multifunctional ▪ Multiple layers can be glued together for different purposes
	(c) Durable materials	▪ Timber modules	▪ Aluminum structural frame	▪ Mineral-coated honeycomb
(4) Sharing platforms	*(a) Maximize utilization*			
	(b) Industrial symbiosis			▪ Waste streams of paper industry
	(c) Co-creation	▪ Users participated to some extent by providing feedback regarding the application of products and materials		
(5) Resource recovery	*(a) Maximum reintroduction materials*	▪ Recycled insulation ▪ Bricks made from construction waste without using mortar	▪ Recycled plastic for landing deck	▪ Wastepaper for honeycomb structure
	(b) Material tracking	▪ Material cadaster - Madaster		
	(c) Standardization		▪ Aluminum modules	▪ ECOCELL panels
	(d) Mass customization		▪ Extend or shorten dimensions of structure with modules	▪ Alter dimensions of houses by adding or leaving out panels

(1) Circular materials

Both the ICEhouse and ECO Solar Houses considered the use of **lightweight materials** to construct the buildings. For the UMAR unit, specialized trucks were needed to lift the heavy modules into the building. The unit does showcase more material selection criteria including biodegradability, non-toxicity, reusability and recyclability as more materials were used here. Importantly, it should be noted that including more materials in a building will make it more challenging to recover each element. Despite the reusability of the ECOCELL panels, the components cannot be recycled due to its coating.

All practices demonstrate **waste minimization**. To illustrate, the design of the ECO Solar Houses incorporated cable canals in the panels and for the ICEhouse, holes were created in the members of the modules prior to on-site assembly. For the ECO Solar Houses, **separation of the biological and technical cycles** was not present. Biological nutrients (paper) and technical nutrients (cement) were mixed preventing the reintroduction of used materials in both cycles at the EOL phase. Likewise, the case study only demonstrated the separation of the stuff, structure and site. The other **building layers** are not disconnected from one another. For example, wiring and electrical cables (part of services) are placed inside the panels and thus the whole component must be replaced in an event of maintenance or repair. The ICEhouse and UMAR unit do not illustrate the **avoidance of life cycle impacts** - an area for further enhancements. On the contrary, the ECO Solar Houses dealt with the transportation stage by shipping smaller components and reducing the operation demand of the buildings by installing PV panels as a renewable partner for heat pumps.

(2) Product-as-a-service

The ECO Solar Houses did not apply any product-as-a-service strategies, leaving room for improvement. The other cases however do reveal **material property extension** by the use of carpets in the projects. Moreover, the UMAR unit was the only case study to demonstrate **ownership extension** of the whole building by planning to deconstruct the separate modules after a five-year term to use for other purposes.

(3) Product lifetime extension

For this strategy, the three practices contain many similarities. It was found that all case studies apply **lifetime extension principles** by designing for disassembly. The projects are considered **flexible** with respect to future alternations by using mechanical joints instead of chemical fixtures. The UMAR unit and ECO Solar Houses both applied tongue-and-groove connections to facilitate its disassembly. Acknowledging **adaptability** is key in the three practices, for example, by enabling changes in the space plan (UMAR unit), extending the main structure through the addition of modules (ICEhouse) or panels (ECO Solar Houses). Finally, different materials were selected that are **durable**, elongating the lifetime of the buildings.

(4) Sharing platforms

Interestingly, maximizing utilization by sharing products and materials was not found in the case studies. Even more so, none of the further characteristics of sharing platforms were detected in the ICEhouse, circular economy potential that could have been unlocked. **Industrial symbiosis** did play a role in the ECO Solar Houses by repurposing wastepaper as a building material. Furthermore, the UMAR unit revealed a collaboration between the initators and the end users of the building, **co-creating** solutions for issues encountered related to the use of the building.

(5) Resource recovery

Maximum reintroduction of materials was identified in all case studies. Conversely, the UMAR unit was the only project to make use of **material tracking**, a complementary technology for circular IC, particularly valuable at the EOL phase. Nevertheless, the ECO Solar Houses and the ICEhouse did apply **standardization methods** by designing elements with a standard dimension, a preferred strategy enabling easier recovery and greater potential to reuse somewhere else in a building. For the same two case studies, possible **mass customization** can be achieved in the future by high-volume production of personalized products. The two aforementioned elements, characterized as IC methods, reduce the uniqueness of material recovery and thus contribute toward resource recovery.

6.2. Network Formation

For niche creation, it is important to build broad stable social networks. This section provides in-depth insights into the composition and functioning of the different case study networks. First, the individual networks are highlighted showcasing the primary actors and their corresponding relationships, activities and resources. A comparison is presented revealing contrasts and resemblances between the structures. Secondly, the main similarities and differences between the three cases are identified and discussed.

Individual Case Study Networks

Figure 6.1 shows the networks of key actor groups in the (A) UMAR unit, (B) ICEhouse and the (C) ECO Solar Houses. What stands out in the diagram is that the first two networks consist of more relationships and dependencies between stakeholders compared to the ECO Solar Houses. This has to do with the fact that the latter is comprised of a smaller and less diverse network. Likewise, no framework agreement was drafted to formally establish the network and thus this relationship is missing in Figure 6.1C as well.

In all networks, the initiators contribute to the projects in a similar manner. Knowledge and ideas are translated into a tangible building by design, conceptualization and development. Moreover, a facilitating party is present in each structure and in both case studies A and C this actor supplies financial capital and flexibility. On the contrary, there is a separate client actor in project B who provides the aforementioned resources. Each client receives a different activity or resource from the initiators by participating in the project. In A, knowledge transfer and development coming from the initators were key. For case study B, the initiators transfer knowledge as well as the creation of space provision during the World Economic Forum. Finally, the initiators provided an innovative solution for the vacant property in case study C.

Regarding the suppliers of building and construction materials, it is evident in case A, that there is a separate group of parties delivering resources to the builders for further processing. In the B network, it is the client who supplies the builders with the cladding material – one of the four components of the building. However, in the final case C, the initiator is the one to directly provide its in-house developed technology to the builders.

Lastly, it can be concluded that in case studies A and B, the builders have an open mindset toward innovation and circular economy in construction and communicate that to the initators. In project C, the client is the party to be receptive to a new technology, enabling the success of the project. This open mindset is considered to be key in the development of circular IC in general.

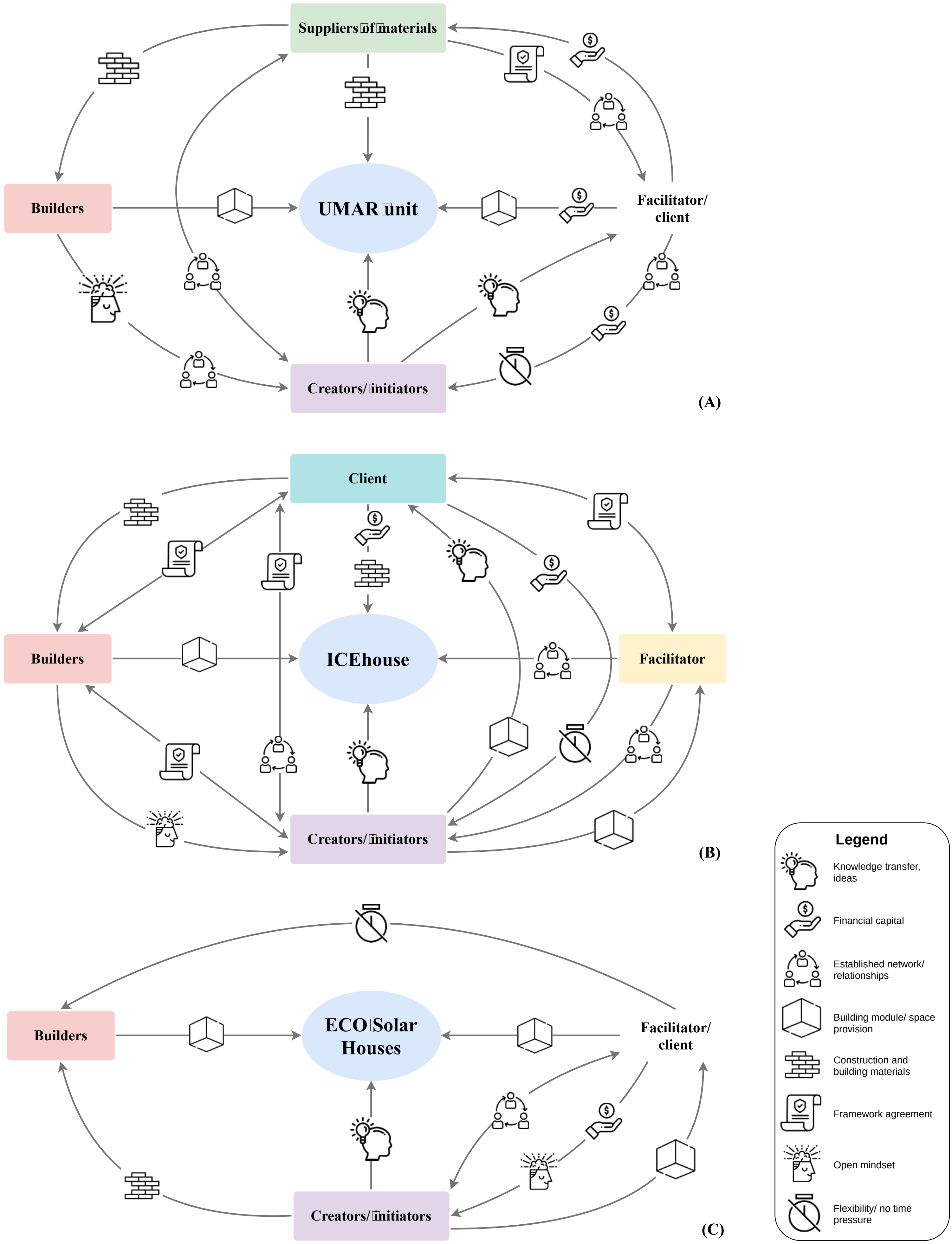

Figure 6.1. Simplified network of the (A) UMAR unit, (B) the ICEhouse and (C) the ECO Solar Houses (own illustration).

Table 6.5 presents in tabular form, the type of key stakeholder groups and corresponding number of parties involved according to the three networks based on the visuals in Figure 6.1. The UMAR unit comprises the most stakeholders, whereas the ECO Solar Houses the least. Both the UMAR unit and the ICEhouse consist of four different stakeholder groups in contrast to three types for the ECO Solar Houses, illustrating a more network.

Table 6.5. Number of stakeholders for different stakeholder groups according to Figure 6.1 for the three case studies.

Case study	Type of stakeholder group	Number of stakeholders
(A) UMAR unit	Creators	3
	Facilitator/ client	1
	Builders	6
	Suppliers	35
(B) ICEhouse	Creators	3
	Facilitator	1
	Client	1
	Builders	6
(C) ECO Solar Houses	Creators	2
	Facilitator/ client	1
	Builders	1

Table 6.6 illustrates the relationships and corresponding strength per case study. The strength varies between strong (+), moderate (0) or weak (-), depending on the intensity and involvement of a relationship. The ICEhouse records a high level (++) in terms of overall relationship strength; the UMAR unit achieves strong relationships strengths (+) as well. The ECO Solar Houses ranks average (0). A smaller network with less suppliers (B) can promote a more intense collaboration.

All case studies demonstrate a strong relationship between creators and facilitator/ client. This resonates with the nature of the circular IC niche – a facilitating party or client has a high stake in the project, providing the necessary financial and political means to increase alignment and thus these two parties hold strong ties. A weaker connection between the facilitator and builders was also revealed. The main goal of the facilitator was to support the creators directly leaving it up to the initators to select which building party to involve. Principally, the creators were, in contrast to the facilitators, all architects or designers by nature and had the know-how and expertise to advice the builders on how to carry out the plans. This illustrates that supply-chain integration, crucial to IC and CE, has not been completely achieved as involved actors were still working separately without communicating and sharing information.

Table 6.6. Type of relationships and level of strength (strong/ moderate/ weak) according to Figure 6.1 for the three case studies.

Case study	Relationship	Strength
(A) UMAR unit	Creators <-> Facilitator/ client	Strong
	Creators <-> Suppliers	Moderate
	Creators <-> Builders	Strong
	Facilitator/ client <-> Suppliers	Moderate
	Facilitator/ client <-> Builders	Weak
	Builders <-> Suppliers	Moderate
(B) ICEhouse	Creators <-> Facilitator	Strong
	Creators <-> Client	Strong
	Creators <-> Builders	Strong
	Facilitator <-> Client	Moderate
	Facilitator <-> Builders	Weak
	Builders <-> Client	Moderate
(C) ECO Solar Houses	Creators <-> Facilitator/ client	Strong
	Creators <-> Builders	Moderate
	Facilitator <-> Builders	Weak

Comparison of Network Formation

The main similarities and differences are summarized in Table 6.7 and analyzed according to two elements: network composition and network alignment.

Main similarities

Regarding **network composition**, all three case studies showcased minimal direct government involvement. This is related to the nature of a niche, for which there is no support available yet coming from this particular party. Moreover, the three case studies engaged with different research partners to develop innovations integrated in the projects. As mentioned before, all cases encompassed a facilitating party promoting and enabling support within the network. Furthermore, an interesting aspect observed is that the mission of the project was made clearly explicit by the initiators. In the UMAR unit and the ICEhouse, this drew the attention of other interested stakeholders. Finally, there was a party present in all three case studies that was open-minded toward the idea of implementing circular IC methods. This was found to be beneficial in supporting the conceptualization of the ideas of the initiators.

For **network alignment**, it was identified that all three cases reveal history between initiators and other important stakeholders. This demonstrates that prior (strong) relationships and familiarity with each other's way of working were essential for the establishment of the projects. It is apparent that cross-relations are present, leading to complexity in the networks. Regarding the type of communication and connectivity, the UMAR unit and the ICEhouse were organized through regular meetings on a more personal level, the former through face-to-face meetings whilst the latter through video conferencing as the team worked remotely.

Main differences

The **composition of the network** was different for each case study. There was diversity in the networks of the UMAR unit and the ICEhouse with stakeholders originating from different disciplines. However, the ICEhouse did consist of a smaller number of involved parties as revealed in Table 6.5. Furthermore, the client supplied each network with different resources revealing sponsorship as most important. The ICEhouse secured complete financial means from the client. In contrast, the ECO Solar Houses received a portion of the financial capital from this party but with additional investments coming from friends and family. Likewise, the client in the UMAR unit supplied only a part of the total budget. Suppliers of materials covered the remaining sponsorship.

Considering **network alignment**, the ECO Solar Houses differ greatly from the other two case studies. The network does not include a macro-actor nor do core stakeholders remain in the network after completion of the project. Furthermore, a framework agreement was not established here leading to a lower alignment of stakeholder activities and resources. Professionalism of the team was also not mentioned. The UMAR unit was the only case study to refer to trust as an improvement of the collaboration between the most important actors. The other projects do not consider this to be an essential requirement for facilitating the partnership. Finally, reasons for complexity in the network vary between the three cases. For the ICEhouse, the client had a different motivation for participating in the project in relation to the initators' mission, which could possibly lead to a conflict. For the UMAR unit, the strong partnership of two architecture companies with contradictory perspectives on designing 'sustainably' created an interesting collaboration. Ultimately, it enabled the creation of an innovative and advanced circular and prefabricated modular building. Thirdly, the investments made to develop the technology as part of the ECO Solar Houses were based on personal relationships instead of external business clients. This can be considered a less stable source of financing in the event of changes in such relationships.

Table 6.7. Comparison of network formation for the three case studies.

	Sub-category	UMAR unit	ICEhouse	ECO Solar Houses
Network composition	*Composition*	Diverse network with many stakeholders.	Diverse and small network.	Uniform and small network.
		Indirect governmental involvement through facilitator.	No governmental involvement.	Little governmental involvement.
		A number of research partners involved.	Client's in-house research.	Many research partners involved.
	Participating/ desired actors	Facilitating and connecting role of client.	Partially facilitating role of client. Commissioner also facilitating project.	Facilitating role of client.
	Essential activities	Initiators had clear mission for project – attracted other stakeholders.	Initiators had clear mission for project – attracted other stakeholders.	Initiator had clear mission for project.
		Suppliers of materials had open and circular mindset.	Smaller assembly firm more open toward innovation.	Client wanted to support innovative project.
	Resources supplied	Safety net provision through client supplying part of financial capital, network of partners and no time pressure conditions.	Client supplied full financial capital and provided room for experimentation.	Client provided room for experimentation and part of the financial budget.
		Suppliers of materials covered remaining costs.	No other income streams.	Majority of financial capital from family and friends.
Network alignment	*Stability*	Client is a macro-actor.	Client is a macro-actor.	Client is not a macro-actor.
		History between various suppliers and initiators.	History between initiators themselves and with facilitator and client.	History between client and initiator.
		Builders and initiators worked on later project together.	Initiators worked on later project together.	Stakeholders did not remain in network.
		Professionalism of team.	Professionalism of team.	Professionalism not mentioned.
	Complexity	Cross-relation of client acting as facilitator as well.	Cross-relation of client acting as facilitator as well.	Cross-relation of initiator acting as architect and founder of technology as well.
		Two different architectural firms working closely together.	Client has different motive to participate than initiators – clash between missions.	Investments based on personal relations.
	Type of collaboration	Partnership in place for collaboration of builders and facilitators.	Framework agreement between client, initiators and builders.	No type of framework agreement in place.
		Trust between core stakeholders mentioned.	Trust not mentioned as a requirement.	Trust not mentioned as a requirement.
	Type of communication	Through regular 'live' meetings.	More frequent meetings as date of launch gets closer.	Not identified.
	Type of connectivity	Connectivity improved with whole construction team always present during meetings.	Through virtual meetings instead of impersonal email communication.	Small team on-site to improve connectivity and speed up decision-making.

6.3 Learning

To facilitate the diffusion of circular industrialized construction methods, it is key to learn about the barriers of its development and how they may be overcome. This entails first-order learning, answering the question: are we doing things right? However, lack of second-order learning can lead to unsuccessful niche development. Thus, it is important to take the question 'are we doing the right things?' into consideration as well. Table 6.8 is subdivided into these two types or order learning and its corresponding sub-categories, highlighting the main similarities and contrasts across the case studies.

Main similarities

With respect to first-order learning, it was revealed that the three case studies learned about the first CE strategy (**technical**), namely circular materials. Overall, material selection and waste minimization were identified as the main elements. **Perceptions** about the UMAR unit and the ICEhouse were generally considered less positive. However, for the ECO Solar Houses the situation was more optimistic, presumably due to a higher environmental consciousness in its network. All three projects recognize the importance of streamlining **industry** processes to speed up and reduce costs of manufacturing. The ICEhouse and the UMAR unit mention 3D printing as a solution, whereas the merging of two production facilities into one location is considered important for scaling up the ECO Solar Houses. For **social and environmental impacts**, learning was evident in the latter case, bearing in mind the impact of transportation by opting for individual panels instead of large modular systems. Finally, the UMAR unit and the ECO Solar Houses mentioned that Swiss **governmental** support is desired, yet effective measures and connections with this party in the network are missing.

Similarities in second-order learning were less apparent. For **problem-solving**, it was observed that the presence of a multi-disciplinary team was beneficial for the development of the UMAR unit and the ICEhouse. By bringing together different disciplines, innovative new solutions were created – a process that was not identified in the ECO Solar Houses, seemingly as a result of a uniform network.

Main differences

In term of first-order learning, each case study comprises different **users**, yet the UMAR unit and the ECO Solar Houses both include tenants because the buildings serve as living space. There is no possibility to use the current ICEhouse for living purposes and thus it is only available temporarily as a meeting venue during the World Economic Forum.

As part of second-order learning, **problem-framing** appeared to be different for each project. For the UMAR unit, it was learned to bring together the concept of prefabrication and the application of reused building materials through the collaboration of two individual architectural firms learning to extend the scope. For the ICEhouse, a few stakeholders broadened their frame to accommodate the initators' primary goal with the project. As the goal was made very explicit from the start, problem-framing occurred to a lesser extent than for the UMAR unit. For the third case study, the network was not motivated to engage in problem-solving as the frame was already determined. **Joint-learning** surely took place in the UMAR unit. By involving all stakeholders in the construction team from an earlier stage onward, actors started to share the initiators' problem definitions.

Table 6.8. Comparison of learning processes for the three case studies.

	Sub-category	UMAR unit	ICEhouse	ECO Solar Houses
First-order	*Technical*[1]	▪ 1a ▪ 3a	▪ 1b ▪ 3a	▪ 1a ▪ 1b
	Market and Users	▪ Negative perception: ○ Aesthetics essential ○ Unawareness amongst building professionals ▪ Users: tenants, tour visitors and NEST partners	▪ High risk perception – smaller firms more willing to participate ▪ Users: invitees of WEF	▪ Positive perception – people involved were environmentally conscious ▪ Users: tenants
	Industry	▪ Streamline processes by 3D printing building elements to reduce time and costs	▪ Cast or 3D print elements to speed up manufacturing process	▪ Merging of two production facilities to streamline manufacturing processes

[1] Figures in sub-category 'Technical' refer to the circular strategies and sub-categories presented in Table 6.4.

	Societal and Environmental	▪ Environmental impact transport of prefab modules high	▪ Manufacturing outside Switzerland - increases environmental impact of transportation	▪ Components instead of modules increases carrying capacity -> less transport -> less environmental impact
	Policy and Regulations	▪ Swiss government should supply ‘safety nets’ ▪ VAT reduction for recycled materials	▪ No learning identified	▪ Swiss government needs to introduce stimulating measures instead of hindering circular IC
Second-order	*Problem-framing*	▪ Part of core team learned to extend scope by applying reused material in prefabrication	▪ Some stakeholders learned to broaden their frame slightly – direction was already somewhat set	▪ Stakeholders not stimulated to broaden their frame as direction was already clearly set
	Problem-solving	▪ Multidisciplinary design team to develop innovative solutions	▪ Multidisciplinary team: o Different disciplines to develop systems solutions o Stakeholders learned to look in other ways of applying their products	▪ No multidisciplinary team
	Joint-learning	▪ Involve stakeholders early on to establish circular mindset	▪ Circular economy aspect was integral in project – stakeholders involved were already aware of this	▪ Did not take place – no fundamental norms or cognitive frames changed

6.4 Expectations

Expectations and visions are of paramount importance for the development of circular IC, giving grounds for stakeholders to collaborate, investing money and time into projects. The Subchapter provides an analysis on the main similarities and differences of expectations (see Table 6.9) and the three elements of visions (see Table 6.10) for the cases studies.

Expectations

Main similarities

It is expected for the UMAR unit and ICEhouse that the **users** will be different in the future compared to the current situation. For the former, the multiple modules can be used for different purposes such as office space. For the latter, there is a possibility that the structure is applied for refugee housing elsewhere. All three case studies reveal a similar pattern for **social** impact. Dissipating knowledge and information about the projects and the circular IC niche is of paramount importance. Likewise, the ICEhouse and the ECO Solar Houses are expected to be employed as a solution for emergency relief. For expectations in terms of **policy and regulations**, the UMAR unit and the ECO Solar Houses believe that once certifications and standards are developed for novel building materials, market acceptance is gained quickly which in turn boosts the niche.

Main differences

Regarding the **technical** aspect, each case study presents a different outlook. For the UMAR unit, it is expected on a more general level that the availability of a comprehensive database of (circular) construction materials will improve. In contrast, it was identified that expectations for the other cases were more focused on the projects themselves – 3D printing of the ICEhouse structural frame to speed up production and an improved renewable power system fir the ECO Solar Houses. The cases believe that different target groups will be identified. The UMAR unit, presumably due Empa’s ties with the Swiss Federation, will focus on Switzerland, whereas the Swiss **market** is not of importance for the ICEhouse and the ECO Solar Houses. The expectations considering the **industry** are not alike, yet all practices believe that changes characterized by industrialized construction principles must take place – standardization, increased pre-assembly flexibility and mass production in the UMAR unit, the ICEhouse and the ECO Solar Houses respectively.

Table 6.9. Comparison of the expectations for the three case studies.

	Sub-category	UMAR unit	ICEhouse	ECO Solar Houses
Expectations	*Technical*	▪ Better accessibility database construction materials	▪ 3D printing ▪ Use of locally sourced materials	▪ Residential decentralized power system
	Market and Users	▪ Focus on Switzerland ▪ Users do not have to remain the same -> modules can be used elsewhere	▪ Not primarily focused on Switzerland ▪ Users might not remain the same -> refugee housing	▪ No focus on Switzerland but primarily US ▪ Users will remain the same
	Industry	▪ Increased standardization	▪ Increased flexibility in pre-assembly ease of transport	▪ Increase mass production ▪ Increase automation
	Societal and Environmental	▪ Information point – sharing knowledge and insights regarding circular IC	▪ Use as platform to communicate circular IC ▪ Use as refugee housing	▪ Proof of concept for future projects ▪ Use as disaster relief
	Policy and Regulations	▪ Building norms altered to allow use of novel construction materials	▪ No expectations identified	▪ Stimulate development of novel building materials

Visions

Main similarities

All case studies used two **metaphors** to express their visions for the projects. Interestingly, the statement 'temporary material storage' (UMAR unit) and 'like a cherry blossom: it comes and it goes' (ICEhouse) are even related to each other. Both convey the message that a building is not built to last endlessly but its elements are: they can be deconstructed without loss of value. In contrast, for the ECO Solar Houses, the circular economy aspect is not clearly portrayed through the metaphors.

The three projects reveal the presence of **shared goals**, albeit it was evident that for the UMAR unit collaborating actors were clearly guided by the vision. In the initial phase of development, it is of paramount importance that **leadership** is present as leaders can raise ambitions for the project. Here, the architects predominately started with creating the vision. However, for the UMAR unit the facilitating party co-developed with the architects. The most striking result regarding the establishment of **new rule sets**, was that for the ICEhouse and the UMAR unit both a new perspective of ownership of building material was developed - linked to the second circular strategies product-as-a-service. Likewise, new rule sets are closely related to second-order learning, in particular collective learning, by jointly changing perspectives. For the ECO Solar Houses, this contradiction if clearly visible. Table 6.6 reveals that joint-learning did not take place here and thus the creation of an alternative rule set is not present.

Motivation was identified in all cases. For the ICEhouse and UMAR unit, professionalism was considered key to the success story and therefore refrained the team from having conflicting views. Enthusiasm was mentioned by the ECO Solar Houses and the UMAR unit as well, creating an environment in which members of the team felt that they wanted to be part of the design. Finally, **direction** was observed in all cases. For the UMAR unit, the decision to build with prefabricated modules enabled the possibility to easily store the materials, reflecting the first metaphor. The metaphor 'Like a cherry blossom: it comes and it goes' directed the idea of employing the ICEhouse as emergency shelter, whereas 'High-tech at low-cost' gave direction in wanting to reform labor in construction.

Main differences

Surprisingly, only a few differences between the visions were identified. The ECO Solar Houses did not make the vision **explicit**, whereas the UMAR unit and ICEhouse did, albeit through different ways. Regarding **inspiration**, the three cases show different degrees and development. For the UMAR unit, stakeholders were gradually inspired because of a slow recruitment process of the team. Not all actors recognized the opportunity of circular IC from the start, but this changed through increased collaboration. For the ICEhouse, stakeholders were encouraged right from the start and thus inspiration did not increase over time. The same accounts for the ECO Solar Houses.

Table 6.10. Comparison of functioning of the vision concept for the three case studies.

	Sub-category	UMAR unit	ICEhouse	ECO Solar Houses
Image	*Metaphors*	▪ Function as materials laboratory ▪ Temporary material storage	▪ Designed for next use ▪ Like a cherry blossom: it comes and it goes	▪ LEGO for grown-ups ▪ High-tech at low-cost
	Explicitness	▪ Via book published on waste building materials	▪ Via Cradle to Cradle design framework	▪ Not made explicit (in words).
Guidance	*Shared goals*	▪ Presence of shared goals	▪ Goals were mostly shared	▪ Presence of a shared goal
	Leadership	▪ Leadership of architects and facilitator	▪ Leadership of Cradle to Cradle founder/ architect	▪ Leadership of architect/ founder ECOCELL
	New rule set	▪ New perspective of ownership of building materials	▪ New perspective of ownership of building materials	▪ Not clearly present
Orientation	*Motivation*	▪ Enthusiastic, dedicated and professional team	▪ Professionalism amongst team and high level of connectivity	▪ Enthusiasm amongst construction workers
	Inspiration	▪ Stakeholders were gradually inspired	▪ Stakeholders inspired by Cradle to Cradle founder at start of project	▪ Stakeholders were inspired at start of project
	Direction	▪ Presence of direction	▪ Presence of direction	▪ Presence of direction

6.5 Conclusion and Reflections

This Chapter provided the analysis of the cross-case comparison of the three case studies according to circular IC characteristics and the three internal niche processes. A conclusion is given, answering the third research sub question: What practices and strategies can be observed from emerging circular industrialized construction case studies in Switzerland?

Circular IC indicators

⇒ To maximize the circularity potential of an industrialized construction project, building layers should to be separated. Moreover, for a building containing a lot of different materials and components, a higher degree of pre-assembly is required to increase control of construction and the possibility of reusing recovered materials. In any event, the five circular strategies should be harnessed and work together to create the greatest circular impact.

⇒ The strategies circular materials and product lifetime extension are complementary and most applicable: prolonging the lifespan of a material implies that a material must be circular, thus reusable or recyclable.

- **Circular materials**: (1) More materials incorporated in a building project means more material selection characteristics identified. (2) The impacts of the complete lifecycle must be considered, including transportation.
- **Product lifetime extension**: (1) The use of tongue-and-groove connections enabled design for disassembly. (2) Consider full recyclability of reusability in

case technical and biological cycles are not separated. This is linked to the circular materials strategy.

⇒ The strategies product-as-a-service and sharing platforms are less apparent, showing room for improvement. For both, actors must work closely together and share risks and are presumably less willing to do so.
  - **Product-as-a-service**: (1) The use of carpets (material ownership). For a complete building, this is more complicated as different actors and types of ownerships are involved.
  - **Sharing platforms**: (1) Different industries should work jointly to discover opportunities for industrial symbiosis. This is not common in the construction sector. (2) To co-create, various stakeholders in the value chain must collaborate to design solutions related to the use of a building. This can be achieved by involving users in the design or use process.

⇒ The strategy resource recovery is partly visible. In order to support the possibility for recovery, the strategy is dependent on the selection of (circular) materials.
  - **Resource recovery**: (1) Material tracking is an important technology for reclaiming value of resources but not widely used. (2) Standardization is preferred enabling easier recovery and possibilities for reuse elsewhere within the same building. (3) Mass customization has not been applied as projects are individual small-scale buildings. However, by adapting to future requirements by standardizing production processes and manufacturing on a large-scale, this will become possible.

Network formation

⇒ A more diverse, not necessarily larger, network is required to create a multidisciplinary team and the existence of more learning processes and systems solutions.

⇒ Governmental involvement through policy support or funding is limited for the case studies because there is no applicable framework in place yet. To stimulate the development of more circular IC projects, supportive measures and financial incentives (e.g. VAT reductions) are required.

⇒ A facilitating party providing a network of relevant stakeholders, financial capital and not imposing any time restrictions is a key success factor in all case studies.

⇒ Initators explicitly sharing their mission for the project attracted stakeholders to collaborate.

⇒ The presence of a macro-actor helps in improving the network alignment by creating a professional work environment with more frequent meetings and closer collaboration.

⇒ Network alignment is increased when core stakeholders share history with other stakeholders, either through personal contacts or as former colleagues.

⇒ A lack of formal agreement results in lower alignment of the network and reduced possibility for core actors to stay together after completion of the project.

Learning

⇒ First-order learning is more clearly identified than second-order learning as it demands less time and effort amongst stakeholders and is easier to detect through interviews.

⇒ First-order:
  - There is a less positive perception about the circular IC niche. Creating awareness through the establishment of more projects can help.

  - Industry processes have to be optimized by streamlining processes, e.g. 3D printing of building elements.
  - Environmental impact of transportation has not been fully recognized. This is linked with the strategy circular materials (avoidance lifecycle impact).
  - Governmental support is needed to stimulate development as no supporting measures are currently available, relating to network formation as well.

⇒ Second-order:
  - It is important to learn to broaden the scope of the project combining the concepts of CE in the built environment and industrialized construction.
  - A multidisciplinary team is necessary for 'thinking outside the box' to develop new solutions. This learning process in linked to network formation.
  - Collective learning is not clearly evident. However, the importance of involving stakeholders early in the process of project development was shown. It leads to a collective open and circular mindset, which is an essential activity in a network, linking back to network formation.

Expectations

⇒ Receiving indirect governmental support influences the project's specific market purposes in terms of location, e.g. specifically for the Swiss market.
⇒ Increasing the applications of a building project, e.g. refugee housing, can attract the interest over external parties.
⇒ Improvements of IC methods are required, such as standardization and mass production to speed up (large-scale) manufacturing.
⇒ Circular IC projects will function as information point to dissipate knowledge about the project and help the establishment of new projects.
⇒ Building norms need to be altered to include novel circular building materials.

Visions

⇒ Through metaphors, the importance for constructing a building that can be deconstructed again without loss of value is emphasized. Relevant frameworks make a metaphor explicit and provide stakeholders direction about the ultimate goal of the project.
⇒ Leadership is mainly through the architect(s) of the projects, presumably because they have great influence in design of the building and as such in selecting the materials and methods of construction.
⇒ If no new rule sets have been established, a lack of higher-order learning, in particular joint-learning, is determined. Thus, the vision is related to learning.
⇒ Motivation and inspiration contribute to development of the vision.
⇒ By expressing the vision through metaphors, a presence of direction amongst stakeholders is created.

7. Multi-level Perspective Analysis and Scaling Up Circular IC

The previous Chapter evaluated the socio-technical niche level. In the first part of Chapter 7, the analysis of the socio-technical levels continues by studying the socio-technical landscape and regime levels in Subchapter 7.1 and Subchapter 7.2, respectively. Changes that might not directly have an impact on circular IC in Switzerland but could potentially play a role in the landscape or regime are presented in Appendix G. The PESTEL framework is used to categorize all identified developments (highlighted in bold): **P**olitical, **E**conomic, **S**ocial, **T**echnological, **E**nvironmental and **L**egislative. A summary of the socio-technical transition is presented in 7.3. In the second part of this Chapter, additional enablers and barriers that have not been mentioned before are presented (7.4). Subsequently, the pathway for scaling up circular IC growth on different terms are studied, answering the fourth sub question: "How can the outcomes of the practices in circular industrialized construction be scaled up in Switzerland?" (7.5).

7.1. Socio-technical Landscape Analysis

The landscape level includes the developments occurring at the macro-level that in turn (de)stabilize the regime (A. Smith et al., 2010). Here, the landscape is defined as the national landscape of Switzerland. The discussed developments are characterized into one of the three macro-level factors: slowly changing factors, long-term changes or rapid external changes.

Since 2008, a *CO_2 tax* (CHF 96 per ton of CO_2) has been levied as an **political** instrument for achieving Switzerland's CO_2 emissions targets (Hebel, personal communication, December 4, 2019). This measure is characterized as a long-term change. A part of the revenue has been used to promote investments in energy-efficient construction and building technologies, yet such investments specifically supporting circular economy technologies still lacks (Interviewee 2, December 12, 2019). An increasing CO_2 tax in the future will however enforce construction companies to select materials with a low CO_2 impact, shifting toward sustainable construction materials.

Another **political** factor that does not change or only changes slowly is the limited involvement of the Swiss Federal Council. The economy is *driven by the industry* rather than by the government (Interviewee 4, December 19, 2019). From the moment that the industry starts to praise a technology that is potentially interesting, the government will pursue in supporting this certain innovation. This entails that the circular IC cannot be instantaneously reliant on the Federal Council to stimulate its growth through incentives or fiscal policies.

There is a growing concern about the climate crisis in Switzerland, defined as a **social** long-term change. Three interviewees explained that the '*Greta Thunberg effect*' is the main driving force. More awareness is created amongst society and people are beginning to understand that resources are finite (Interviewee 4, December 19, 2019). In response, the Swiss Confederation has set out an "Education and Communication Climate Program" to encourage inclusion of the issue of climate protection in trainings and by disseminating knowledge and advice amongst municipalities and cities (Swiss Federal Council, 2018). In turn, it helps change processes in social behavior of society leading to more acceptance amongst circular IC.

The *raw material consumption* in Switzerland, with an average of 14 tons per capita, is considered relatively high compared to other European countries (Swiss Federal Council, 2018). Switzerland is a wealthy country and has not been able to decouple GDP growth from its consumption rate completely, in other words, achieve resource decoupling. From 2000 to 2015, Switzerland experienced a total growth of material consumption of 7% in absolute terms due to an increasing population. This long-term **environmental** development implies that measures taken to strive for material efficiency have not been effective. By applying circular industrialized construction methods, it is assumed that the dependency on materials can be lowered drastically.

7.2. Socio-technical Regime Analysis

The region dimensions analyzed include policy regulations, research programs dedicated to further research in this field, industry players focusing on CE or sustainability in the Swiss construction sector and market's perceptions.

7.2.1. Public Policy

Switzerland has a clear policy for the output of construction waste, yet lacks a regulatory **legal** framework in terms of *building material input* (Interviewee 3, December 20, 2019). The Ordinance on Waste Avoidance and Disposal targets recycling of secondary raw materials from waste with the aim to recover secondary raw material to the fullest extent possible for the manufacturing of construction materials (Ordinance on the Avoidance and the Disposal of Waste, 2016). However, the Waste Ordinance does not impose specific standards for the recovery of waste. There is a great number of associations with diverging interest and together with a direct democracy structure where any party decides on policy, the development of such standards is hindered (Interviewee 2, December 12, 2019). For now, niche practices are obliged to consider their waste streams but do not have to take the use of circular products from the start into account. To facilitate circular IC growth, it is essential that an appropriate regulatory environment in place to impose measure on the input of building materials.

The City Council of Zurich (**political**) plays a pioneering role in ambitious goals for sustainable *public procurement*. The Council has set a minimum of 40% recycling content for the concrete used in the construction and renovation of public buildings and housing (Heisel & Hebel, personal communication, December 4, 2019). The City Council is a very large building stockowner, investing annually 400 million Francs in their buildings (Interviewee 2, December 12, 2019). It is considered a very safe investment, investing their stakes into their own housing projects while simultaneously controlling the rents to a certain extent. Thus, public procurement is an important driver to facilitate change in the conservative construction industry. However, as each Cantonal parliament develops its own regulatory framework, the transition to green purchasing will evolve very slowly (Interviewee 2, December 12, 2019).

From 2020 onwards, the new EU **legal** *standards for construction products* will be amended. The European Commission is urged to incorporate the circularity aspect of construction products as part of the Construction Products Regulations revision (Council of the European Union, 2019). Such measures include the integration of circularity principles, life-cycle thinking and modular design. A few measures applicable to circular IC are listed below:

- ⇒ Clarification of the Waste Framework Direction including end-of-waste criteria regarding reusable construction productions and material recovered from C&D waste,
- ⇒ Possibilities to facilitate wider adoption of modular structural elements and modular construction products,
- ⇒ Digitalization as a tool to facilitate the circular economy in construction.

More importantly, Switzerland has formed a group of experts that will be collaborating on this issue together with the EU (Interviewee 4, December 19, 2019). This could potentially have a large impact on the construction industry and the growth of circular IC in Switzerland, as the country will be aligning its policy with the European Union.

7.2.2. Science

From a **technological** aspect, the Swiss government invests a substantial amount of money into research (Interviewee 2, December 12, 2019). The National Research Program (NRP) 73 conducts research with reference to the circular economy in the built environment (Swiss National Science Foundation, 2020). Within this Program, there are different projects. The most applicable to the thesis topic are mentioned below:

⇒ **Towards A Sustainable Circular Economy (TACLE)** (Interviewee 1, December 5, 2019). Here, a holistic approach is taken on how to manage the transition from a linear to a CE by combining a resource perspective with a socioeconomic perspective. It is unclear if this involves the construction industry value chain.

⇒ **Co-Evolution of Business Strategies in Material and Construction Industries and Public Policies** (National Research Programme, n.d.). The aim is to develop new business models and draw up recommendations for political leaders and administration for developing measures and instruments for a circular economy in the construction industry as well as the promotion of resource efficiency of construction minerals.

⇒ **Shrinking Housing's Environmental Footprint (SHEF)** (National Research Programme, n.d.). The project examines measures for improving resource efficiency in housing considering the construction, use and renovation phases of residential buildings.

The aforementioned projects have recently started, emphasizing just how novel this topic truly is. Upon completion, this research can facilitate in removing barriers for circular IC whereby new measures, technologies and business models can be developed.

7.2.3. Industry Structure/ Infrastructure Developments

The following developments are categorized as **technological** elements. Multiple External Actors mentioned the *Madaster* platform as a promising player in the construction industry (Heisel & Hebel, personal communication, December 4, 2019; Interviewees 5, January 16, 2020). Madaster acts as a library and generator for material passports and through data transparency, the platform can contribute to CE in the built environment (Interviewee 6, January 24, 2020). Madaster offers a Circular Indicator and Financial value to enable a perspective on the value of material built in real estate. Design using different sources can be compared driving lifetime extension, reuse capability and value creation. As a result, it allows stakeholders to make well-informed decisions about material choice, construction techniques and planning for renovation and deconstruction. For circular industrialized construction practices, this platform is in particular very beneficial for enabling the integration of CE strategies that can be achieved with the use of IC methods (e.g. design for disassembly).

Losinger Marazzi is a prominent player in the Swiss construction industry experimenting with supply chain integration to improve the resource efficiency and environmental impact of their projects. By creating *guidelines for the standards* used with respect to construction materials, the firm hopes to resolve any issues from the start of the project (Interviewees 5, January 16, 2020). To illustrate, an architect might choose to use 16 cm wooden element, whereas the Swiss industry only delivers 12 cm wooden components and as such, the wood had to be imported from abroad leading to an unnecessary environmental impact of transportation. With standardization, achieved through IC, problems during the design phase can be detected earlier and altered in the sketch. Likewise, having standard dimensions contributes to adaptability – important for the circular economy.

Over the past two years, the use of BIM has been shaping the construction industry. The Swiss Federal Railway company (SBB) is one of the largest Swiss portfolio owners. The company decided to make *BIM mandatory* for its new infrastructure projects (Interviewee 4, December 19, 2019). Other big public and private owners have agreed to move towards SBB's strategy as well. As such, BIM will be mandatory for new building projects from 2021 onwards. In 2025, it is expected that BIM will be implemented in the whole infrastructure of Switzerland. As of now, BIM has not been adopted for circular motives yet. However, the collaboration tool has great potential to support CE due to its capability to accumulate lifecycle information about a building, the status and quality of building materials to identify recoverable elements. Moreover, a BIM model can be used as input in the Madaster platform to retrieve all information about a building and perform calculations about its circularity potential.

Finally, there are several *industrialized construction companies* offering *sustainable IC solutions*, such as Erne and Renggli. The firms bring together all process steps by prefabricating modules entirely using timber. Hence, they deliver a sustainable energy and material conscious system and remain in complete control of the system. Even though it is a step in the right direction, it is important that the entire life cycle is considered, as now the aforementioned companies are not responsible at the EOL phase of a building. By adopting a product-service systems approach, the modular systems can be leased and returned back, enabling the reuse of materials.

7.2.4. Market and User Preference

The Greta Thunberg Effect has enabled a shift in market force. New tenants start to consider the environmentally sustainable performance of a building to be important (Interviewee 2, December 12, 2019). This is translated in the increased demand for Ecolabels such as Minergie ECO (Appendix B). The last five to ten years, big investors have been investing in sustainable buildings as a means to provide the highest value and best environment for people. However, since recently, other market sectors including private renters, are *interested* in the *construction of sustainable circular buildings*. Companies renting office spaces are becoming more aware of their impact requesting environmentally friendly options, which influences decision-making. Investors are recognizing this **social** development and have started charging higher rents for such buildings. In turns, this drives CE in the built environment and possibly creates a new market for circular IC.

7.3. Summary Multi-level Perspective

The appearance of circular industrialized construction can be assigned to the numerous changes taking place on the socio-technical landscape and regime level (see Figure 7.1). Ultimately, the niche will follow a *transformation path* (F. W. Geels & Schot, 2007). In this pathway, there are no large nor sudden landscape changes but moderate landscape pressure is exerted. Niche-innovations cannot take full advantage of this situation yet because they have not sufficiently developed. Concurrently, pressure from the macro environment will not change the regime actors' activities and practices at once. New regimes emerge from old regimes through cumulative improvement and reconstruction. Construction industry regime actors will survive by adding circular IC to the architecture of the regime.

Zooming in on the landscape level developments, environmental taxation such as a CO2 levy, puts pressure on the construction industry to lower its environmental impact. Moreover, raising awareness on climate change and its risks as well as the material consumption that continues to increase play an important role in destabilizing the regime.

On different dimensions, various processes occur that influence the stability in the meso-level. Although the current Swiss construction regime is characterized by slow adoption of innovation, public procurement with ambitious goals in terms of input and output flows could speed up this process. The revision of construction standards could potentially have a large impact on the regime provided that Switzerland continues its collaboration with the European Union. NRP research can lead to the development of new instruments and technologies complementary to circular IC. Finally, increased documentation of materials and their interconnectivity between components in buildings is essential for circular IC. The use of Madaster or enforcing the use BIM in new large construction projects are examples of such approaches. All in all, the future for circular industrialized construction is considered to be positive due to the aforementioned developments taking place.

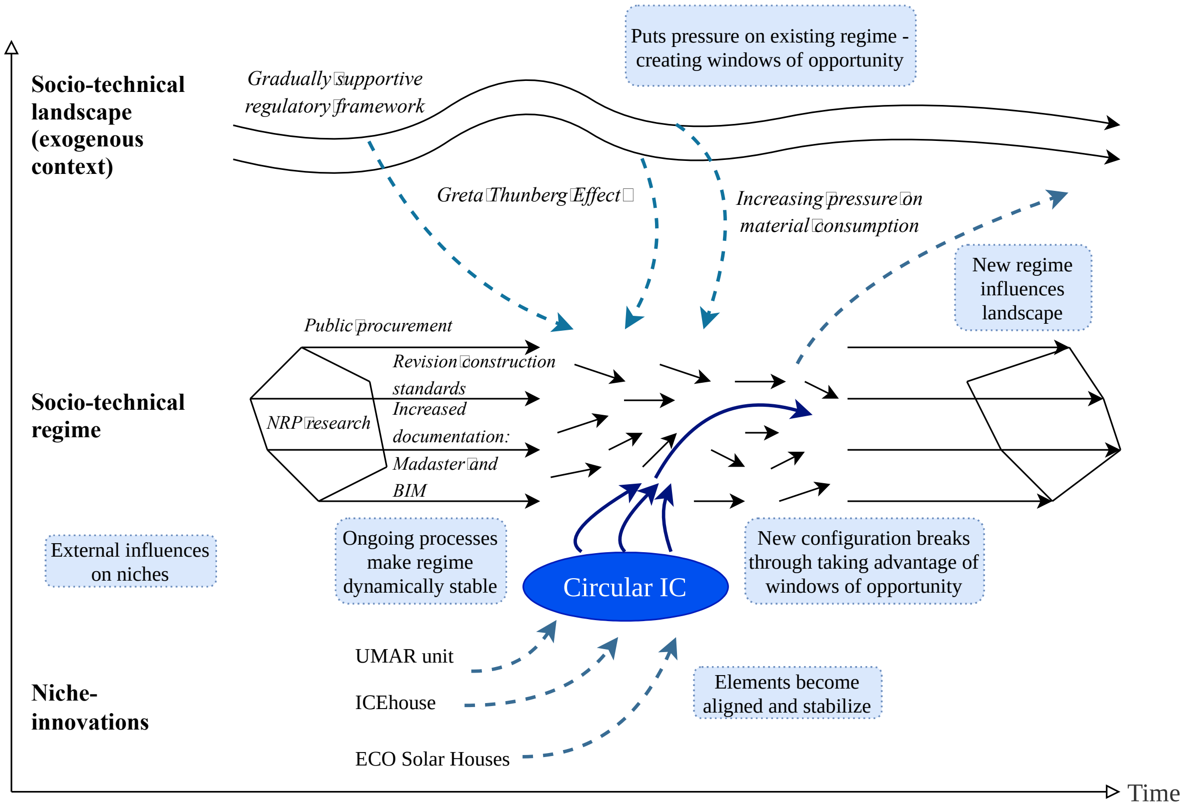

Figure 7.1. Multi-level Perspective on circular industrialized construction in Switzerland. Adapted from Geels & Schot (2007).

7.4. Additional Enablers and Barriers

Both Case Study and External Actors were asked about the broader implications for circular IC growth. Additional enablers and barriers that have not been mentioned as part of the SNM and MLP analysis have been identified. An enabler is defined as a factor that could facilitate the development of the niche, whereas a barrier can hinder such development. The elements are categorized according to recurring themes across the different interviews. The list is presented in Table 7.1.

Table 7.1. Additional enablers and barriers for circular industrialized construction in Switzerland.

Category	Enabler	Barriers
Technical	▪ Leasing of complete building modules and components ▪ Retraining architects and engineers	▪ Storage issues for used or recycled building materials ▪ Lack of availability material bank or database
Market	▪ Establishment of more circular IC demonstrators ▪ Building labels include CE and IC	▪ Silo-thinking business models ▪ Smaller companies do not have resources to employ tracking tools
Financial/ Economic	▪ Lower labor costs ▪ Residual value of building ▪ Green bonds	▪ Construction industry driven by investors ▪ No warranty on reclaimed building materials

Technical

A technical enabler to adopt the product as a service business model can be for IC companies to lease building modules and components to users (Interviewee 4, 2019). At the EOL phase, the module can return back to the corresponding firm and be disassembled in order to reuse elsewhere. Moreover, it was mentioned during five interviews that architects and engineers need to be retrained to become aware of the possibilities of CE strategies in industrialized construction by offering courses focused on applying CE in IC.

Storage problems for used or recycled building materials has been identified as a barrier. The construction company Losinger Marazzi is making efforts to reuse components for new projects originating from earlier constructed buildings (Interviewees 5, 2020). However, due to inadequate storage facilities, they were pressured to donate the valuable components to parties that were able to reserve them. Additionally, a lack of a comprehensive material bank or material database is considered a hindering factor (Hebel, 2019). There are several material banks on the market, albeit only one material bank in Europe revealed to have a circularity potential section for each material. Madaster was mentioned as a key player in facilitating this. However, due its novelty, there is an only a few partners that are collaborating and thus few use cases to attract other potential stakeholders to engage in circular IC.

Market

Three interviewees mentioned that an increase in circular IC demonstrators could be beneficial for increasing awareness and contribute to a more positive perception of the niche. Large construction players taking up such projects can be effective in communicating circular industrialized construction to society. As of now, there is potentially one large project that is planning on employing circular IC principles (see Appendix G). Furthermore, a researcher mentioned that building labels can be used to promote circular economy in industrialized construction (Interviewee 2, 2019). By covering CE and IC principles in building labels, parties that wish to receive such recognition will be enforced to apply both concepts.

It was found that many construction companies have silo-thinking business models that obstruct supply chain integration (Interviewee 4, 2019). Such companies do not want to share information and data, which is crucial for IC and CE at different life stages of a building. Furthermore, the development of impose BIM on new building projects will have detrimental consequences for smaller construction companies. They will not have the manpower and financial means to retrain their people to employ such tools, leaving them unprepared to engage in circular IC to track materials for example.

Financial/ Economic

One interviewee mentioned that lower labor costs by employing industrialized construction methods will result in higher economic benefits than a reduction of material costs through CE principles (Interviewee 2, 2019). This accounts especially for a wealthy country like Switzerland. Thus, it might be more effective for the government to incentivize the advancement of IC methods instead of providing economic benefits exclusively for the use of circular materials. Another financial enabler is the residual value of a building that can be determined and utilized. Money is saved by repurposing materials instead of having to invest in demolition at the end of its lifecycle (Interviewee 4, 2019). This also tackles resource depletion in the future for which a rise in price of resources is expected. Finally, the growth of green bonds is considered to be a driver. Companies are changing their perceptions and viewing sustainability central to their strategies placing greater value on its reputational benefits (Climate Bonds Initiative, 2019). Eligible projects covering the circular economy including upgrades of manufacturing processes or facilities to improve resource efficiency can receive green financing (Credit Suisse, n.d.). This trend entails that more financing can be allocated to further development of the circular IC niche.

In the construction industry, the customer is generally a professional investor and not directly the end user, which forms a barrier (Marchesi, 2019). The user has no influence on decision-making and requirements for a building. Due to the nature of a fragmented customer, the end user cannot impose or drive circular IC measures and thus it is the investor who can only decide whether to invest in this niche. Furthermore, a large construction firm explained that no warranty can be claimed on reused building materials (Interviewees 5, 2020). As such, architects become reluctant to work with materials that are in their second lifecycle. This hinders the adoption of circular economy principles, in particular resource recovery.

7.5. Scaling up Circular IC

In this second part of the Chapter, the pathway for scaling up circular IC growth is studied, answering the fourth sub question: “How can the outcomes of the practices in circular industrialized construction be scaled up in Switzerland”?. The SNM and MLP analysis derived various lessons learned essential for drawing up a pathway to scale up circular industrialized construction in Switzerland. A pathway has been developed for which new projects are established, essentially to break through into the regime. The conclusions of the case analysis are presented in Subchapter 6.5. The MLP developments and additional drivers and barriers are summarized in Subchapter 7.3 and 7.4, respectively. The transition toward circular IC is explained according to three time frames: short-term (2020 – 2023), medium-term (2023 – 2030) and long-term (from 2030 onwards). Once again, the PESTEL categorization (in *italic*) is applied including the addition of the **O**rganizational perspective, as proposed in the thesis by Browning (2018) to cover the outcomes found in the SNM analysis. Different stakeholder groups are allocated to the identified actions (in **bold**).

Short-term (2020 – 2023)

☑ Demonstrator projects	☑ Early involvement stakeholders
☑ Availability material database	☑ Clear mission and vision
☑ Increased building documentation	☑ Multidisciplinary team
☑ Presence of facilitating party	☑ Governmental support

From a *technological* point of view, the establishment of new **pilot projects** demonstrating circular industrialized construction is of paramount importance on the short-term. Different actors mentioned that tangible examples in the construction sector are needed in order to create a sense of recognition (Marchesi, 2019; Iseli, 2020). Amongst building professionals, there is a negative perception about the niche due to unawareness of its potential. Industrialized construction companies are reluctant to apply circular economy principles to their methods of construction due to high (upfront) costs and a lack of request coming from the client's side. Initiators can play a key role in this process by creating new successful building projects. In turn, this will attract the IC companies to rethink their current business models and shift to the use of CE strategies.

Another *technological* element is the availability of a comprehensive and clear **material database** including the circularity potential – crucial in making informed decision about selecting materials suitable for development of a circular IC project. Materials should be chosen with characteristics such as non-toxicity and recyclability. More importantly, the **impact of transportation** of materials has to be considered as this is not recognized sufficiently now. Here, database system providers have to transform their building information systems to include this feature.

Additionally, an **increased documentation** of a building from the start can facilitate in retaining the value of such building materials. This is considered a *social* component as it entails a culture change in collaboration during a project. It is advised to store all information about the different components and materials and how they are connected with each other in a database for later use during different lifecycles. The use of a platform that builds on the information of Material Passport data integrated within a BIM model is required. Madaster has, for now, been recognized as the only party in Switzerland to fulfill this action and thus it is recommended to store all relevant data on this platform (Interviewee 6, 2020).

The formation of a circular IC project network relies on specific *organizational* properties. The presence of a **facilitating actor** can help in creating a higher stability and alignment within a network. This will can be a macro-actor that has the financial resources and connections to assist the project further. Moreover, such an actor can establish a sense of professionalism amongst a team reducing the risk of conflicting views. Setting up a formal agreement can help in uniting the team, conceivably convincing the organization to remain working together on other circular IC projects. **Involving stakeholders early on** in the project, even those that might not be directly relevant from the start, will create a sense of willingness to engage in circular IC. By creating a common shared mindset, stakeholders will be more willing to act in accordance with the ultimate aims, speeding up decision-making. To achieve this, initators of projects are responsible. Furthermore, a leader is required to define and communicate the **mission and vision** of a circular industrialized project clearly. It has shown to attract stakeholders who might potentially be advantageous to the success story of project whilst simultaneously giving a sense of direction into the right path. With this in mind, a **multidisciplinary team** brings together multiple disciplines leading to more learning processes about the niche and the creation of (better) system solutions. The initiator(s) of a project can attempt to collaborate with stakeholders coming from different disciplines. Likewise, the presence of two different architectural firms can bring about new ideas, as such actors can start to look differently at applying their initial designs by integrating both CE and IC principles (Hebel, 2019).

To support the establishment of demonstrators in Switzerland, **governmental support** is required, linking to the *political* element. Even if it is not exactly clear which measures will be able to cover all initiating projects, it is advised that the government implements financial incentives to compete with the dominant existing technologies. By imposing a VAT reduction on secondary building and construction materials the reuse of (C&D) waste is stimulated (Hebel, 2019). Likewise, additional subsidies can play a role in lowering the higher costs for an initiator. To illustrate, cost for storing retrieved building components and modules for a later building could be (partially) covered.

Medium-term (2023– 2030)

☑ Pilots as information centers	☑ Circular IC labels
☑ Transforming business models	☑ Changing teaching practices - architects and engineers
☑ Standardization and mass production	

When multiple circular IC demonstrators have been established, the goal of such projects can start to shift. On a *social* dimension, **sharing experiences, knowledge and information** about engaging in this niche starts to become vital. This includes initators or representatives providing recommendations to potential creators on which strategies and practices to apply such as design for disassembly methods and materials to select (Marchesi, 2019). Likewise, advice can be given on which stakeholders possibly could contribute to the network in terms of financial capital or other resources.

Industrialized construction companies will be more aware of the potential of applying CE to IC methods when more demonstrators are established and information is readily available (Interviewee 4, 2019). Related to the *economic* view, IC companies should **transform their own business models** by extending ownership of materials and the building as a whole. A new perspective must be established in which a building functions as a temporary material storage creating an extension of responsibilities to stakeholders along the project's supply chain (see Subchapter 6.4). At the EOL phase, firms can take back their modules or prefab elements and recycle or reuse the materials and components in order to retain its value. Product-as-a-service is an appropriate strategy to achieve this, by leasing a building system for example (see Subchapter 7.4).

Additionally, the potential for industrialized construction has not been fully untapped in current circular IC projects. As of now, many individual decisions are made to conceptualize a circular IC building (Hebel, 2019). To scale up the niche, the possibility for **standardization** and **mass production/ customization**, related to the *technological* aspects, must be evaluated. A project that contains many different materials and components is much harder to standardize, as seen in the UMAR unit. However, this can be achieved by using panels or components with a standard dimensions or design as observed in the ICEhouse and ECO Solar Houses. Subsequently, mass production of standardized prefabricated components can become feasible, taking into consideration that an IC company is able increase its manufacturing capacity off-site.

From a *legislative* perspective, **certification labels** can be employed to speed up the integration of circular IC principles into buildings (Interviewee 2, 2019). There are various labeling bodies that consider some circular economy principles such as BREEAM and LEED or the building standard specifically for the Swiss market named Minergie (see Appendix C). However, no certification tag has included not only CE strategies (e.g. MP's and DfD) but also IC characteristics such as off-site construction, modular building and mass customization. The government is generally related to certifying parties and thus serve as a role model in checking and bring the certifications up to date. It is advised that the different label parties work together to from consistency and ensure both concepts are covered within their certification schemes. In turn, building owners who wish to receive recognition will be enforced to apply circular industrialized construction practices.

From a *social* perspective, it was mentioned that to create awareness of the circular economy and industrialized construction methods it is most effective to start with **changing teaching practices** (Hebel, 2019; Interviewee 4, 2019). At present time, courses dedicated to the circular economy in the built environment are being introduced in the curriculum of Architecture and Engineering studies, yet CE in IC methods is still lacking. In the course of time, when students become familiarized with CE and the integration into IC, it gives them the tools, skills, experiences and strategies needed to design and build in such a manner. The result is that the moment these graduates enter the labor market, they will have a tendency towards circular IC instead of traditional construction, facilitating the growth of the niche.

Long-term (from 2030 onwards)

☑ Framework for input materials	☑ Research outcomes
☑ Public procurement	☑ Secondary marketplace

On the long-term, it is crucial to implement a comprehensive **regulatory framework** that considers the **input of construction materials** in buildings, related to the *legal* dimension. In Switzerland, the Ordinance on Waste Avoidance and Disposal is in place, targeting recycling and reuse of secondary materials. However, Switzerland lacks a clear policy in view of the input (Interviewee 3, 2019). To ensure the circular loop is fully closed, circular materials must be selected from the start. To illustrate, construction companies can be enforced to use a minimum amount of recycled content or eliminate materials that do not meet the requirements as discussed in the circular materials strategy (Subchapter 6.1). The current developments taking place with regards to the revision of construction standards can play a significant role in establishing such a policy. Presumably, measures will be taken to use construction products that adopt modular building and circularity principles. Here, the Federal Office or Swiss government is responsible for taking actions.

The second action, also related to the *political* dimension, considers **public procurement**. Here, the government or specifically the Cantonal and City Councils can contribute. As illustrated in the regime analysis (Subchapter 7.2.1), the City of Zurich has developed internal guidelines for the construction of its buildings. On the long-term, different Cantons and cities could ask for specific requirements in favor of CE practices using industrialized methods. For example, a council could demand for a building that uses prefabricated elements which can be disassembled and reused or recycled to a minimum percentage.

From a *technological* outlook, **research outputs** of science programs conducted at universities and research institutions in Switzerland could ultimately lead to improving regulatory measures to facilitate the growth of circular industrialized construction. Recommendations for political leaders can be formulated about ways in which resource efficiency can be enhanced. Moreover, new business models can be discovered appropriate to circular IC business. However, it is uncertain which direction research will take and what the exact outcomes specifically for the niche will be. Hence, it is advised not to rely fully on the results for the moment but await further developments.

From an *organizational* point of view, a **secondary raw material and component marketplace** is lacking. To stimulate other demonstrators to use secondary materials or elements, a platform needs to be created to make such exchanges. It is important that not only materials that have undergone a first lifecycle can be offered, but also larger (prefabricated) components and modules. To illustrate, used panels offered by ECOCELL could be sold on this market to a potential buyer for a new building project. It is also advised to have a storage location in place where sellers could bring materials and elements, relieving them from the problems they currently face with lack of (Interviewees 5, 2020). For this development, an intermediary stakeholder could coordinate the marketplace and exchanged between buyers and sellers.

8. Discussion

The research aim of this thesis is to assess the current situation of circular industrialized construction and identify opportunities to facilitate the growth of this niche in Switzerland. There were a few constraints that may have impacted the findings of the research. However, the results of this study also suggest significance in the broader context. This Chapter reveals the methodological limitations and conceptual reflections (8.1), novelty of research (8.2) and the broader implications and relevance of this study (8.3).

8.1. Limitations of Research

8.1.1. Methodological Limitations

Due to the uniqueness of this topic, the conducted interviews are considered the most prominent data source for this thesis. Due to time constraints, a total of 8 stakeholders were questioned for the case study analysis. The intention was to question a minimum of two stakeholders per case study to incorporate different perspectives. However, only one interview was conducted for the ECO Solar Houses case study for two reasons. As identified in Figure 5.18, the network is small in terms of the number of stakeholders, leaving options for potential candidates to a minimum. Moreover, a delay occurred in the schedule of interviewing, which meant that the snowball sampling method could not be used. Nevertheless, the information that was collected is considered very pertinent and important to the analysis. Moreover, during interviews with both with the Case Study and External Actors, participants may have set limits on self-disclosure have different agendas for taking part in the discussion. In response to this, an attempt was made to uncover the certainties important to the analysis by asking follow-up questions. Furthermore, some of the interviews were not conducted in-person but through email communication. This created a very different structure of communication as opposed to the semi-structured interviews. It was identified that answers were more concise and less apprehensible, leaving no room for discussion. Hence, a follow-up email was generally sent to the participants for further clarification.

The language barrier was another limitation of the research. During the process of conducting the literature review and in particular the MLP analysis, many relevant documents were only provided in the German language. This hindered the search for gathering information. With the help of translation software, the text could be evaluated. The same accounts for the interviewees as many were non-native English speakers, possibly hindering the transparency of communication. The interview recordings were put into Otter.ai converting the voice conversations into text. Even so, this software did not detect Germany-accented English fully, misunderstanding quite a few words. Therefore, the transcriptions were reviewed twice to verify the text.

The outcome of the cross-case comparison illustrated an unexpected result. A higher degree of preassembly, leading to an improved control of construction, was assumed to be preferred as a means to increase the circularity potential of an IC building. Surprisingly, this was not automatically true. For the UMAR unit, various materials and components were provided by multiple parties, as illustrated by the large number of suppliers in this network. Here, modular construction was adopted, offering the highest level of pre-assembly. In contrast, the ECO Solar Houses and the ICEhouse demonstrate a lower degree of preassembly yet are not necessarily able to reuse less recovered materials. This is due to the fact that less elements were used in both case studies, implying that it is less challenging to recover and restore materials compared to the UMAR unit.

Along with this, measuring the circularity in quantitative terms according to the three case studies is missing. It makes it challenging to compare the results of the five circular strategies identified in each project and express which strategy creates the most impact and is most effective in contributing to the CE development. This limitation is touched upon in the Recommendations section. Regardless, this research focusses on researching possible CE strategies that can be applied to IC methods using qualitative methods. Finally, the study the circular IC strategies in Table 6.4 indicates a complementary relationship between the individual design principles. They were found not to be mutually exclusive but have the potential to generate maximum CE value when cooperating. For instance, material selection (circular materials) is crucial to support the extension of a product's lifetime and its possibility for recovery.

There was an interesting finding regarding the data collected for each individual framework. For the case study analysis, the questions asked to the Case Study Actors Group according to the SNM framework were considered more specific and relevant to them. This resulted in a comprehensive analysis presented in Chapter 5. In contrast, the interview protocol intended for the External Actors Group was formulated in a more general sense. It is likely that here stakeholders might have overlooked crucial enablers and barriers for circular IC growth. Likewise, this group of actors was very diverse including researchers, construction companies and organizations. Hence, the questions might not all have been appropriate to the participants. This is reflected in the Subchapter 7.3 and 7.4, which lacks similarity between the developments occurring in the landscape or regime level. Overarching themes, patterns and relationships have therefore been hardly found.

The cross-case comparison revealed less political first-order learning. It was expected that specifically niche projects require much more governmental involvement compared to existing technologies, yet learning was reflected more on the circular IC level than on a project level. Conceivably, as a facilitating party fully supported the cases, help from the government became dispensable. In addition, second-order learning was also not well-defined in the case study analyses. Such learning processes can occur at the initiation phase of collaboration functioning as a motive for stakeholder participation. As the interviews were conducted at a much later stage, it is important to bear in mind that these findings may be limited because of this. Presumably, if a larger number of stakeholders were interviewed earlier on in the process of participation in each case study, it might have been less challenging to discover.

Due to time constraints, the transition pathway toward circular industrialized construction presented in Subchapter 7.5 have not been validated. The recommendations derived from the interviews were carefully considered for this elaboration, however, it would have been interesting to determine if actors share the same idea as what this thesis proposed. Parties might foresee a different future for circular IC breaking through, for example, by co-existing with other sustainable innovations in the construction industry or completely reconfiguring the old regime (F. W. Geels & Schot, 2007). An extensive stakeholder (round-table) discussion should have been coordinated, questioning them whether the proposed measures were feasible and implementable in the Swiss construction industry context.

8.1.2. Conceptual Reflections

In this thesis, two methodological frameworks were integrated, namely the Strategic Niche Management and Multi-level Perspective. Prior studies discuss the importance of MLP-insights complementing SNM analysis (Schot & Geels, 2008; Turnheim & Geels, 2019). There are different publications that report on niches by applying both methodologies (Linda M. Kamp & Vanheule, 2015; van Eijck & Romijn, 2008). As such, the conclusion can be drawn that the combination of SNM and MLP was a useful method to demonstrate the on-going processes in the circular IC niche. Simultaneously, it was an effective policy tool to identify further actions for further development within the Swiss construction industry. However, for the sake of simplicity, circular industrialized construction was referred to as *the niche* in this thesis. In fact, circular IC is a sub-niche belonging to the industrialized construction niche. At the time of writing Chapter 3, a guideline of applying both methodologies to this sub-niche was lacking. Hence, difficulty was encountered trying to verify if the right approach had been taken.

Another interesting element that could possibly be integrated in the conceptual framework is the provision of protective spaces for sustainable innovation. This concern is central with the emergence of the Strategic Niche Management framework. The implications for niche dynamics are extensively explored in literature, yet the concept of protection has received little attention (A. Smith & Raven, 2012). Recent work argues that such spaces promote three properties in wider transition processes – shielding, nurturing and empowering (A. Smith et al., 2014; A. Smith & Raven, 2012). In the wider context of this thesis, three processes have been identified to varying extents. Protective space can contribute to *shielding*, which involves both the exploitation of passive pre-existing situations, for example, establishing circular IC in locations with limited material resources or more active protection. Characteristics of *nurturing* include (1) positive expectations that are robust, credible and specific, (2) broad and deep networks and (3) second-order learning processes next to first-order learning. Several aspects of nurturing are noticeable in the different case studies, such as the presence of second-order learning processes and broad networks with high stability. Thirdly, *empowering* comprises two forms: fitting and conforming into regimes or stretching and transforming regimes. Evidently, this process is currently not visible for this niche, as circular IC has recently emerged. Various measures have to be taken before a regime shift can occur. All in all, shielding, nurturing and empowering properties are not clearly evident. The limited number of cases studied suggest that the results are not reliable enough to draw the conclusion that protective spaces facilitate the aforementioned processes. If protective spaces were necessary for sustainable innovations, then circular industrialized construction would require such an arrangement as it fits poorly into the established infrastructure, practices and preferences of the construction industry. Thus, analyzing the significance of protective spaces could potentially lead to new insights into the development of the niche.

Finally, a potential link can be made integrating industrial ecology literature with the SNM framework. Industrial symbiosis (IS) initiatives are part of the IE field and contribute the circular economy strategy sharing platforms. Susur et al. (2019) studied how industrial symbiosis practices can contribute to the development of regional industrial ecosystems using the Strategic Niche Management approach. An emerging regional network can provide support and protection for new experiments, enabling more real symbiotic exchanges. The cross-case comparison revealed a case of industrial symbiosis for the ECO Solar Houses, repurposing wastepaper to manufacture building panels. Focusing on the network element, Domenech et al. (2019) suggests three typologies: (1) self-organized activity, emerging as a result of direct interaction among stakeholders (2) facilitated networks, having an intermediary party coordinating the activity and (3) planned networks, resulted from a central plan or vision for a specific industrial area. For the ECO Solar Houses, the IS activity can be categorized as a self-organized network. The creator of the houses worked in the paper and cardboard industry prior to setting up the project and recognized the opportunity to use local recycled wastepaper for construction purposes. This perspective was not carefully considered between stakeholders in the case study networks. To identify and gain a deeper understanding of such IS initiatives and its contribution to a regional industrial ecosystem, it would have been valuable to include this in the conceptual framework.

8.2. Novelty of Research

The concepts of industrialized construction and the circular economy in the built environment have been discussed to some extent in scientific literature. The barriers discussed in 2.1.4. (IC) and 2.2.3. (CE in the built environment) reveal similarities with the barriers identified for circular IC (Adams et al., 2017; Hart et al., 2019). For example, a lacking secondary raw material market infrastructure, insufficient use of collaboration tools/ information and cost related issues plays a role in this niche. However, the true novelty of this research lies in integrating CE in IC, a unique aspect which has not been found in any previous publication yet.

A small number of researchers detect the benefits of material reuse by adopting IC methods in contrast to traditional construction, yet the papers do not elaborate further on this favorable condition, ultimately linking it to the circular economy (Aye et al., 2012, 2014). This idea does play into the thesis statement that industrialized construction enables the ability to disassemble and reuse construction elements at the EOL phase in a new building. Likewise, articles have been published showcasing circular IC principles in various examples, albeit without explicitly mentioning the niche. To illustrate, Kozminska (2019) presents a project in Germany that applied prefabricated modular elements made from reused aluminum bolted together with mechanical joints to enable further disassembly. This publication addresses the design process for achieving such circular design in buildings. However, the coverage of the topic is limited to highlighting the challenges and the role of the architect here. The research conducted in this thesis, adds to the challenges as well but more importantly, provides a guideline with concrete actions concerning the other involved stakeholders.

Hitherto, only one academic paper was discovered evaluating different strategies for applying CE to prefabricated buildings (Minunno et al., 2018). The paper recommends validation of the proposed strategies as future work. This report adds to the academic literature by analyzing such case studies and identifying which strategies and practices have been applied. Furthermore, the study demonstrates the advantages of prefabrication over traditional construction in terms of the circular economy but does not specify to what extent prefabrication is assembled off-site. The authors define prefabricated buildings "as constructions manufactured at an industrial site and moved and assembled in *different* degrees on-site" (Minunno et al., 2018). In contrast, this thesis mentions explicitly the degree of pre-assembly for the three case studies, revealing the different practices for achieving this. However, the novelty of the topic reflects great differences in terms of industrialized construction methods applied to the case studies – it being a modular building or a prefabricated panel. Moreover, an interviewee for the UMAR unit even stated the following: "I am not sure if I would necessarily place our building within the category of industrialized construction … There are a lot of unique decisions that have been made for the UMAR unit." (Heisel, 2019). As such, it is debatable whether the selected case studies are most suited for this thesis or if the projects are too different to permit comparison. A recommendation for improvement in this area is provided in Chapter 9.

Interestingly, van Egmond - de Wilde de Ligny (2009) published a paper about the use of the SNM for the wider diffusion of a prefabricated building in the Dutch context. Some similarities have been identified – it was found that the actor group responsible for initiating the project faced problems with negative perceptions amongst clients and governmental bodies.

Moreover, the author acknowledges that the investors of a particular technology are not in all cases the most appropriate party to successfully facilitate diffusion in the market. This is in line with the cross-case comparison conclusion that all networks of the case studies include an initiator/creator group which designed, planned and/or conceptualized the project from the start. Nevertheless, research efforts applying the SNM as well as the MLP approach to circular industrialized construction have not been found in the literature and thus from this perspective, the thesis contributes to the scientific body of knowledge.

8.3. Broader Implications and Relevance

Broader implications of this study can benefit initators of circular IC demonstrators but also the wider context. The thesis provides guidelines for initators to engage in circular industrialized construction in Switzerland. It present key processes that can facilitate the development of this niche. To illustrate, the presence of a facilitating stakeholder and a multidisciplinary team approach, amongst other things, are essential factors for a successful formation of a circular IC project. By analyzing the internal elements of additional case studies, it is possible that more opportunities are discovered. Furthermore, for the industrialized construction companies, future solutions are touched upon but should be further explored in order to accelerate change towards a more circular system. When such players start to embrace this concept, it will start to have a positive effect on the broader context, namely the construction industry.

There is also a broader significance of this thesis, represented in particular by the recommendations for scaling up highlighted in Subchapter 7.5. The geographical boundary is considered to be Switzerland identifying several developments that are only compatible with such circumstances. However, it is possible to extend this scope to Europe or other Western countries. In principle, almost all short-term steps are considered relevant for scaling up circular IC, regardless of the location. It is important however to acknowledge the different pilot projects that have been established a certain place. In some countries, there may be far more demonstrators set up and therefore it is interesting to compare such projects with the cases presented in this thesis. Nevertheless, recommended governmental actions are considered different for each country. In this context, innovation is driven by industry instead of the government. Thus, an advice is presented for industrialized construction companies to intervene and transform business models, for example by leasing their own building systems. Only on the long-term will it be appropriate to expect support from the Federal Office to help the niche along. However, a country with higher governmental involvement might happen to implement effective measures faster through subsidies or green public procurement for instance. Thus, it is crucial to assess the conditions for each country separately to assure that the proposed actions can be applied to that situation.

9. Conclusions and Recommendations

9.1. Conclusions

Based on case study research, this thesis aimed to provide insights into the opportunities for facilitating the transition of circular practices in industrialized construction with a focus on Switzerland. After conducting literature review and analyzing two innovation and transition frameworks, three cases of circular IC projects were investigated, ultimately deriving recommendations for scaling up. Four sub research question structured the thesis.

The first sub research question goes as follows:

1. *What are the main developments of integrating the Circular Economy in Industrialized Construction?*

Little past scholarship has focused on the integration of CE into IC methods. The concepts have been discussed separately in scientific literature, identifying enablers and drivers for future development, yet the combination of applying such methods in buildings has not been found. Until now, one article was discovered that reviewed multiple strategies for applying circular economy principles to prefabricated buildings (Minunno et al., 2018).

Despite the limitations of research, the relevance of circular industrialized construction was clearly supported by the current findings. It was found that CE and IC are complementary concepts. In the context of the circular economy, three advantages of using industrialized construction approaches compared to traditional construction were identified. The IC nature of supply chain integration with a long-term partnership culture supports the notion of shared responsibility for a circular economy. Likewise, IC is characterized by a longer planning phase to ensure successful assembly on-site. In turn, this enables planning for disassembly allowing material recovery and value retention at the EOL phase. At last standardization, an approach associated with industrialized construction, facilitates adaptability as standardized parts can maximize reutilization of materials and products.

The second sub question looks at the theoretical and conceptual part of this research:

2. *How can niche initiatives in circular industrialized construction be researched from a niche transition perspective?*

Circular IC initiatives were researched accordingly using a combination of two innovation and transition frameworks, namely the Strategic Niche Management and Multi-level Perspective. SNM has been designed to assist in the introduction and diffusion of new sustainable technologies through societal experiments. Three internal niche processes are key for successful development – network formation, learning and expectations. A vision element was added to expectations in order to study the promises of the niche as a whole. Furthermore, additional characteristics were identified and applied to the niche initiatives to discover the circular strategies in the different IC practices. To obtain a complete understanding of the development of circular industrialized construction, the wider context (socio-technical regime and landscape) in which the niche level is embedded in, was considered. By integrating the Multi-level Perspective, these additional levels were analyzed.

Here too, it holds that the SNM and MLP framework complement each other and can be coupled to form the basis for a comprehensive conceptual framework. In this thesis, the Strategic Niche Management was first applied to the selected case studies within the predefined circular IC subniche. The outcomes of the analysis related to the identification of the enablers and barriers for the growth of the niche. Subsequently, the MLP analysis was conducted to determine the external developments occurring. The changes were categorized based on pre-set dimensions. All in all, the different parameters and dimensions as part of the SNM and MLP frameworks laid the foundation for structuring the two interview protocols.

The third sub question sought to determine the strategies and practices found based on the case study- and cross-case analysis:

3. *What practices and strategies can be observed from emerging circular industrialized construction case studies in Switzerland?*

In addition to studying the niche internal processes, circular IC indicators were analyzed to reveal practices and strategies in the projects. It was found that in order to increase the circularity potential of an IC building, building layers should be separated, a high degree of reuse of recovered materials is preferred and a higher level of pre-assembly is favored for a building with many different materials and layers to maintain control of construction. Additionally, the five CE design strategies are important. They are not mutually exclusive but will generate the largest circularity impact when combined. Materials selection is in particular important to support the extension of its lifetime and possibility for recovery.

A diverse, multidisciplinary team is required to 'think outside the box', stepping out of the existing disciplines and creating new innovative system solutions. A facilitating party, generally a macro-actor, can support an initiative network and create a professional work environment by setting up a formal agreement. The role of a leader must be fulfilled sharing their mission and vision in order to attract important stakeholders, such as a facilitator.

Regarding the contribution of the learning processes, there is a need to record the findings of second-order learning. For first-order learning, it was discovered that there is not a common positive perception regarding circular IC. This impression must be adjusted by informing industry practitioners' of the beneficial opportunities. Moreover, industry processes must be optimized to streamline processes e.g. 3D printing, the environmental impact of transportation must be considered and governmental support is required. Second-order learning was challenging to determine, yet several processes were observed. Broadening the scope of stakeholders is important, not only to apply CE principles but also recognizing the possibilities for fabricating off-site. Furthermore, involving stakeholders early in the process of development is crucial to establish a common circular and open mindset.

The objective for setting up circular IC projects will start to shift. If such projects are designed as multi-purpose buildings (e.g. refugee housing), it can attract the interest of external parties. Projects can start to function more as information points to encourage and inform interested parties about engaging in this niche. Vision development is important for the development of circular IC initiatives as well. A prefabricated modular design can enable a vision emphasizing the temporary storage of materials in a building. Choosing a relevant framework to make the vision explicit, such as Cradle to Cradle design, provides stakeholders clarity on the goal of the project and in turn, inspires and motivates them.

The fourth sub question was designed to provide recommendations for scaling up circular IC:

4. *How can the outcomes of the practices in circular industrialized construction be scaled up in Switzerland?*

The case study observations in combination with the regime and landscape developments and additional drivers and barriers formed the foundation for a pathway for scaling up circular IC.

On the short term, it is important to set up more demonstrator projects. To provide a facilitating environment for establishment, the aforementioned network characteristics need to be considered. Before constructing a circular IC building, the initiator(s) must use a material database that provides information related to the circularity potential of materials to make informed decisions. Likewise, documentation of a building's materials and interconnectivity between components is very important during the design phase. An updated building model using BIM that integrates data provided by Material Passports, possibly stored on the Madaster Platform, is required to retain and recover the material value during the life cycle of a building. Subsequently, such materials and components can be easily disassembled and reused in future projects. Governmental financial support in the form incentives and subsidies is required. For instance, imposing a VAT reduction on secondary materials and by subsidizing new circular IC projects, the government can facilitate the scaling up.

On the medium-term, established demonstrators start to fulfill a new role and look into possibilities of modifying its designs. Pilot share knowledge and insights with parties who are potentially interested. Such projects have to consider other IC practices, e.g. standardizing elements or scaling up processes to achieve mass production. At the same time, business models of conventional IC firms need to be transformed to incorporate CE principles. Ownership of materials must be extended to enable leasing of building modules or components to make it easier for producers to take back elements and reuse in new IC building systems. Certification labels can also play a role in stimulating CE and IC principles applied in a building's design. It enforces designers to comply with the certification guidelines in case they want to receive recognition. Furthermore, the curriculum for architects and engineers should be modified to ensure the topic of circular IC is included, equipping students with the tools, knowledge and mindset to design and construct future buildings in such a manner.

Legal measures are desirable on the long term. A regulatory framework considering the input of construction materials in buildings is lacking and need to be adjusted, for instance, by imposing a minimum requirement of recycled content. A secondary raw material market in place could support such a framework. Research outputs can further help to discover effective policies favoring the circular economy and industrialized construction.

Finally, the main research question is answered according to the four sub research questions: *What circular practices can be adopted in industrialized construction and how can this integration be more widely diffused and scaled up?*
To increase the circularity potential in IC, the five **circular strategies** should be present and work together: circular materials, product as a service, product lifetime extension, sharing platforms and resource recovery. Importantly, **selecting circular materials** will contribute to possible recovery and lifetime extension. Use of a comprehensive **material database**, **increased documentation** and **separation** of **building layers** at the start of a project is important to make informed decisions to retain value at a building's end-of-life phase. Provided that a project incorporates various types of materials and components, a **higher level of pre-assembly** is preferred to allow increased control of construction and thus a higher reuse of recovered material. For a CE, new business models need to be reconfigured, which can be achieved by **extending ownership of materials and components** through product-as-a-service systems. Transformation in design is recommended incorporating **standardization** and **design for disassembly** practices enabling adaptability for future reuse. To scale up the integration of CE into IC, more **demonstrators** need to be established. A facilitating environment for such projects requires a diverse **multidisciplinary** team with stakeholders **involved early** on in the process learning to **broaden** their **scope** and create a common circular mindset, a **facilitator** and a **leader** sharing the mission and vision to attract stakeholders. Governmental support through subsidies and a VAT reduction on secondary raw materials is crucial to financially assist projects. A **regulatory framework** specifically for the **input** of construction materials needs to be developed. A **secondary raw material marketplace**, **outcomes of research** by universities and **certification labels** can support such a framework. All in all, scaling up circular industrialized construction through new projects will contribute to fostering the transition of a sustainable construction industry and therefore integrating CE into IC points the way forward in achieving this goal.

9.2. Recommendations

Recommendations for different actors are presented based on the discussion in Chapter 8.

For the **industrialized construction industry**, conducting interviews specifically with IC companies is recommended to analyze if the actions proposed in the pathway are feasible and most effective to this group of stakeholders. Moreover, to obtain not only a comprehensive image of the circular IC niche but also the IC niche, the SNM framework should be with reference to this scope. Subsequently, the differences between the niche and 'subniche' can be determined, possibly clarifying certain insights concerning circular IC.

Concerning **policy makers**, suggestions classified as concrete actions or strategic long-term goals are revealed. For the former, it is recommended to provide financial assistance whilst streamlining communication about governmental support regarding circular IC. This can be achieved by offering financial incentives for niche initiatives and informing people through a central information center. Imposing a VAT reduction on secondary raw materials can help as well to stimulate the purchase of materials that have undergone a lifecycle. To enable this, the government can experiment with the establishment of secondary raw material marketplaces to assess the demand per region and facilitate the set up by offering space for storage of materials and components. Additionally, an environment can be created for initators to experiment with circular IC to discover new successful opportunities that can be further developed and validated. This is possible by conducting a trial with research and innovation testing locations, such as the NEST building.

On the long-term, the policy framework of the input of construction materials needs to be reviewed to ensure that this perspective is considered in new building projects and in line with the requirements for circular IC. By collaborating with niche initiatives and research institutions such as universities, policy makers can take advantage of experiences and acquired knowledge to develop effective measure and policies that are not limited to a certain project. Finally, the public procurement strategy or guidelines have to modified to include circular IC strategies in order to increase its uptake. For instance, a City Council will be enforced to use prefabricated modular structures made from reused materials.

For **further research**, recommendations regarding the analyzed case studies and at a more general level are discussed. To obtain more qualitative data about each project, it is recommended to conduct more interviews with different stakeholders involved in order to draw more reliable conclusions. Moreover, to quantify how well a building performs in the context of CE and identify areas for improvement, data can be collected on the circularity strategies and their impact on the case studies, for example through a lifecycle analysis.

It is recommended to analyze multiple case studies from other European countries to identify if this thesis is applicable to other regions and as such prove its broader implications. Likewise, case studies that demonstrate the same degree of pre-assembly as the selected cases should be reviewed to create more consistency between case studies and compare cases based on the same level of off-site fabrication. The conceptual framework and its integration of the SNM and MLP framework should be tested and improved by conducting empirical research through an iterative process of additional case study work. Finally, to validate the proposed actions in the Swiss construction industry in terms of feasibility, value and relevance, an extensive stakeholder (round-table) discussion should be conducted.

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11. Appendix

Appendix A - Additional Industrialized Construction Concepts

Modular construction
Modular construction is defined as three-dimensional or volumetric units primarily manufactured off-site and transported to the site as the main structural elements of the building to be assembled as a series onsite (Bertram et al., 2019; Lawson et al., 2014). Common materials include timber, steel or concrete, with the former two being preferred due to its weight and logistics advantages. This type of construction is generally used to construct cellular-type buildings, comprised of room-sized units that are easy to transport. However, modular units can also be created for higher-value components of a building such as elevator shafts, toilet pods or mechanical serviced units. There are various applications for modular construction but it is mainly applied in student residences, medium-rise residential buildings, hotels and a wide variety of temporary and relocatable solutions (Gibb, 1999). Adopting modular methods can rapidly increase the efficiency, speeding up factory processes and reducing onsite work (Lawson et al., 2014). Nonetheless, trade-offs need to be made regarding transportation costs and limits to the size of the modules to avoid having to use police escort (Bertram et al., 2019). Higher investments are needed as well to have fixed manufacturing facilities and receptiveness of the output is required to achieve economy of scale benefits during production. Because the design and manufacturing of the prefabricated elements are carefully optimized, this stage will take longer in comparison to traditional construction.

Off-site fabrication
Off-site fabrication encompasses the fabrication of a large variety of elements and modules, with perhaps the simplest prefabricated component being the building brick (Gibb, 1999). The concept, also called off-site manufacture, refers to "making all or part of an object in some places other than its final position" (Hui & Or, 2005). Fabricating off-site covers both prefabrication and pre-assembly. Gibb (1999) describes off-site fabrication as: "Off-site fabrication is a process which incorporates prefabrication and preassembly. The process involves the design and manufacture of units or modules, usually remote from the work site, and their installation to form the permanent works at the work site. In its fullest sense, off-site fabrication requires a project strategy that will change the orientation of the project process from construction to manufacture and installation.". Currently, in industrialized construction, the proportion of actual construction content executed off-site ranges between 10 and 70% (de Laubier et al., 2019; Fraser et al., 2014). This wide range is caused by the different levels of pre-assembly. For example, for a prefabricated elemental or planar system such as a structural steel frame, the proportion of off-site fabrication is maximum 25%. Yet, for complete building systems, the typical range is between 60 and 70% (Lawson et al., 2014).

Open Building Design
Open Building Design supports the relation between industrial manufacturing and the user of the building (Habraken, 2003). Spaces must offer flexibility to adapt to individual's ever-changing preferences. A distinction is made between the 'base-building' and the 'fit-out'. The base-building includes the primary structure and building envelope as well as the building services. The latter is defined as the physical products and spaces controlled by the tenants to make the building livable. The separate configurations entail the potential for systematization and industrialized production of the base-building. At the same time, individual households and users are under control of designing the fit-out.

Appendix B - CE Schools of Thought

Cradle to Cradle

The Cradle to Concept can be defined as the design and production of all product types in a way that at the EOL phase, they can be recycled or upcycled, imitating nature's 'biological metabolism' with everything either recycled or returned to the earth, directly or indirectly through food, as a completely safe, non-toxic and biodegradable nutrient (Sherratt, 2013). Thus, it aims at creating efficient, sustainable and waste-free systems (Geisendorf & Pietrulla, 2018). Chemist Baungart and architect McDonough are the founders of the Cradle to Cradle (C2C) principle. They presented a manifesto on their developed C2C design model in the book "Cradle to Cradle: Rethinking the Way We Make Things" in 2002 (Braungart & McDonough, 2002). C2C is primarily applied on a micro level but can also be found in architecture and construction, urban environments and infrastructure design. Cradle to Cradle covers most elements of CE and is regularly used as a synonym (Esposito et al., 2017).

Performance Economy

The Swiss architect and industrial analyst Walter Stahel was the first to sketch the concept of a Performance Economy in a research report published in 1981, which was co-authored with Genevieve Reday (Stahel, W.R. and Reday, 1981). It insists on the importance of selling services rather than products, focusing on four main goals: product-life extension, long-life goods, recondition activities and waste prevention (Ellen Macarthur Foundation, 2013; Wautelet, 2018). Stahel and Reday argued that an economy with closed loops favoring reuse, repair and remanufacturing over the manufacturing of new goods would have a positive impact on job creation, resource savings, economic competitiveness and waste prevention.

Biomimicry

Within biomimicry, nature's best ideas are studied and imitated to solve human problems. Janine Benyus is considered the founder of the concept, publishing the book Biomimicry: Innovation Inspired by Nature (Benyus, 1997). Biomimicry relies on three principles:

- ➔ Nature as a model – look at nature's forms, processes and designs and emulate them to solve human issues.
- ➔ Nature as a measure – use ecological standards to evaluate sustainability of innovations and designs.
- ➔ Nature as a mentor – view and value nature in a way on how we can learn from it instead of how we can 'use' it.

Industrial Ecology

Industrial ecology (IE) is a concept that takes a systematic approach to human problems, integrating environmental, technical and social aspects (Leising, 2016). The approach aims at studying material and energy flows through industrial systems and using this analysis as a basis to optimize the total materials cycle and minimize energy use along its lifecycle. IE is sometimes referred to as the 'science of sustainability', due to its interdisciplinary nature (Ehrenfeld, 2008).

Natural Capitalism

Paul Hawken, Amory Lovins and Hunter Lovins (2010) describe in their book Natural Capitalism: Creating the Next Industrial Revolution, the interconnections between the production and use of human-made capital and natural capital flows (soil, air, water and all living creatures). Natural capitalism relies on four principles:

- ➔ Increase the productivity of natural resources to make them last longer resulting in savings in cost

- ➔ Shift to biological production models and materials to reduce the wasteful throughput of materials, eliminating the very idea of waste.
- ➔ Shift to service and flow economy to provide continuous flow of value through services instead of the traditional acquisition of goods.
- ➔ Investing in natural capital to restore and generate natural resources which have been put under pressure by humans.

Blue Economy

The Blue Economy is an open-source movement bringing together concrete case studies to stimulate entrepreneurs to implement new innovative business determined by their local environment and resources (Pauli, n.d.). Gunter Pauli is a Belgian businessperson and is the initiator of this movement. It is based on 21 founding principles inspired by nature and ecosystems. Pauli published a report named '100 innovations that can create 100 million jobs within the next 10 years' which doubled as the Blue Economy's manifesto, popularizing the movement and demonstrating many successful cases (Wautelet, 2018).

Regenerative design

Regenerative design is a principle that relies on designing products or services that contribute to systems that renew or replenish themselves (CEguide, n.d.; Lyle, 1996). This entails that energy and materials entering a product or service can be reintroduced into this same process, requiring little to no input to maintain it (e.g. renewable energies). John Lyle developed the concept and introduced it in his book 'Regenerative Design for Sustainable Development' in 1996.

Appendix C - Assessment of Circular IC Buildings

BREEAM

BREEAM, short for Building Research Establishment Environmental Assessment Method, dates back to 1990 and was first launched as an assessment for new office buildings in the United Kingdom (BREEAM, n.d.-b). It is the oldest and most widely used (in Europe) certification method for buildings, setting the highest possible standards in terms of sustainable design for buildings and able to describe the environmental impact of a building (Green Building Schweiz, n.d.-a). Three elements comprise the assessment: (1) the environmental performance of the building's form, construction, fixtures and installed facilities, (2) the management and operation of the building and (3) the management of building users and their activities and services within the building (BREEAM, n.d.-a). For each part, the following nine categories are assessed – energy, transport, health, water, waste, management, material, environmental and ecology (Green Building Schweiz, 2017). The methodology is finally evaluated using five categories: Pass, Good, Very Good, Excellent and Outstanding.

The German Private Institute for Sustainable Real Estate (DIFNI) is the representative body of BRE, the center that developed BREEAM, in Germany, Austria, Luxembourg and Switzerland (Caminade, 2015). The institute develops specified requirements for Switzerland and has been applied to several (pilot) projects. The interest in sustainable buildings in Switzerland has increased in recent years and therefore this certification scheme is expected to gain prominence in the Swiss building sector. The adoption of industrialized construction methods plays an essential role in particular in the waste and material category. To minimize waste generation, designing for off-site or modular build is promoted by the scheme as a solution (BREEAM, 2018). For a higher material efficiency, fewer materials in combination with lower waste levels is required and this is met by manufacturing off-site.

Metabolic

Metabolic, a consultancy specialized in sustainability challenges, has contributed to integrating circular building principles in the Dutch BREEAM certification scheme (Metabolic, 2018). The following six crucial aspects have been identified: accountability and substantiation of building volume, design for reassembly, maximize amount of reused materials and renewable materials, availability of information (of element/material) and the building design should not embody toxicity. Moreover, circular strategies were suggested to integrate such principles in a building project.

LEED

Leadership in Energy and Environmental Design (LEED) is from origin an American building label and most recognized scheme globally (Green Building Schweiz, n.d.-b). Buildings in more than 150 countries have been LEED-certified. In Switzerland, the Olympic House located in Lausanne received a LEED Platinum certificate, obtaining the highest level of the international LEED green building program (The Olympic House, n.d.). The Green Building Association in Switzerland is the official Swiss representative at the International Round Table of the U.S. Green Building Council – the advisory body that actively promotes the international development of the LEED certification system (Green Building Schweiz, n.d.-b). The American system is adapted and formed to fit the Swiss context with the help of LEED specialist partners.

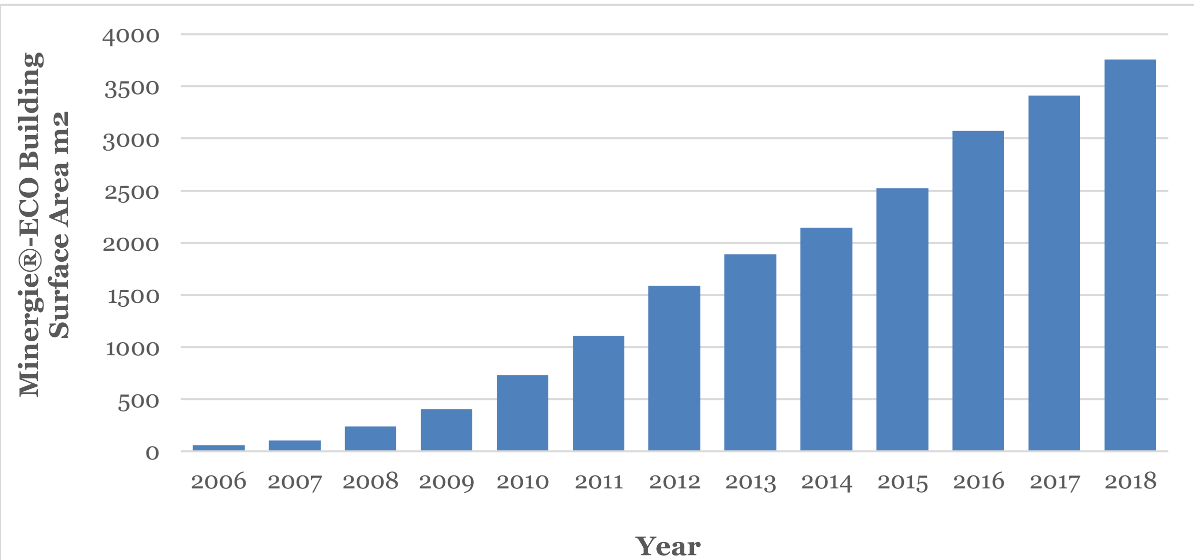
There are four levels of certification depending on the amount of points received: Certified, Silver, Gold and Platinum (USGBC, 2019). The points are earned across nine categories: integrative process, location and transportation, sustainable cities, water, energy and atmosphere, materials and resources, indoor environmental quality, innovation and regional priority (USGBC, n.d.). LEED looks at all phases of development of a building: building design and construction, interior design and construction, building operations and maintenance and neighborhood development. The materials and resource focusses on minimizing and optimizing products and materials throughout the project life cycle, which is considered part of addressing the circular economy (Hughes, 2019). For example, reducing waste generation during construction and operation by reusing building elements will be rewarded. This is also considered a key benefit for off-site construction, reducing on-site waste and regulating the quality of the materials used and recycled in the waste stream. Moreover, the purchasing of prefabricated elements within 800 kilometers of the building site offers additional LEED credits (R. E. Smith, 2011).

Minergie

Minergie is a Swiss building standard for new and renovated buildings and is used by the industry, different Cantons and the Federal Government (Minenergie, 2017). Its focus point is on comfortable living and good working conditions for users, categorized in three building standards: Minergie, Minergie-P and Minergie-A. The Minergie standard fulfils above average requirements for quality and efficiency, Minergie-P ensures maximum comfort at lowest level of energy consumption and the latter combines the first two standards with energy independence, such as with PV.

An additional supplement is the integration of ECO, guaranteeing healthy and green building materials as well as sustainable construction. Different factors are taken into account here, such as resource conservation (an important segment of the circular economy) and a low environmental impact on the whole life cycle of the building project. This criterion of adaptability of the structure and façade is also part of the assessment system of Minergie ECO (ERENBUILD, 2011). Regarding IC, adaptability is a method than can be accomplished by the use of design for disassembly strategies.

In the Figure, it is viewed that the cumulative building surface area, which included all floor areas that require heating or air-conditioning, has increased over the years (Federal Office for the Environment, 2018). The assessment of the trend is considered to be positive, but its current state is still considered poor as this constitutes a very small share of the total Swiss building surface area.



Minergie®-ECO Building Surface Area m2 per year in Switzerland (Federal Office for the Environment, 2018).

Madaster

The Madaster Platform, based in the Netherlands, provides a repository for building, material and product data and facilitates circular management using the Madaster Circularity Indicator (CI) (Madaster, 2018). The CI is based on the Material Circularity Indicator framework developed by The Ellen MacArthur Foundation measuring the circular economy potential of a material (Ellen MacArthur Foundation, n.d.-a). This framework has been adapted to the specifics of the building industry.

The tool assesses the degree of circularity of a building project between 0 and 100 percent during three phases of its lifetime - construction phase, use phase and end-of-life phase (Heisel & Rau-Oberhuber, 2020). For the construction phase, the ratio between the volume of virgin materials and the volume of recycled, reused or renewable materials is measured. See the simplified Equation 1 below for an understanding (Madaster, 2018):

$$CI_{\text{Construction}} = F_R + F_{RR} + F_U \quad \text{(Equation 1)}$$

F_R = fraction of recycled materials (% of total mass)
F_{RR} = fraction of rapidly renewable materials (% of total mass)
F_U = fraction of reused products/ components (% of total mass)

For the use phase, the expected lifespan of the products used as opposed to the average lifespan of similar products is calculated. Equation 2 is used during this life phase:

$$CI_{\text{Use}} = L / L_{av} \quad \text{(Equation 2)}$$

L = potential functional lifespan of a product (years)
L_{av} = industry average lifespan of the building layer this product is applied in (years)

Finally, the end-of-life phase measure the ratio between the volume of waste and the volume of reusable and recyclable materials and products derived from a building when it is refurbished or demolished. Equation 3 illustrates this phase:

$$CI_{\text{End of Life}} = C_R * E_C + C_U \quad \text{(Equation 3)}$$

C_R = fraction of materials that can potentially be recycled at EOL (% of total mass)
E_C = efficiency of recycling process at EOL (%)
C_U = fraction of components/products than can potentially by reused at EOL (% of total mass)

The CI is evaluated for each phase on a 0-100% scale, with a low percentage presenting a more 'linear' building, as opposed to a high percentage stating that a building is more circular. A maximum CI score of 100% signifies that a building is entirely circular. In this case, all materials and products can completely be reused for future purposes.

In the case of off-site construction, the three life cycle phases can be carefully managed. For the construction phase, materials can be selected for industrialized construction methods that minimize the environmental performance of the end product (Minunno et al., 2018). In the use phase, life extension can be obtained with adaptable elements. This can be achieved by design in modularity, increasing the potential functional lifespan of a product. At the end of life phase, prefabricated materials and components can be easier to manage in contrast to traditional construction that uses elements, which are more complex and varied. This increases the fraction potential of materials and components to be recycled or reused.

Appendix D – Case Study Methodology and Approach

Methodology

There are three types of case studies used for research purposes: (1) explanatory case studies, (2) descriptive case studies and (3) exploratory case studies (Yin, 1984, p. 17). The most important classification, explanatory case study, is to explain the causal links in a current intervention that are too complex to emphasize in a survey or experimental design. It has set out to identify causes and reasons why an actual phenomenon occurs (Boru, 2018). Descriptive case study is used to describe an intervention and the context it is embedded in, without explaining why it has happened. This strategy is most applicable to new or unexplored research field. The third approach is to explore new terrain in which the intervention occurs. Exploratory research is performed when there is adequate information available about a phenomenon but the problem has not clearly been defined.

Accordingly, it is important to mention what these types are before diving into the specific design that is selected. In total, there are four types of designs – single or multiple-case studies and within these design situations there are two variants: unitary or multiple unit of analysis (Yin, 2018, p. 47). This results in the following types:

1. Single-case holistic designs
2. Single-case embedded designs
3. Multiple-case holistic designs
4. Multiple-case embedded designs

As the name suggests, a single-case study implies that only one individual case study is analyzed, whereas for a multiple-case study two or more case studies are examined. The difference between holistic versus an embedded case study is that for the latter attention is paid to a subunit or subunits within each individual case study. This offers opportunities for an extensive analysis of each case study but is more complex to conduct, demanding more time and data required.

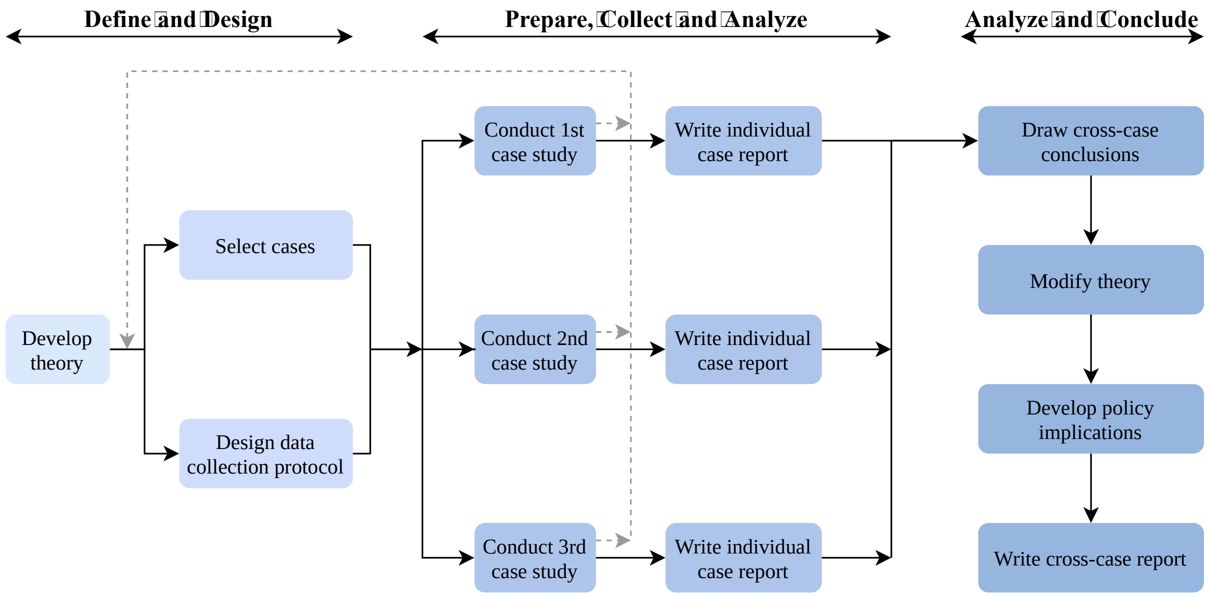
Case Study Approach

An important strength of case study research is that novel theory can be derived from the results, specifically for a phenomenon where current knowledge on the topic seems inadequate, as preliminary research has demonstrated that little empirical evidence is available (Eisenhardt, 1989). In this thesis, **exploratory research** is conducted. The phenomenon, in this case circular IC, is described but new terrain in which it occurs in is also explored. Put differently, opportunities are identified for which the niche can be scaled up, leading to a wider adoption and potential regime shift.

Due to the novelty of this topic, it is not certain that one single case study will be considered an adequate representative case. Thus, a **multiple case study design** is chosen examining three individual case studies. The main advantage of a multiple case study framework is that evidence is provided using a number of sources that share methodological similarity. However, this type of design is considered resource intensiveness (Emerald Publishing, n.d.). Finally, the thesis will make use of a **holistic design** exclusively examining the global nature of the organization of each case study (Yin, 2018, p. 52).

Multiple-Case Study Procedure

To proceed forward with conduct case study research, there is a certain procedure to follow as depicted in the Figure below. The initial step is to define and design the study. Prior to selecting the case studies, theory should be developed. Simultaneously, the specific measures are defined to collect data (Yin, 2018, p. 57). In this case, a reference is made to the conceptual framework. The second part of the procedure is to prepare, collect and analyze the case studies. Each individual case study becomes the subject of the whole case study, in which evidence is sought to serve as purpose for the outcomes and conclusions of the study. Before the final conclusion is derived, an individual report is created for each case indicating how and why a specific proposition was or was not demonstrated. Subsequently, cross-case conclusions are drawn – a technique that can only be applied to a multiple-case study design (Yin, 2018, p. 195). In this synthesis, it is of utmost importance to identify differences and similarities among the individual cases. The integrity of the entire study is retained whilst within-case patterns across the cases are compared. The challenge is to develop well-substantiated arguments that are supported by the results, finally reporting them in a cross-case report.



Multiple-case study procedure. Adapted from Yin (2018, p. 58).

Appendix E - Interview Protocols

Interview Protocol Case Study Actors

Description

Circular industrialized construction combines circular economy principles (e.g. Cradle to Cradle) with industrialized construction (IC) methods. IC methods include concepts such as pre-assembly, off-site construction and prefabrication. IC accounts for a very small share in the Swiss construction industry and is considered a niche. Even more so is circular IC and therefore this development is named a niche-within-a-niche.

Goal

Gain insights into the developments taking place in circular industrialized construction. How do actor's experience, collaborate and envision circular IC? What factors do they believe hinder or enable circular IC and what are the possibilities for scaling up in Switzerland?

Introduction myself – 5 min

1. Fleur van den Broek, 23, Dutch, MSc. Student IE, collaborating with ETH Zurich for thesis
2. Topic: circular IC in Switzerland - current practices and potential for expansion
3. Goal: Gain insights into ways/factors to enable the development circular IC in Switzerland.
4. Specific objectives:
    a. Involvement in project and general experiences of project
    b. Visions created and expectations for project
    c. Composition and collaboration of network
    d. Learning processes from participating in the project
    e. Drivers, opportunities and barriers of circular IC
5. Confirm signature of consent template, scan and send to you next day.
6. Ask to record interview. A transcript will be created and send to you within 3 weeks to check if anything is missing or misinterpreted.

Interview questions

Skip questions in red when limited time available

1. **Introduction**– max. 3 min
    a. Who are you?
    b. What is your role in this organization/ company?
    c. What does your organization/ company do?

2. **Topic exploration** - 4 min
    a. How would you describe CE and what does CE in construction/ the built environment mean? What do you mean/ how would you describe IC (methods) and how can that contribute to CE?
    b. How does your organization/ company contribute to CE in (industrialized) construction? Through which activities/projects?

SNM framework

3. **Vision creation** – 7 min
    a. Is there a vision for the project? If so, what is it?
    If not, what is the underlying vision of the project for CE and IC? / What is your vision for CE in IC? [Vision content, Vision image]

Follow-up questions:

   i. How was this vision established? Who initiated this vision? [Vision development, Vision guidance]
   ii. To what extent did stakeholders involved share this vision? [Vision development]
   iii. What was required to achieve this vision? [Vision guidance]
   iv. Did the vision lead to motivation and inspiration throughout the project? If so, how did this evolve? [Vision orientation]

b. What are you expectations for the future for this particular project and circular IC? [Expectations]
   i. Technical aspects
   ii. Market and user needs
   iii. Industry developments
   iv. Societal and environmental impacts
   v. Policy and regulations

4. **Network formation** – 15 min (start at 20 min)

a. What is your role as an individual/ organization in this project?
b. Which parties were involved in the project and what were their activities/ contributions/ responsibilities? [Network composition]
c. How was the network organized? Was there a project agreement, e.g. signing a contract? [Network alignment]
d. Where there external parties involved, e.g. as an advisory group or educational institution, or otherwise? Who else is important for the project (or its follow-up)? [Network dynamics]
e. How did you experience the collaboration and communication to be? [Network alignment, Network dynamics]
   Follow-up questions:
   i. Was there sufficient trust? How good was (confidential) information shared? [Network dynamics]
   ii. Were there any changes in the composition of the network during the project, e.g. parties that left or joined later? [Network alignment]
   iii. Where there any conflicts or conflicting views and how were they resolved? [Network alignment]
f. How will the collaboration/ network develop after the project has been completed? [Network alignment]

5. **Learning processes** – 16 min (start at 35 min)

a. What (societal/technical) problem did the project aim to solve? Was the problem definition changed during the project? [Problem framing shift, joint learning shift]
b. What is the main solution (approach) for solving the problem or contributing to this (e.g. methods for CE)?
c. What do you think others have learned from this project and what have you learned together? [Problem solving/ priorities shift]
d. What have you learned on an individual level and as organization participating in this project? [First order learning]
e. What was learned in the project? [First order learning]
   i. Technical aspects

CE assessment:

1. Which principles of CE were applied to this project? E.g. product lifetime extension, use of circular materials, resource recovery?
2. Looking back at the project, what methods do you believe were missing, and would be applicable to the project?
3. If applicable: Will you be able to share your CE assessment analysis with me?

ii. Market and user needs
iii. Industry developments
iv. Societal and environmental impacts
v. Policy and regulations
vi. What would you have done differently?

f. What are the most important lessons for others who are involved in the circular economy and circular IC?

MLP framework

6. **Scaling up circular IC** – 5 min (start at 50 min)
   a. What is required to scale up circular IC (activities/ resources/ actors), how can this project contribute to the transition of circular IC?
   b. What are the drivers and barriers for transitioning to circular IC, e.g. financial/political etc. factors?

7. **Closing** – 5 min
   a. Short summary/ reflection of conversation
   b. Can you recommend other contacts I could interview for my thesis research?
   c. Do you wish to receive my results / executive summary of the thesis after I have completed my research?
   d. Do you have any other remarks/ questions?
   e. Thank you for your time!

Interview Protocol External Actors

Description

Circular industrialized construction combines circular economy principles (e.g. Cradle to Cradle) with industrialized construction (IC) methods. IC methods include concepts such as pre-assembly, off-site construction and prefabrication. IC accounts for a very small share in the Swiss construction industry and is considered a niche. Even more so is circular IC and therefore this development is named a niche-within-a-niche.

Goal

Gain insights into the developments taking place in circular industrialized construction in Switzerland. What factors do you believe hinder or enable the circular economy and industrialized construction in the construction industry? What are possibilities for scaling up circular IC in Switzerland?

Introduction myself – 5 min

7. Fleur van den Broek, 23, Dutch, MSc. Student IE, collaborating with ETH Zurich for thesis
8. Topic: circular IC in Switzerland - current practices and potential for expansion
9. Goal: Gain insights into ways/factors to enable the development circular IC in Switzerland.
10. Specific objectives:
    a. Main developments in Switzerland that influence the construction industry
    b. Development in the construction industry (in terms of circular economy and industrialized construction)
    c. Drivers, opportunities and barriers of circular IC
11. Confirm signature of consent template (send prior to date of interview), if not yet filled in, ask to send after the interview.
12. Ask to record interview. A transcript will be created and send to you within 3 weeks to check if anything is missing or misinterpreted.

Interview questions

Skip questions in red when this is not applicable to a certain interviewee

8. **Introduction and topic exploration** – 8 min
    d. Who are you?
    e. What is your role in this organization/ company?
    f. What does your organization/ company do? How does your organization contribute to sustainability/ innovation in the construction industry?
    g. How would you describe CE and what does CE in construction/ the built environment mean? What do you mean/ how would you describe IC (methods) and how can that contribute to CE?

9. **Multi-level Perspective** – 20 min
    a. What are the main developments in and for the construction sector in Switzerland?
        I. Technical aspects
        II. Market and user needs
        III. Industry developments
        IV. Societal and environmental impacts
        V. Policy and regulations

b. What are the most important developments regarding the circular economy and industrialized construction in the construction industry in Switzerland? Who are key actors and what should they do/ provide? [Regime]
   I. Public policy e.g. regulations/ subsidies
   II. Techno-scientific knowledge e.g. research at institutions/ universities
   III. Industry structure e.g. IC/ CE players
c. What is required to transition to circular IC in Switzerland? [Niche]
   I. Actors
   II. Activities
   III. Resources
d. What are the drivers and barriers for transitioning to circular IC in Switzerland? [Niche]
   I. Technical aspects
   II. Market and user needs
   III. Industry developments
   IV. Societal and environmental impacts
   V. Policy and regulations
e. Do you know any companies/ organization in Switzerland that focus on the circular economy/ IC in the construction industry?

10. Closing – 5 min

f. Short summary/ reflection of conversation
g. Can you recommend other contacts I could interview for my thesis research?
h. Do you wish to receive my results / executive summary of the thesis after I have completed my research?
i. Do you have any other remarks/ questions?
j. Thank you for your time!

Appendix F - Consent Form Interviewees

Consent Form – semi-structured interviews

Study title: Integrating circular economy principles with industrialized construction methods

Researcher's Name and First Name: Fleur van den Broek

Participant's Name and First Name:

The objective and aim of this interview is to conduct a case study focusing on the integration of circular economy principles in industrialized construction methods in Switzerland. This information will be used for **research purposes only**.

Any **confidential information** will be treated and respected with the sensitive nature and trust provided. **Please indicate within your answers if confidential information is provided.**

During the interview, you will be asked questions that explore the enablers and barriers on the development of circular industrialized construction in Switzerland. The research will conduct a recorded interview lasting a maximum of 1 hour. You are free to skip any questions that you would prefer not to answer. You may end your participation at any time within the interview process. Recordings will be used to transcribe the interview.

For any further information or questions please contact researcher Fleur van den Broek:
Telephone: xxx or Email: fleur.vandenbroek@hotmail.com

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Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	[]	[]
I understand that taking part in the study involves an audio-recorded interview and that the researcher might take written notes as well. The audio recordings will be transcribed as text and will be stored safely. Only the researcher will have access to the original data.	[]	[]
Use of the information in the study		
I understand that information I provide will be used for the researcher's Master thesis report.	[]	[]
I agree that my name, job title, company and information I share can be quoted in research outputs.	[]	[]
I understand that any other personal information collected about me that can identify me, such as my email address, will not be shared beyond the study team.	[]	[]

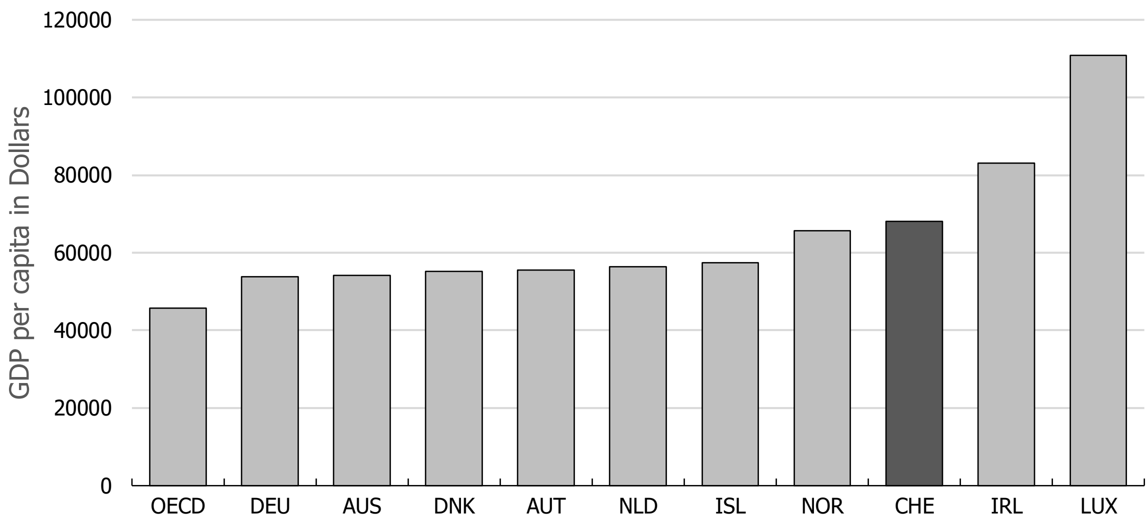
Signatures

Click or tap here to enter text.	Click or tap here to enter text.	Click or tap to enter a date.
Name of participant	**Signature**	**Date**
Fleur van den Broek		Click or tap to enter a date.
Researcher name	**Signature**	**Date**

Appendix G - Background Information Landscape and Regime Developments

Landscape

Switzerland ranks the third-highest by GDP per capita in the OECD due to high employment and productivity levels (see Figure below) (OECD, 2019). Since the economic crisis, **economic** growth has quickly recovered in the country compared to its European trading partners. Living standards have continued to increase ever since with an average growth of 0.6% between 2009 and 2017 (OECD, 2017). Nevertheless, growing incomes and consumption have led to a higher material consumption, waste generation and environmental impact. This development is defined as a long-term change.

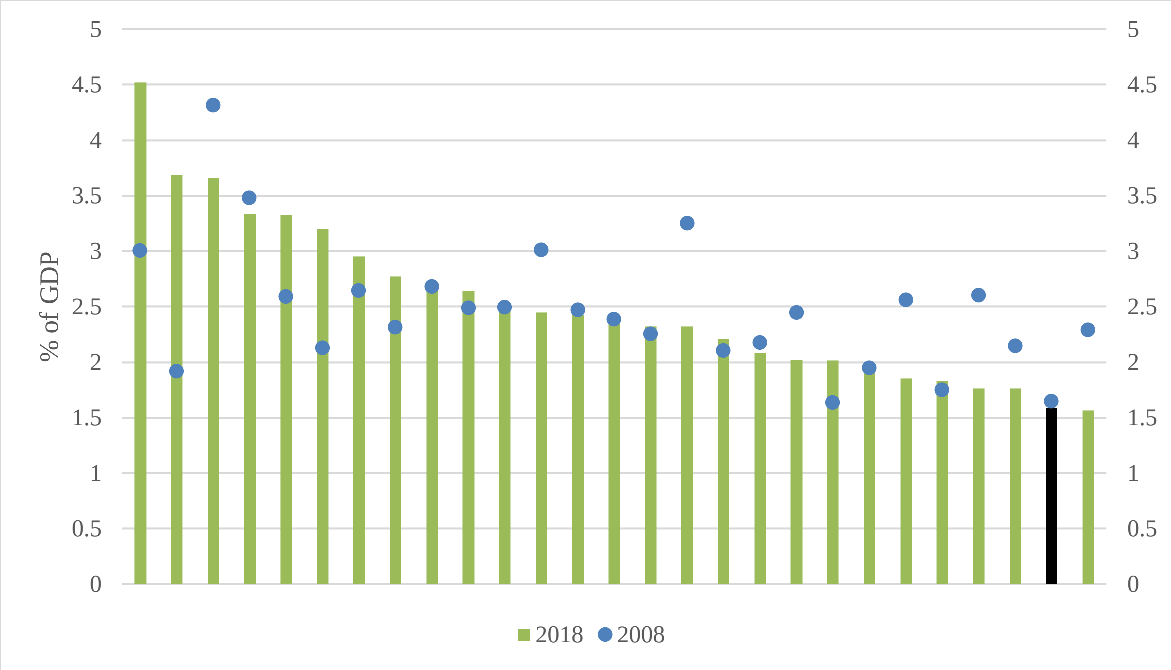


GDP per capita (in dollars) for the ten richest countries including Switzerland highlighted in dark grey (OECD, 2019).

Favorably, the country's emission intensity of economy (GDP) is listed at the bottom of the rank for OECD countries. Thanks to high shares of renewable energy including hydropower and nuclear energy in the energy mix and a service-based economy, the economy's carbon intensity has been noticeably low.

From 2007 until 2015, government **environmental** protection expenditure increased lightly to around 0.7% of Switzerland's GDP (OECD, 2017). The rise of this spending, a long-term development, might aid in curbing CO2 emissions, however no recent data to substantiate this argument was found.

Accrued environmentally related tax revenue was equal to 1.65% of GDP in 2008 and 1.59% in 2018 (see Figure below). This number is far behind the European OECD average of 2.36% of GDP. Surprisingly, the share of tax revenue was slightly higher in 2008 than 2018, even though there has been a growing level of environmental awareness over the course of this period. It is assumed that this number was influenced by the introduction of a CO2 tax in the same year.



Share of environmental taxation in percentage of GDP – Switzerland in black (OECD.stat, 2018).

Regime

Science

An expert of the construction industry commented about a new **technological** research project initiated by industry partners starting in the near future called Lab North (Interviewee 4, December 19, 2019). The main goal is to create a living area considering the topics of CE and digital fabrication located just outside the city area of Zurich. The notion of gathering information and research created within Switzerland instead of looking international is key here. Supposedly, the living lab will combine innovations originating from research institutions, education and the industry. Due to the novelty of this project, there is no additional information available. However, this initiative does entail that not only the government has a stake in this topic, but industry is also interested in further developing the circular IC.

Industry Structure

Another **technological** element is Eberhard Unternehmungen, a construction materials recycling company producing (high quality) structural concrete entirely from recycled aggregates. The company is considered a pioneer in the field of urban mining in Switzerland. Despite the availability of this advanced technical solution, the industry is picking up at a slow pace (Interviewee 2, December 12, 2019). Through public procurement, the diffusion of such an innovation can be accelerated. As mentioned before, the City of Zurich decided to construct new buildings exclusively with recycled concrete. This provided a competitive advantage for Eberhard to pioneer in this field, having a stationary plant close to the city allowing for short transport distances. It has led to a great impact in the concrete recycling industry. Even so, concrete is not considered an environmentally friendly building product using vast amounts of water and energy. The use of recycled concrete would only make sense in a dense urban environment, as waste streams are located closer to such areas and do not have to be transported over long distances.