Modular Building in a Circular Economy

An exploratory research

Astrid Potemans

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Preface

This report is the result of, what I would like to call, my greatest joy and my greatest struggle during my years at the TU Delft.

My greatest joy, because the graduation laboratory of circular economy has allowed me to rediscover the subjects that I had long left behind in high school – economics and physics as well as discover the subjects that I had never dared to dig into before – philosophy and politics.

My greatest struggle, because more than ever, I became aware of my own limitations. As Isaac Newton once said: “To explain all nature is too difficult a task for any one man or even for any one age. ´Tis much better to do a little with certainty, and leave the rest for others that come after you, than to explain all things”.

In my research process I often found myself trying to explain all: expanding my knowledge with every article I read, discussing new insights with my supervisors. In the first few months, every month I came up with something new.

I would like to thank my supervisor Matthijs Prins for encouraging me to stay open-minded. I sometimes wondered how I was going to make sense of all the data I had gathered. I would like to thank my supervisor Ad Straub for encouraging me to do little, but with certainty.

In addition, I would like to thank Luuk Gremmen, who is also soon to graduate in the circular economy lab. It was great to be able to share articles, discuss each other’s work and drink coffee when we were stressed out (although neither of us will admit we were ever stressed out).

I would like to thank Clarine van Oel for taking the time to read my report and provide me with very useful feedback. Even though it may have bewildered me at first, it has allowed me to reflect upon my work.

Last but not least, I would like to thank my father for his enthusiasm for my graduation project; your feedback, though sometimes unsolicited, always proved to be extremely helpful. I am glad to see that your eagerness to learn has not decreased with age; neither does your persistence. I am glad to have inherited these traits.

Astrid Potemans

Delft, June 29th, 2017

Summary

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Abstract

A circular economy has gained attention as a potential solution to the tension between the increasing demand for and the limited supply of materials. The construction industry consumes a great amount of global resources and generates a great amount of waste, and can contribute to the shift towards a circular economy by means of a more circular building stock. In theory, modular building can contribute to a circular building stock, by securing the future utility of the stock. Multi-configuration modular building allows for adjustment and relocation of the building and deconstruction and reuse of its piece parts. Based on a collective cases study of five suppliers of modular building, the degree to which modular building can contribute to a circular economy depend on the reason for, the interpretation of and the operationalisation of modular building.

Keywords: circular economy, modular building, exploratory research, case study

Introduction

In the past few years the concept of a circular economy has gained attention as a potential solution to the tension between the increasing demand for and the limited supply of materials. The construction industry is said to consume more than half of the global resources and generate the greatest waste stream globally buildings (Iacovidou & Purnell, 2016). Thus, it seems as if there is potential for the building industry to shift from a linear to a more circular economy. This research is focused in the Dutch building industry.

The tension between the increasing demand for and limited supply of materials is more nuanced, especially when considered in the context of the Dutch building industry. In the Netherlands, it is expected that the natural growth rate will be, and will continue to be negative as of 2038 (CBS, 2016). Furthermore, most materials used in the sector are not considered scarce (Rijskwaterstaat, 2015). However, there are other drivers for a circular economy in the Dutch built environment: the pressure on the living environment and the ecosystem caused by the extraction and use of resources, and the size of the waste stream (Rijskwaterstaat, 2015).

The building industry is experimenting with circular buildings. However, as the concept and operationalisation of a circular economy is interpreted in various ways, the experiments with circular buildings yield a variety of results (Linder, Sarasini, & van Loon, 2017). Some authors (Addis,2006; Allwood, 2014; Iacovidou & Purnell, 2016) propose the reuse of components to reduce the need for new raw materials. Modular building seems to be a promising and straight-forward means to increase component reuse.

The concepts of a circular economy, a circular building stock and modular building remain open to interpretation. The objective of this research is to explore how modular building can contribute to a circular building stock and, consequently, the transition towards a circular economy.
The main research question in this research is: *How can modular building contribute to a circular building stock?*

The relevance of this research is threefold. In the current economy of growth, scarcity is expected to become a pressing problem. Consequently, an increasingly smaller part of society will be able to enjoy the services and goods produced with these materials. A circular economy is a possible solution to mitigate this societal problem. The concept of a circular economy is not unambiguously defined in literature, especially not in relation to the built environment. Research on this topic focuses mostly on the macro-scale of the city or the micro-scale of the component (Pomponi & Moncaster, 2017). In this research the focus is on the meso-scale — modular building. This connects all three scales of the component, the building and the building stock. The practical relevance of this research is that it can improve the match between demand and supply in the building industry, now and in the future, by focusing on the durability and the long term utility of the building stock.

Methodology

The objective of this research is exploratory, and therefor a research method with a maximum of exploratory power is considered most fit. The research question is answered by means of qualitative methods.

The research consists of three parts. The first part focuses on the concept of a circular economy in general; the second part focuses on the concept of a circular building stock. In the first two parts the following secondary research questions are answered by means of a literature study:

1. What is a circular economy and what is the goal of a circular economy?
2. Is a circular economy of growth possible?
3. What constitutes a circular building stock?
4. How can the current building stock be characterised?
5. What are the different options to make the building stock more circular?

In the third part of the study, the focus is on modular building. It is answered by means of a literature study and by means of a collective case study.

6. What is modular building and what is the current practice of modular building in the Netherlands?

To explore whether modular building can be an effective means to a circular building stock in practice, a collective case study is conducted, in which providers of modular buildings and their products are analysed. The amount of cases should range from three to fifteen to show enough interactivity for the researcher to comprehend (Stake, 2006). The inclusion criteria for the cases are that they provide modular housing solutions; describe their product as "modular"; mention “circular economy” or “scarcity of resources” on their website and are located in the Netherlands.

An email was sent to thirteen firms; nine replied and eventually five firms were included in the case study. Two main sources of data were used: the website of the firm and a semi-structured interview with the firm. The topics of investigation were the idea behind the firm; its interpretation of modular building, reason for building modular and definition of "the module"; and the characteristics of the product.

Findings

The concept of a circular economy is not unambiguously defined. Adams, Osmani, Thorpe, & Thornback (2017) report on the common elements of maximising the value of materials and eliminating waste; materials are kept within a closed loop. Daly (1977) argues that the economic system can be thought of as the intermediate between the ultimate source — low entropy resources — and the ultimate goal — human well-being. The intermediate goal in a circular economy

In the current global economy, a predominant intermediate goal is growth in the Gross Domestic Product (GDP) (Boulding, 1966). Growth in the GDP can be, amongst other things, achieved by increasing production: by discovering and mining raw materials and growing the labour force. Growth in the GDP as an intermediate goal would therefor only aggravate the problem. Daly (1977) proposes alternative intermediate goals and refers to this economic system as a steady-state economy. In a steady-state economy, the quality of the stock of goods is to be improved to provide more services (development); and the throughput required to maintain this stock is to be minimised (increase in durability).

Daly (1977) also argues that the population size is to be held at a constant level. In this research, the concepts of Daly are taken as the basis to define a circular economy. However, the population size is not considered as a controllable variable. A “practical” circular economy therefor is an economy of both growth and development, or a realistic compromise between an economy of growth and a steady-state economy.

A “practical” circular economy is an economy of both development and growth. The goal is to control the size of the stock of goods and to increase the utility and the durability of this stock. A circular building stock “fits” within the objectives of a “practical” circular economy: it has a high utility and a high durability. The current building stock can be characterised by two extremes. The one extreme is characterised by permanence, by immutable and static buildings, that have a high durability but a low utility. The other extreme is characterised by temporality, by adaptable and dynamic buildings, that have low durability and a high utility (Brand, 1995). In reality, the current building stock is a mixture of different types of buildings.

One could say that a building is left obsolete when it has lost its utility. There are a countless number of reasons why buildings are left by their occupants. Thomsen & van der Flier (2011) provide a framework of building obsolescence based on two axes: endogenous and exogenous factors; and behavioural and physical factors. This framework is taken as a bases to develop an alternative framework, that serves as a simplified model, upon which strategies to secure the future utility of the building stock can be placed. Buildings can lose utility due to building-related factors, due to locational factors, or a combination of both. If buildings were designed to anticipate this loss of utility, they could more easily be adapted, relocated or deconstructed and its parts reused.

Modular building seems to be a promising design strategy for adaptability, relocation, deconstruction and reuse. However, in theory and in practice there are different interpretations of modular building.

Based on Lawson, Ogden, & Goodier (2014), modular building is the assembly of prefabricated volumetric units into a complete building on site. This is referred to as single-configuration modular building in this research. Based on Staib, Dörrhöfer, & Rosenthal (2008), modular building is combining pre-determined elements into complete entities in a number of different ways. This is referred to as multi-configuration modular building in this research. Single-configuration modular buildings can be relocated, if the process of assembly is reversible. The same is true for multi-configuration modular buildings, but in addition, they can also be adapted or deconstructed, so that its elements can be organised into other types of entities. Multi-configuration modular buildings therefor “fit” best within the principles of a circular building stock.

Based on a small-scale collective case study of five modular building suppliers in the Netherlands, these two interpretations of modular building are also apparent in practice. Suppliers of modular building build modular to offer the client the freedom to design an affordable dwelling, and sometimes also to allow them to easily relocate or adapt the building after construction. In addition, modular building enables high quality production in factory conditions and quick and easy assembly on site.

The firms interpret modular building differently, but interpretations include building in a permanently adaptable manner; an industrial way of building; an advanced form of prefabrication; building on a fixed grid; and building with modules that have a standardised dimension. The “modules” are either standardised panels or a volumetric units, that can be assembled in a number of configurations on site (multi-configuration modular building); or jigsaw puzzle pieces, that can be assembled in a single configuration on site (single-configuration modular building).

Multi-configuration modular building has the potential to contribute to a circular building stock. Most suppliers mention that the product can be adjusted in the design as well as in the operations phase. If the module is an element rather that a building part of segment, many configurations are possible. The degree of customisation is however constrained by the chosen building construction, rules and regulations and integrated service installations. Most suppliers also mentioned that the product can be relocated. In this way, it can cope with a loss of utility due to locational factors. A possible constraint is the financing construction: if the building serves as collateral for the bank, it can not simply be relocated. With regards to the possibility to deconstruct and reuse the parts, the firms mentioned that the parts at least can be reused within the building system of the firm; whether these parts can be reused outside of this building system is not investigated further.

Conclusion

Modular building can contribute to a circular building stock. It is a means to secure the future utility of the building stock, and in theory, it allows for adjustment and relocation of the building; and deconstruction and reuse of its piece parts. However, this is only true for multi-configuration modular building. In practice, the degree to which modular building can contribute to a circular economy depend on the reason for, the interpretation of and the operationalisation of modular building.

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Introduction

Problem statement

Since the Industrial Revolution mankind generally has, on a large scale, extracted raw materials from the earth to turn them into products, as shown in Figure 1. Today, the world's population is growing steadily, as shown in Figure 2. This development results in an increasing demand for economic goods and services. As a result, there is an increasing need for materials, whilst the supply is limited (Reh, 2013).

In the past few years the concept of a circular economy has gained attention as a potential solution to the tension between the increasing demand for and the limited supply of materials. In a circular economy the extraction of raw materials is minimised by maintenance, reuse, remanufacturing and recycling (Ellen MacArthur Foundation, 2013). The concept of a circular economy is in contrast with the more linear economy of today, in which raw materials are extracted, used and disposed, as shown in Figure 3.

The construction industry is said to consume more than half of the global resources and generate the greatest waste stream globally (Iacovidou & Purnell, 2016). Thus, it seems as if there is potential for the building industry to shift from a linear to a more circular economy.

Complexity of the problem

The problem of the tension between the increasing demand for and the limited supply of raw materials is more complex than one might assume at first glance. This is linked to the scale levels at which the demand and supply are considered.

Demand

The world's population is expected to grow, but the natural growth rate is declining (U.S. Census Bureau, 2016). Furthermore, there are differences in natural growth rates between nations; in some nations this rate is negative (CBS, 2017). In the Netherlands, it is expected that the natural growth rate will be, and will continue to be negative as of 2038 (CBS, 2016).

The demand for economic goods and services is not only determined by the size of the population, but also

Figure 1 (top left): The extraction of raw materials (own figure)

Figure 2 (top right): The world's population is expected to grow (own figure)

Figure 3 (bottom): A linear economy in which materials are extracted, made into products and disposed (left); in contrast, a circular economy in which materials are reused and recycled (right) (own figure) by the wishes and needs of that population: "human demand for energy and material has proved insatiable" (Allwood, 2014, p. 447).

Supply

Also on the supply-side, the problem is more nuanced. A material can be scarce because it is geologically rare; because its extraction is financially unviable; or because the supply of the material is concentrated in politically unstable or centrally controlled countries (Hobson, 2016). In addition, not all materials are considered scarce — especially in the Dutch building industry, resource scarcity does not seem to be a pressing problem (Rijkswaterstaat, 2015):

"In the [Dutch] building industry, [resource] scarcity mostly does not seem to be a driver for a circular economy; the size of the waste stream is" (p. 9).

"The resources that are currently used in the building industry, do put pressure on the living environment; and the extraction of resources puts pressures on the ecosystem" (p. 20).

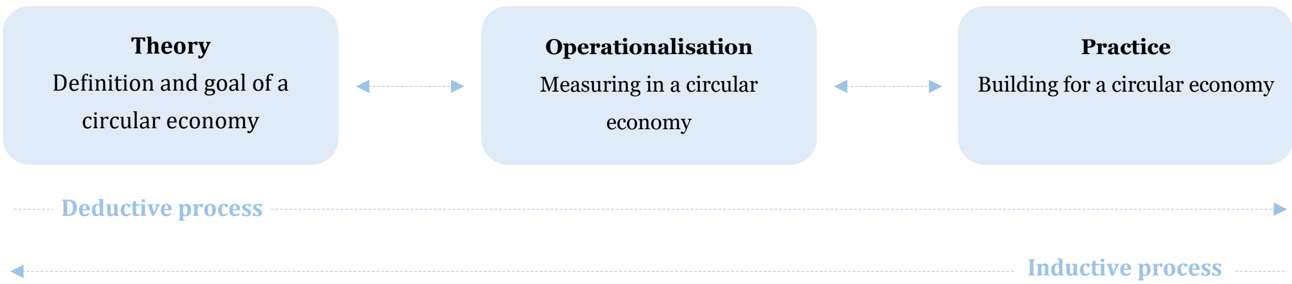
Based on the above, the transition towards a circular economy in the built environment seems desirable. The building industry is experimenting with circular buildings, but there are still gaps in knowledge (Iacovidou & Purnell, 2016).

Gaps in knowledge

The concept of a circular economy is not clearly defined in literature; it is used in several ways as a means to various goals, or is sometimes presented as a self-contained goal. Accordingly, a number of circularity metrics is designed for different spatial levels, ranging from the global level to the level of a single company, as well as for different industries (Linder, Sarasini, & van Loon, 2017). The experiments with circular buildings yield a variety of results, greatly dependent on how a circular economy is interpreted and which principles and metrics are applied.

A circular economy can be considered as an ideal that "ought" to be implemented in a top-down manner. Simultaneously, it can be considered as a phenomenon that manifests itself in practice and is then induced into theory (Pomponi & Moncaster, 2017). This iterative process is resulting in conflicts *within* but also *between* theory, operationalisation and practice, as shown in Figure 4.

Figure 4: Gaps in knowledge within and between the theory on, the operationalisation and the practice of a circular economy in the built environment (own figure)



Research objectives

As mentioned in before, the building industry is experimenting with circular buildings. Some authors (Addis,2006; Allwood, 2014; Iacovidou & Purnell, 2016) propose the reuse of components to reduce the need for new raw materials. Modular building seems to be a promising and straight-forward means to increase component reuse:

> "The end of a product's life is generally determined by one subassembly, module, or component, while the remainder of the product has residual life. If this life cannot be extended for the whole of the original product, it may be possible to exploit the residual life of the modules through partial disassembly of the original product into modules, some of which can then be reused in other assemblies" (Allwood, 2014, p. 462).

The concepts of a circular economy, a circular building stock and modular building remain open to interpretation. The objective of this research is to *explore* how modular building can contribute to a circular building stock and, consequently, the transition towards a circular economy.

Indeed, there are many ways to think about and to practice circular building, but the emphasis of this research lies on modular building, as it seems a promising, practical and straight-forward solution.

This research is not merely conducted as a fundamental research, aiming to contribute to the existing body of knowledge. This research is conducted as an applied research, aiming to resolve or improve a situation in practice — to stimulate the transition towards a circular economy in the built environment (Boeije, 2010). The recommendations from this research are an integral part of this.

Research questions

The main research question in this research is: *How can modular building contribute to a circular building stock?*

This question is answered by means of the following secondary research questions:

1. What is a circular economy and what is the goal of a circular economy?
2. Is a circular economy of growth possible?
3. What constitutes a circular building stock?
4. How can the current building stock be characterised?
5. What are the different options to make the building stock more circular?
6. What is modular building and what is the current practice of modular building in the Netherlands?

Relevance

The relevance of this research is threefold, as shown in Figure 5 and is elaborated upon below.

Societal relevance

The demand for materials is expected to grow, whilst the supply is limited. In the current economy of growth, scarcity is expected to become a pressing problem. Consequently, an increasingly smaller part of society will be able to enjoy the services and goods produced with these materials. In a circular economy, future generations will be able to or are expected to be able to do more with less input from raw materials.

Scientific relevance

The concept of a circular economy is not unambiguously defined in literature, especially not in relation to the built environment. Pomponi & Moncaster (2017) argue that the focus of research in this field is predominantly on the on the macro-scale (cities) and the mirco-scale (manufactured components), rather than on the meso-scale (buildings). In this research the focus is on the meso-scale — modular building. This connects all three scales of the component, the building and the building stock.

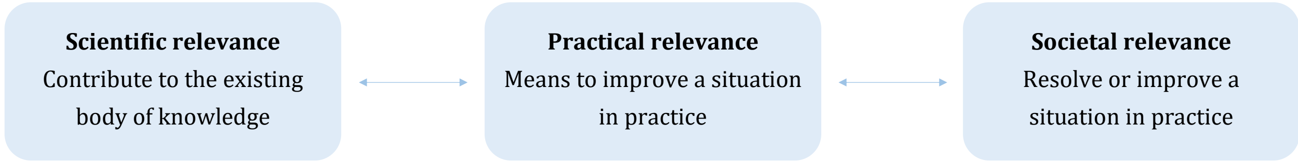


Figure 5: The relevance of this research (own figure)

Practical relevance

The objective of this research is to explore how modular building can contribute to a circular building stock. The focus is on the long-term utility and the durability of the stock. As the costs of raw material extraction and waste disposal are expected to increase, this perspective may inspire the building industry to create new business models that are consistent with a circular economy. The focus on long-term utility is also beneficial for the actual users of the building stock — the occupants of buildings. The supply is expected to better fit the demand.

Readers' guide

The central concept of this research is a circular building stock. However, this circular building stock is embedded within a broader context that needs to be explored first: a circular economy. A possible means to a circular building stock is modular building. This report is structured into Parts I, II and III, starting with the fundamentals of the "why" and the "what", then moving on to the "how", as shown in Figure 6.

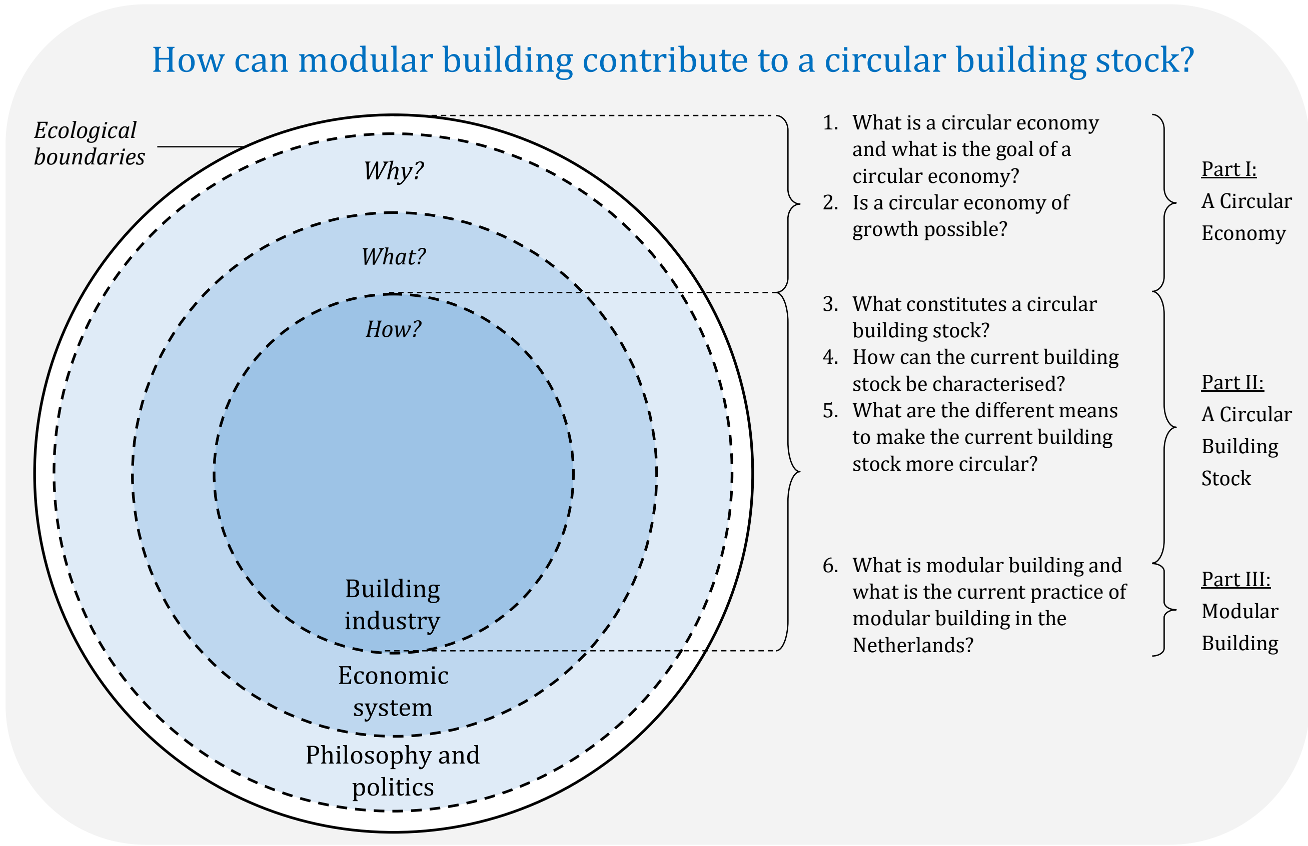


Figure 6: Reader's guide, moving from the "why" to the "what", to the "how" (own figure)

Methodology

Study design

The main research question of "How can modular building contribute to a circular building stock?" is answered in three parts by means of six secondary research questions.

The objective of this research is to explore how modular building can contribute to a circular building stock. Methods with a maximum of explorative power are required, and a qualitative research method for that reason seems most fit.

First, a circular economy as a whole needs to be explored. Second, the focus is narrowed to the built environment. Parts I and Parts II are covered predominantly by a literature study. Third, the status quo of modular building in the Dutch building industry is explored by means of a qualitative case study.

Research strategy

The predominant research strategy in this research is the case study. In a case study the researcher "explores a bounded system (...) through detailed, in-depth data collection involving multiple sources of information (...) and reports a case description and case-based themes" (Creswell, 2007, p. 79). This research strategy is considered suitable to answer the research questions, as case studies allow for the researcher to investigate in-depth how the concept of a circular economy manifests itself in the current "real life" economic context.

The cases selected for this research are instrumental cases, meaning that they have a supportive role in exploring, describing or explaining a certain issue or phenomenon (Stake, 2005). This differs from an intrinsic case study, in which the researcher undertakes the case study because his main interest is that particular case.

Sampling

As the aim of this study is to develop an in-depth understanding, rather than a generalisation or a quantification, samples are selected from which most can be learned. This is commonly referred to as purposive sampling (Merriam, 2009). Two types of purposive sampling can be distinguished:

→ Theoretical sampling stems from grounded theory and is described as "the process of data collection for generating theory whereby the analyst jointly collects, codes and analyses his data and decides which data to collect next and where to find them" (Glaser & Strauss, 2009, p. 45);

→ A priori or predetermined samples are selected before the beginning of the data collection process, based upon a theoretical framework.

In this research both types of sampling are combined.

Parts I and II

Parts I and II are conducted by means of theoretical sampling. The direction of the literature study is guided by interviews and observations:

→ The mentoring discussions with the two supervisors of this graduation research can be considered to be unstructured expert interviews, as a means to enhance the academic knowledge of the researcher and to steer the focus of the research.

→ Semi-structured interviews are conducted to explore the concepts of modular building and a circular economy in Dutch building market. These interviews are conducted with two relatively large contractors; and one small supplier of modular housing. These are convenience samples, suggested by peers. These samples are prone to bias, but are used to become acquainted with the status quo on the Dutch building market rather than to draw generalisations.

→ For the same purpose a symposium of one of the interviewed contractors is attended, in which the researcher observed the actual fabrication of the modular dwelling and the dynamics between parties in the Dutch building industry.

Part III

Part III is conducted by means of a collective case study, in which suppliers of modular buildings are interviewed and their products are analysed. In a collective case study a number of instrumental case studies are used to make comparisons – "so that they effectively illuminate a common program or phenomenon" (Stake, 2006, p. x). As mentioned before, in a case study a bounded system is explored through data collection involving multiple sources of information. Primary data are collected:

→ From the website of the suppliers, including texts and photographs;
→ In semi-structured interviews with the suppliers;
→ Whenever possible, by visiting the building site and observing the prototype or actual dwelling.

A more detailed presentation of the selection process is provided in "Part III: Modular Building".

Synthesis

The main findings of Parts I, II and III are synthesised and placed within a broader context. Kingdon's (2014) multiple streams model is used to illuminate this broader context.

Data collection, analysis and interpretation

In qualitative research, the aim is to transform data into findings. In other words, to use the data to answer the research questions. The degree to which the data are transformed into findings can be linked to the research objective, as shown in Figure 7. What is meant by data collection, data analysis and data interpretation is elaborated upon in Box 1.

This research is exploratory rather than explanatory, as the data available at this point can hardly be used to produce a theory: "an attempt to develop a general explanation for some phenomenon" (Singh & Bajpai, 2007, p. 10). As mentioned, the objective of this research is to develop an in-depth understanding,

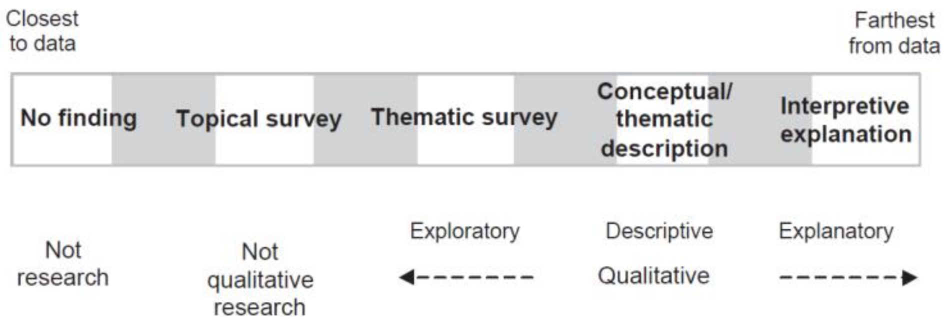


Figure 7: A typology of qualitative findings based on the degree of data transformation, by Sandelowski & Barroso (2003, p. 908).

> Data collection is the process of gathering information from various sources on a specific area of interest. Examples of data collection methods include participant observation, interviewing, focus groups and the production of visual data. Data analysis consists of segmenting and reassembling data, finding patterns and generating categories. Data can be analysed by means of a great number of methods and techniques, such as creating visual displays, matrices or memos. There are no 'right' or 'wrong' methods, however some methods may be considered more suitable than others, depending on the context and the content of the research (Boeije, 2010). The interpretations of the data form the answers the research questions.

Box 1: The concepts data collection, data analysis and data interpretation

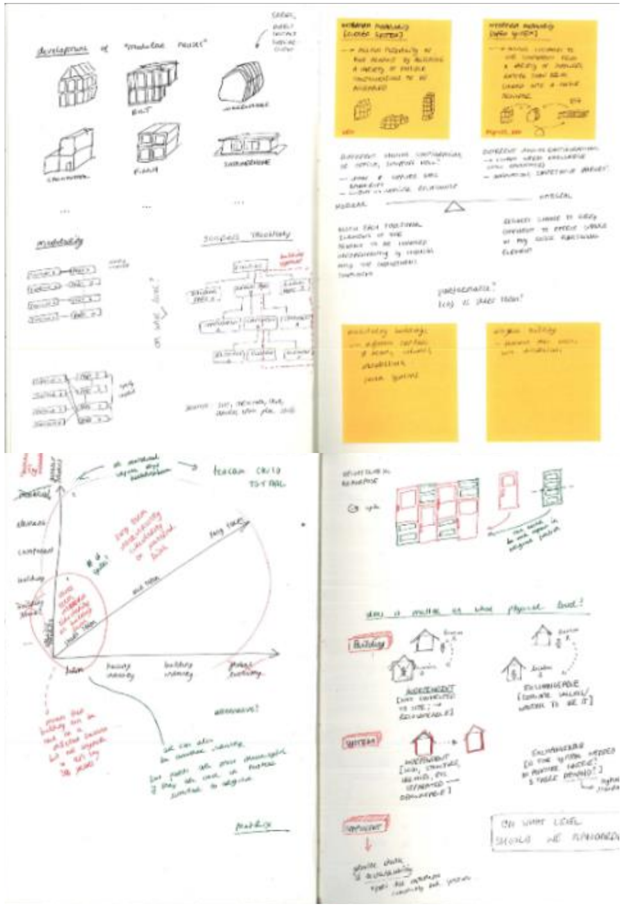


Figure 8: An example of data integration in this research: visual displays and diagrams (own figure)

The data collected in this researched are analysed by means of visual displays, diagrams and memos, of which examples are shown in Figure 8.

Quality of the research: credibility, transferability and consistency

The quality of a quantitative research is ensured in terms of validity, reliability and generalisability. To ensure quality in a qualitative research, Lincoln & Guba (1985) propose the alternative concepts of credibility, transferability and consistency. These concepts are elaborated upon in Table 1, as well as how these concepts are taken into account in this research.

The instrument of investigation is the researcher, the human, that has “shortcomings and biases that might have an impact on the study” (Merriam, 2009, p. 15). These shortcomings and biases may influence the interpretation of the data, and even though they cannot be eliminated, they can and need to be identified. This process of critically reflecting upon oneself as a researcher is called reflexivity. The researcher has obtained a bachelor’s degree in Architecture at the Technical University of Delft; this experience may have shaped the idea of how a building “should” be designed. Furthermore the researcher has her own view upon the concept of a circular economy and believes it can only go hand in hand with economic development, rather than economic growth. The researcher believes that economic growth at the current speed will compromise the living conditions of the coming generations. This view may have steered the interviews and has steered the direction of the research.

Ethical considerations

Following ethical guidelines participants were informed about the aim of the research. Informed consent was obtained at the interviews. Data are treated with confidentiality and interpretations of the data were submitted to the participants; approval by the participants was given.

Limitations

This research is conducted as part of the graduation from the master track Management in the Built Environment and as a result, the research is conducted within a limited amount of time, within a limited budget and within the geographical scope of the Netherlands.

Researcher's note

In reality the research process was organic, and very much resembled the process of theoretical sampling that stems from grounded theory: "the process of data collection for generating theory whereby the analyst jointly collects, codes and analyses his data and decides which data to collect next and where to find them" (Glaser, 1978, p. 36). This is partly due to the nature of the subject, and partly due to the limited experience of the researcher. However, to improve readability, the research is reported thematically rather than chronologically.

Criterion	Description	Tool applied in this research
Credibility (internal validity)	Do research findings match reality?	- Triangulation: - Multiple methods of data collection (interviews, observations and documents) - Multiple investigators (data interpretation is *checked* by colleagues and supervisors, but data are not *interpreted* by other researchers) - Multiple sources of data (different cases, however more variability could have been introduced as well as more interviewees per case) - Reflexivity of the researcher
Transferability (generalizability)	Can research findings be applied to other situations?	- Thick description (detailed presentation of the findings) - Maximum variation in the sample (only in the collective cases, but more variability in terms of market share)
Consistency (reliability)	Are the findings consistent with the data collected?	- Triangulation and reflexivity (see credibility) - Consistency could have been improved by means of an audit trail, which is a detailed log of the research process. A log was kept by the researcher, but unfortunately it lacks in structure and coherence to be able to follow for anyone but the researcher.

Table 1: Criteria for quality in this qualitative research (own table, concepts based on Lincoln & Guba (1985))

Findings

Part I: A Circular Economy

In this part of the research the following research questions are answered by means of a literature study:

→ What is a circular economy and wat is the goal of a circular economy?

→ Is a circular economy of growth possible?

It would seem logical to start with the “why”, in other words: the goal of a circular economy. However, this goal is lacking or is only implicit in most of the literature. As there seems to be consensus on what constitutes a circular economy, this will be the starting point of Part I.

The what: materials in a closed loop

The concept of a circular economy is not unambiguously defined. Adams, Osmani, Thorpe, & Thornback (2017) provide an overview is of the recurring principles of a circular economy, as shown in Table 2. They report on the common elements of maximising the value of materials and eliminating waste. Materials are kept within a closed loop. But *why* should these materials be kept in a closed loop?

A circular economy can be seen as the antonym of a linear economy. In a linear economy, materials are brought into the economic system, are used and disposed. The global economy has shifted more towards a linear economy as of the Industrial Revolution (1760-1840). The current global economy could be placed somewhere on the spectrum between a linear and a circular economy, as shown in Figure 8.

The why: ultimates and intermediates

The economic system can be thought of as the intermediate between the ultimate source and the ultimate goal, in which intermediate means and intermediate goals are specified, as shown in Figure 9. To describe a circular economy as an economic system, the ultimate source and goal are first discussed.

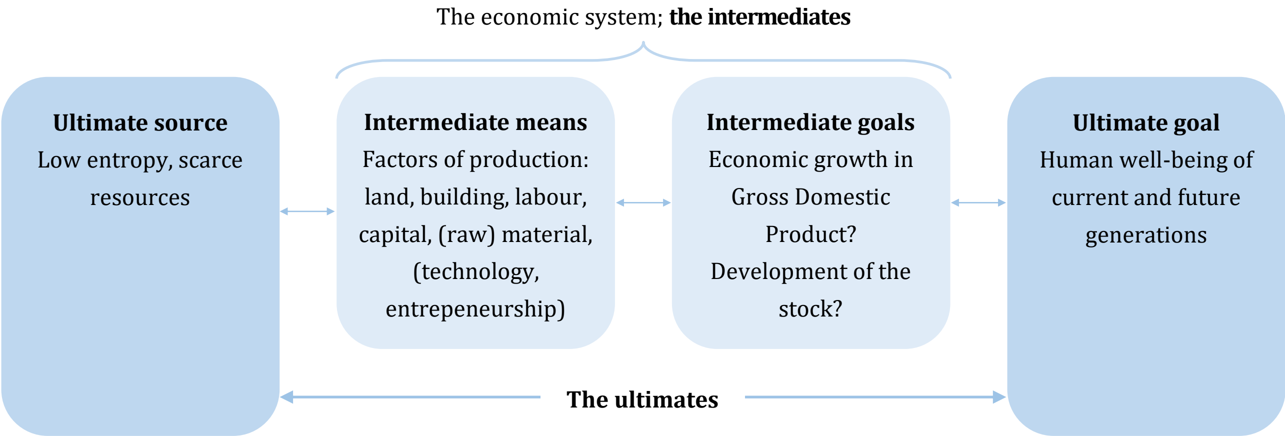


Figure 9: The economic system as the intermediate between the ultimate source and the ultimate goal. Edited version of Schouten, Grootveld, & Bureau de Helling (2016, p. 47) and Daly (1977)

Principle	Source
Increasing the productivity of materials by doing the same or more with less	Fuller (1973), Hawken et al (1999), Lund (1955), Stahel (2010), Womack et at (1990)
Eliminating waste by defining materials as either technical or biological nutrients enabling them to be within closed material loops; “waste as food”	EMF (2013a, 2013b), Lyla (1994), McDonough and Braungart (2002)
Maintaining or increasing the value of materials, environmentally and economically	EMF (2013a, 2013b), Weizsäcker et al (1997)
Thinking in systems by studying the flows of material and energy through industrialised systems, understanding the links, how they influence each other and the consequences, enabling closed loop processes where waste serves as an input	Graedel and Allenby (1995), Meadows and Wright (2008), Pauli (2010)

Table 2: Circular economy principles taken from the article “Circular economy in construction: current awareness, challenges and enablers“ (Adams et al., 2017, p. 16)

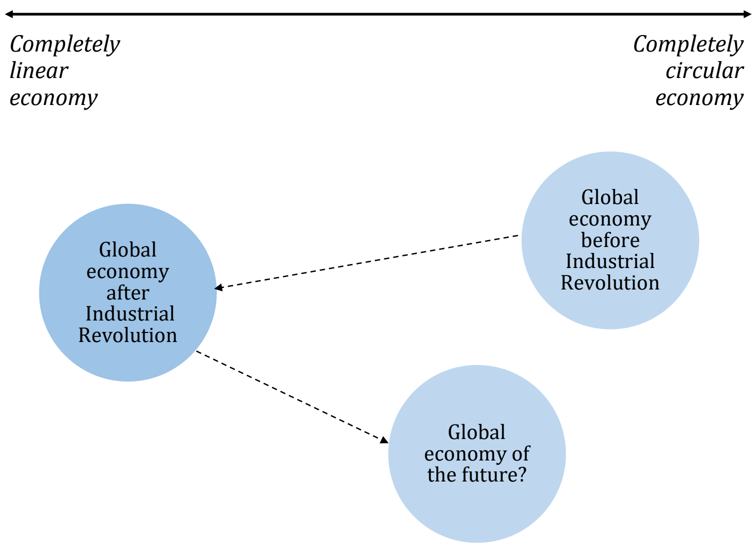


Figure 8: The place of the current global economy on a spectrum between a completely linear economy and a completely circular economy (own figure)

Low entropy sources

Terrestrial stock

→ Renewable

→ Non-renewable

or

→ Materials

→ Energy

Solar flow

→ The solar source is practically unlimited in total amount but limited in its rate of arrival on earth.

Box 2: An overview of low entropy sources after Daly (1977)

The ultimates

The ultimate source

“Scarcity means that society has limited resources and therefor cannot produce all the goods and services people wish to have” (Mankiw, 2012, p. 4). The scarcity principle is the very essence of economics. Material X allocated in good Y cannot be simultaneously allocated in good Z; a client that buys good Y cannot simultaneously buy good Z. This is the concept of relative scarcity. A growing population means that resources will become increasingly scarce, simply because there are more people that wish to have goods and services.

The concept of a circular economy is not only based upon the principle of relative scarcity, it is also based upon the principle of absolute scarcity. As materials are mined and brought into the economy, their organised, structured and concentrated state is transformed into a dispersed and randomised state: they are transformed from low entropy sources into high entropy sources. The same is true for fossil energy sources. This is known as the second law of thermodynamics. In all physical processes the matter-energy inputs in their totality are always of lower entropy than the matter-energy outputs in their totality. An overview of low-entropy sources is shown in Box 2.

The ultimate goal

The ultimate goal a circular economy "should" lead to seems to be lacking or is only implicit in most of the literature. The ultimate goal of humans on earth is arguable, as is the question of which economic system is "most suitable" to achieve this goal. It is assumed that human well-being of current and future generations is the ultimate goal. Indeed, this goal is completely anthropocentric and open for discussion.

Based on the prospect theory, as developed by Kahneman & Tversky (1979), the relatively certain here and now outweighs the uncertain future. "The disadvantages of change loom larger than its advantages, inducing a bias that favors the status quo" (Kahneman, 2012, p. 292). This contradicts the expected utility theory, in which it is assumed that human beings are homo economicus, always behaving rationally. "The humans described by prospect theory are guided by the immediate emotional impact of gains and losses, not by long term prospects of wealth and global utility" (Kahneman, 2012, p. 286-287).

The intermediates

The intermediate means

If the general interpretation of a circular economy is about keeping materials in a closed loop, this can be interpreted as a consensus on the intermediate means. The intermediate means in an economic system are the factors of production: land and building, labour, capital and (raw) material. This list is sometimes expanded with technology and entrepreneurship. At the micro-economic level, the quantity of goods (Q) a firm can produce is a function of the quantity of the production factors. This can be expressed in the long-run production function:

$$Q = f(L, B, Lb, C, M, t)$$

→ L: Land
→ B: Building
→ Lb: Labour
→ C: Capital
→ M: (raw) Material
→ t: time

Technology and entrepreneurship are not included in the formula. It is assumed that technology is intricately tied to the productivity of the inputs; entrepreneurship is tied to the productivity with which the inputs are turned into outputs. (Raw) material is but *one* of the production factors. The factors of production and the ratio in which they are allocated will further be elaborated upon.

Material

As mentioned, the current global economy can be placed somewhere between a linear and a circular economy. In some production processes, raw materials are replaced by secondary materials, as shown in Figure 10. This can be done if the secondary material is available; forms a substitute for the raw material; and has a lower price than the raw material.

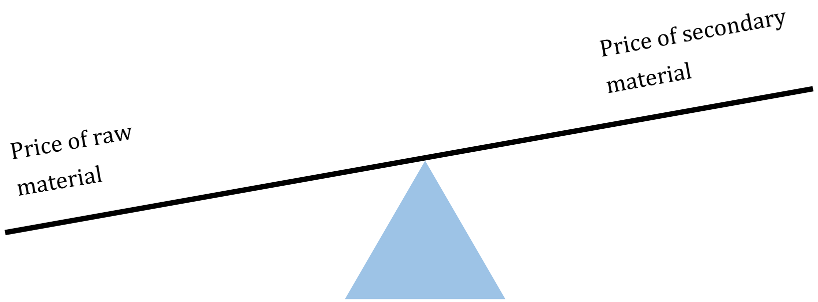


Figure 10: The price of a primary, raw material versus the price of a secondary material that serves as a substitute (own figure)

The raw and the secondary "version" of a material could be near perfect substitutes, but the perceived value, and as a result the price, may differ. The raw material could be preferred because it is perceived to be of higher quality than the secondary material, but the opposite could also be true. The secondary material is preferred because it is "supposed" to be better for the environment; an example of the latter is provided in Box 3.

At the start of the research process, the researcher conducted a series of unstructured interviews with suppliers and contractors, to better understand how the concept of a circular economy had manifested itself in the Dutch building industry. The following excerpts are translated from Dutch to English.

In an interview with the BFBN, an employers' association of concrete suppliers, the director Ton Pielkenrood elaborates on the current image of secondary materials:
"Interviewer: Could it be that a client specifically asks for secondary materials?
Interviewee: Of course. A client could, for example, demand at least 20% use of secondary materials.
Interviewer: How so?
Interviewee: Because of the image of secondary materials. If you use wood, it is considered to be "absolutely environmentally friendly"; the same holds true for the use of secondary materials".

This perceived value is much more apparent in reuse of components than in recycling of materials. In an interview with Bouwcarrousel, a former demolition contractor and second-hand component dealer, the former owner Rob Gort explains that "in the time of my company [between 2000 and 2010], there was relatively little demand for secondary building components — this was partly due to the image of second-hand components". Iacovidou & Purnell (2016) argue that the "changes in the perceived value of secondary construction components will likely put a higher demand for these in the near future" (p. 798).

Box 3: The image of "new" versus "second-hand" in the building industry

The allocation of the production factors

From a micro-economic perspective, a firm can allocate its production factors in any quantity to maximise its profit. A firm could minimise the input from raw material by allocating the production factors in a different ratio: for example by decreasing the amount of material by increasing the quantity of other production factors. However, there are some objections.

→ It is assumed that firms optimise the allocation of production factors to maximise the total profit or the marginal profit. If a firm changes the allocation of production factors, its marginal profit will decline as a result of the law of diminishing returns: "as the proportion of one factor in a combination of factors is increased, after a point, first the marginal and then the average product of that factor will diminish" (Benham, 1960, p. 110). The allocation of product factors will only be adjusted if the ratio of the prices of the production factors change.

→ Even if a firm was to minimise the input from (raw) material as a production factor, all other factors of production require material input in their own production. Buildings and capital (machinery require material input, as well as labour in the form of food. Even "new" land is sometimes created from materials. Allocating production factors in a different ratio is expected to generate an indirect rather than a direct demand for materials.

Therefor, the allocation of production factors in a different ratio will not necessarily result in a decrease in the use of (raw) materials. This requires the production of other *types* of goods and services.

One could argue that the most straightforward way to keep materials in a closed loop is to eliminate economic production altogether — but arguably, this is not likely to lead to the ultimate goal of human well-being of current and future generations. The link between the intermediate means and the ultimate goal is the intermediate goal.

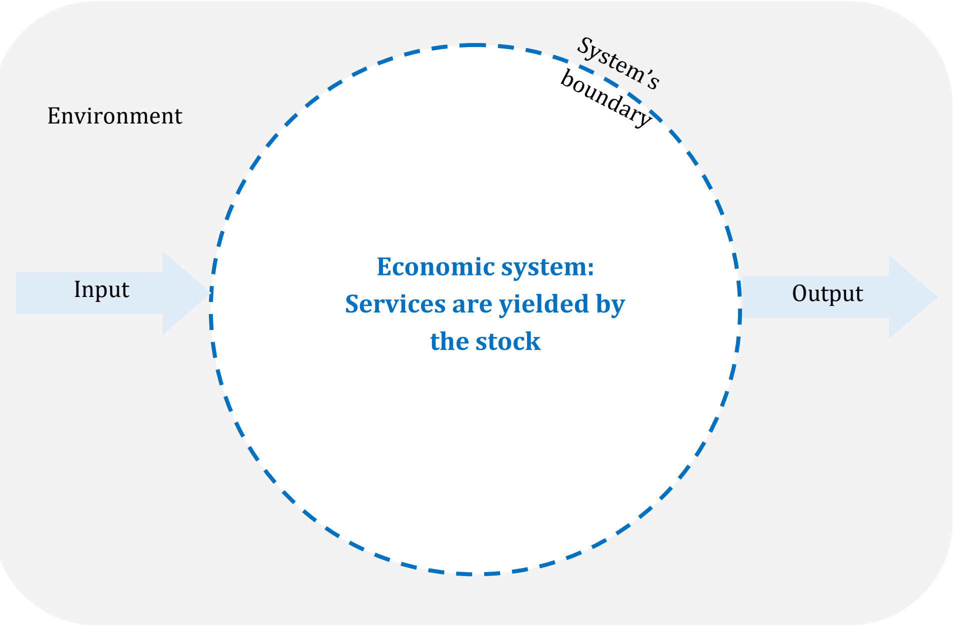


Figure 11: The economic system embedded in its environment, based on Daly (1977).

The intermediate goal

In the current global economy, a predominant intermediate goal is growth in the Gross Domestic Product (GDP). Growth in the GDP can be achieved by increasing production: by discovering and mining raw materials, growing the labour force, creating superior technology and increasing specialisation. As mentioned before, the growing population and the increasingly scarce raw materials form the very roots of the problem. Mining raw materials and growing the labour force would therefor defeat the purpose.

The concept of a circular economy is often placed on the timeline of sustainability thinking. It is argued that the innovative aspect that sets circular economy apart on this timeline is that “an ever-growing economic development and profitability can happen without an ever-growing pressure on the environment” (Pomponi & Moncaster, 2017, p. 713). What is meant by this ever-growing economic development and profitability — is it synonymous with growth in the GDP? What other intermediate goal *is* going to lead to human well-being of current and future generations?

In 1966, Boulding argued that the earth is a closed system which “requires economic principles which are somewhat different from those of the open earth of the past” (p. 7). Boulding describes the economy of the past an open economy, in which growth and consumption are desired, and its success is measured in the size of the throughput — operationalised as the GDP. In contrast, in a closed economy, the throughput is something to be minimised rather than to be maximised. “The essential measure of the success of the economy is not production and consumption at all, but the nature, extent, quality, and complexity of the total capital stock, including in this the state of the human bodies and minds included in the system” (Boulding, 1966, p. 8). However, Boulding does not consent on how to operationalise this goal of a closed economy.

In 1977, Daly adopts the ideas of Boulding, and argues that the notion of the scarcity of the ultimate source is an underexposed criterion for comparing economic systems.

Key concepts in a steady-state economy

→ **Stock** is the total inventory of producers' goods, consumers' goods, and human bodies; the stock is capable of providing service and is subject to ownership;

→ **Service** is the satisfaction experienced when needs are met and is yielded by the stock – both the quantity and the quality of the stock determined the 'intensity' of the service;

→ **Throughput** is "the entropic physical flow of matter-energy from nature's sources, through the human economy, and back to nature's sink" (Daly, 1977, p. 36).

Stock and flow variables

The stock is a stock variable, and is measured at one specific time (for example in volume or weight). Service and throughput are flow variables, and are measured over an interval of time (for example satisfaction per day and volume or weight per day).

Development and growth

→ **Growth** is defined an increase in service by means of an increase of the stock:

$$\frac{service \uparrow}{stock \uparrow}$$

→ **Development** is defined as an increase in the service-efficiency of the stock:

$$\frac{service \uparrow}{stock -}$$

Box 4: stock, service, throughput, development and growth to in a steady-state economy, based on Daly (1977).

Steady-state economy

$$\frac{service \uparrow}{throughput \downarrow} \equiv \frac{service \uparrow}{stock -} \times \frac{stock -}{throughput \downarrow}$$

Increase the service-efficiency of the throughput

Increase the service-efficiency of the stock

Increase the durability of the stock

Figure 12: The intermediate goals in a steady-state economy after Daly (1977)

Daly (1977) uses the terms stock, service, throughput, development and growth to compare and contrast economic systems, as shown in Figure 11 and elaborated upon in Box 4. Daly interprets growth as an increase in the service of the stock by an increase in the size of the stock. Mining new materials and growing the labour force will indeed result in more service in absolute terms. In a steady-state economy, growth is not a desideratum — development *is:* as an increase in the service of the stock relative to the size of the stock. In addition, the throughput ought to be minimised. The size of the stock, human bodies and goods, is to be held at a constant, "optimal" level. This is summarised in Figure 12.

A growth, circular or steady-state economy?

Daly proposes measures to transition into a steady-state economy, where the stock of goods and humans are kept at an "optimal" constant level. However, in a circular economy the growth in the population size is an axiom, rather than something that can – or should – be controlled. In contrast, a circular economy is often presented as a solution to keep providing services, or even provide more services, to a growing world's population, whilst minimising the extraction of raw materials. If the total stock is to be held at a constant level in a circular economy, the goods should decrease as the population grows. However, in practice it would not make sense to "forcefully" reduce the amount of goods. This would mean that goods, even if they are still providing service, are turned into waste.

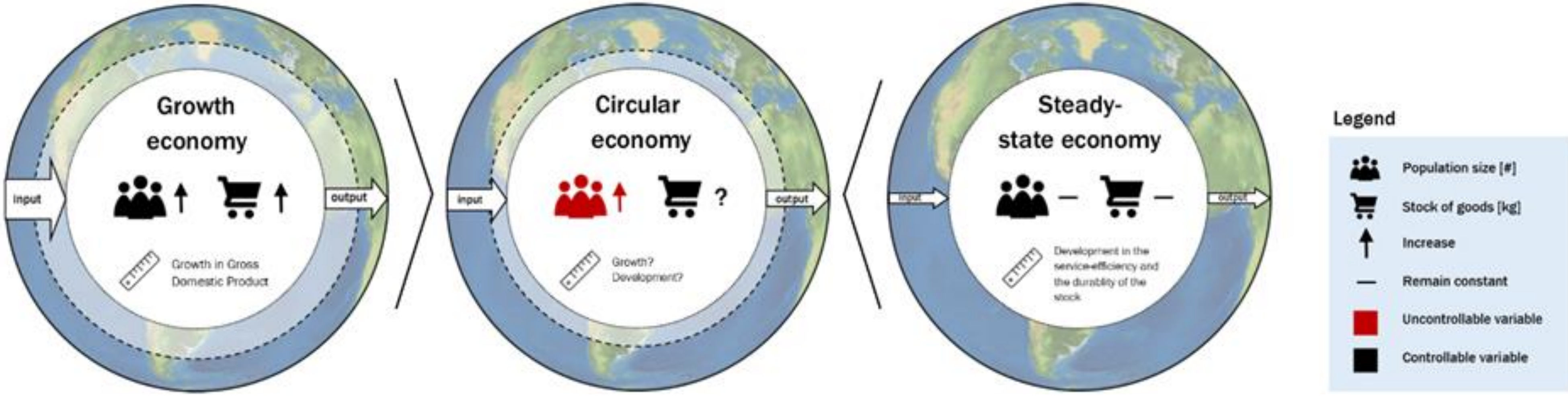


Figure 13: A "practical" circular economy as a realistic compromise between growth economy and a steady-state economy (own figure)

A "practical" circular economy is an economy of both growth and development, or a realistic compromise between an economy of growth and a steady-state economy, as shown in Figure 13.

The concepts and identity that Daly (1977) proposes to describe the steady-state economy do not suffice to define, operationalise and measure a circular economy. The terminology of Daly will be replaced by a more suitable terminology in the economic discourse: service will be replaced by utility, the aspect of time will be introduced, and throughput will be replaced by raw material and waste.

Utility

The concept of service is comparable to the concept of utility in economics – the utility of good X is it the "amount of pleasure" the consumer derives from consuming good X. Classical economist Bernoulli introduced the *util*, a 'psychological unit' to measure utility. Obviously such a subjective measure is hard to operationalise, and it is also unnecessary to try and do so. Neoclassical economists use monetary values, in other words *willingness to pay*, to express utility. Indeed, money is an imperfect measure of utility, as its value depends on circumstances, but it is generally accepted as a good indicator (Baumol & Blinder, 2012).

Time

Up until this point, the aspect of time has only been noted in Box 4, to distinguish between stock and flow variables. Stock variables are measured at one specific time, flow variables are measured over an interval of time. Growth and development are terms that exist only relative to a point of reference.

Primary material and waste

As described before, throughput is "the entropic physical flow of matter-energy from nature's sources, through the human economy, and back to nature's sink" (Daly, 1977, p. 36). However, only in the situation where the size of the stock is constant, the throughput equals the input and the output. The size of the stock can only increase if the input is greater than the output.

What constitutes as input and output depends on the level at which the system is considered. Input into the economic system in the form of raw materials is to be avoided, as is output in the form of waste. Primary materials, the economic stock and waste are distinguished based on their economic value, as illustrated in Figure 14.

→ A primary material is a natural resource that has potential value and is therefor brought into the economic system: the benefits of bringing the material into the economic system outweigh the costs. Not every natural resource is a primary material; it becomes a primary material when the decision is made to bring the natural resource into the economic system.
→ The stock consists of material that is maintained in the economic system because the benefits of keeping the material in the system outweigh the costs;
→ Waste is a material that has not enough value to be maintained as stock in the economic system: the costs of keeping the material in the system outweigh the benefits.

Within the economic system, materials are moved. This does not necessarily require new primary material and does not necessarily generate waste. A part of the stock that has lost its value in one subsystem of the economic system may have value in another subsystem. As a result, the sizes of the subsystems may fluctuate without requiring the input from raw materials or waste generation.

→ A by-product of subsystem X is a part of the stock that has lost its value in subsystem X, but has the potential to be used in another subsystem (Lee, 2012). When it is decided to bring by-product X into subsystem Y, it is referred to as secondary material Y, as illustrated in Figure 15.

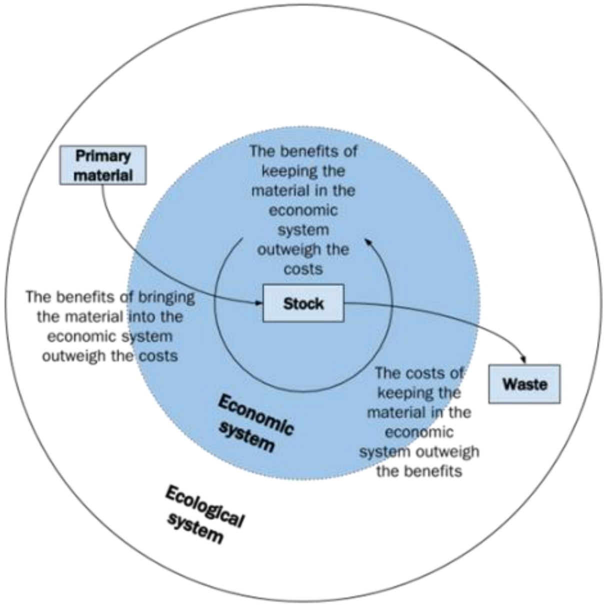


Figure 14: The concepts of primary material, stock, and waste (own figure)

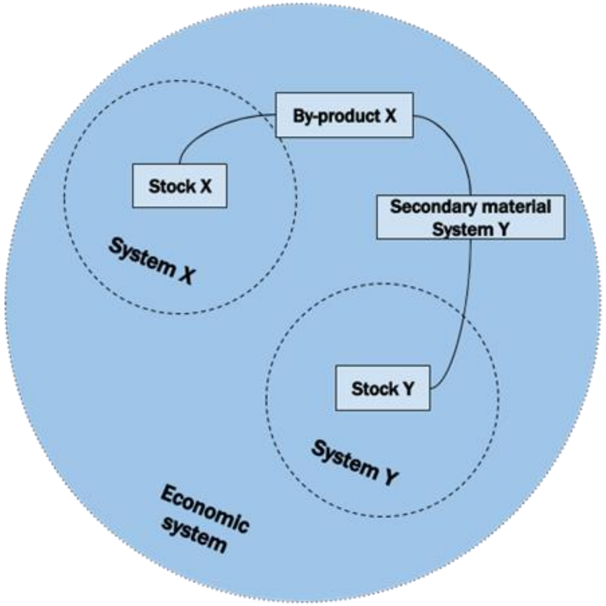


Figure 15: The concepts of by-products and secondary material (own figure)

A “practical” circular economy

Based on these findings, a “practical” circular economy is defined in this research:

A “practical” circular economy is an economy of both development and growth. The goal is to control the size of the stock of goods* and to increase the utility and the durability of this stock.

The stock of human bodies grows as a result of the expected population growth. In this research, this is considered an uncontrollable variable, and is therefor left out of the definition. From this point, “stock” always means “stock of goods”.

*An increase in the size of the stock requires raw material input into the economic system. In addition, a greater stock requires greater throughput for maintenance (provided the same durability of the stock) and therefor even more input from raw materials. However, at a certain point in time the stock of goods may have to increase to provide utility to a larger population. The size, the utility and the durability of the stock should therefor always be carefully balanced.

The measure of a “practical” circular economy, the “CE -index”, is presented in Figure 16. All variables are directly or indirectly controllable:

→ The utility is measured in willingness to pay and is measured per unit of time (€/year). It is, amongst other variables, determined by quality of the stock;
→ The stock is the quantity of the stock of goods, measured in amount of weight (kg);
→ Primary material and waste are measured in amount of weight per unit of time (kg/year).

This formula can be used to compare the mutations of the CE-index of a system in time, or to compare the CE-index of two systems in a given period. The system’s boundary should be clearly defined — benefits and costs cannot be externalised. The formula is applicable at level of the economic system as a whole, but are also at lower systems levels, such as the Dutch building industry or even a single firm.

This definition and formula require some notes. Primary material and waste are counted twice instead of once as throughput, as it allows for a stock to be able to grow or shrink. As the identity is a relative measure, this does not matter.

No statement is made about the distribution of the utility or the types of materials that make up the stock (does a kg of gold equal a kg of wood?), this is clarified in “Discussion”.

It is now possible to characterise the “completely” linear and circular economy of Figure 8. The utility of the stock in both types of economies can be high. However, in a completely linear economy, the durability of the stock approaches zero, in a completely circular economy it approaches infinity.

“Practical” circular economy

$$\frac{utility \uparrow}{primary\ material + waste \downarrow} \equiv \frac{utility \uparrow}{stock -} \times \frac{stock -}{primary\ material + waste \downarrow}$$

Increase in the “CE-index”

Increase the utlity-efficiency of the stock

Increase the durability of the stock

Figure 16: The intermediate goals in a “practical” circular economy, according to the author (own figure based on Daly (1977))

Part II: A Circular Building Stock

In this part of the research the following research questions are answered by means of a literature study:

→ What constitutes a circular building stock?

→ How can the current building stock be characterised?

→ What are the different options to make the building stock more circular?

A circular building stock

In a "practical" circular economy, the size of the total economic stock is to be controlled. The most straightforward means to prevent the stock from growing is by reducing the overall demand for services and goods (Allwood, 2014, p.450). However, within the scope of this study this means will be examined further, because of several reasons.

First, a large part of the building stock consists of housing, and shelter is a basic human need (Maslow, 1943). Second, the demand for buildings is often indirect: as a result of a demand for some other good or service, in which the building is a production factor rather than a production outcome. Third — and this applies to al subsystems of the economic system — within the economic system materials can move freely as by-products and secondary materials from one industry to another. As a result, the size of the building stock may fluctuate.

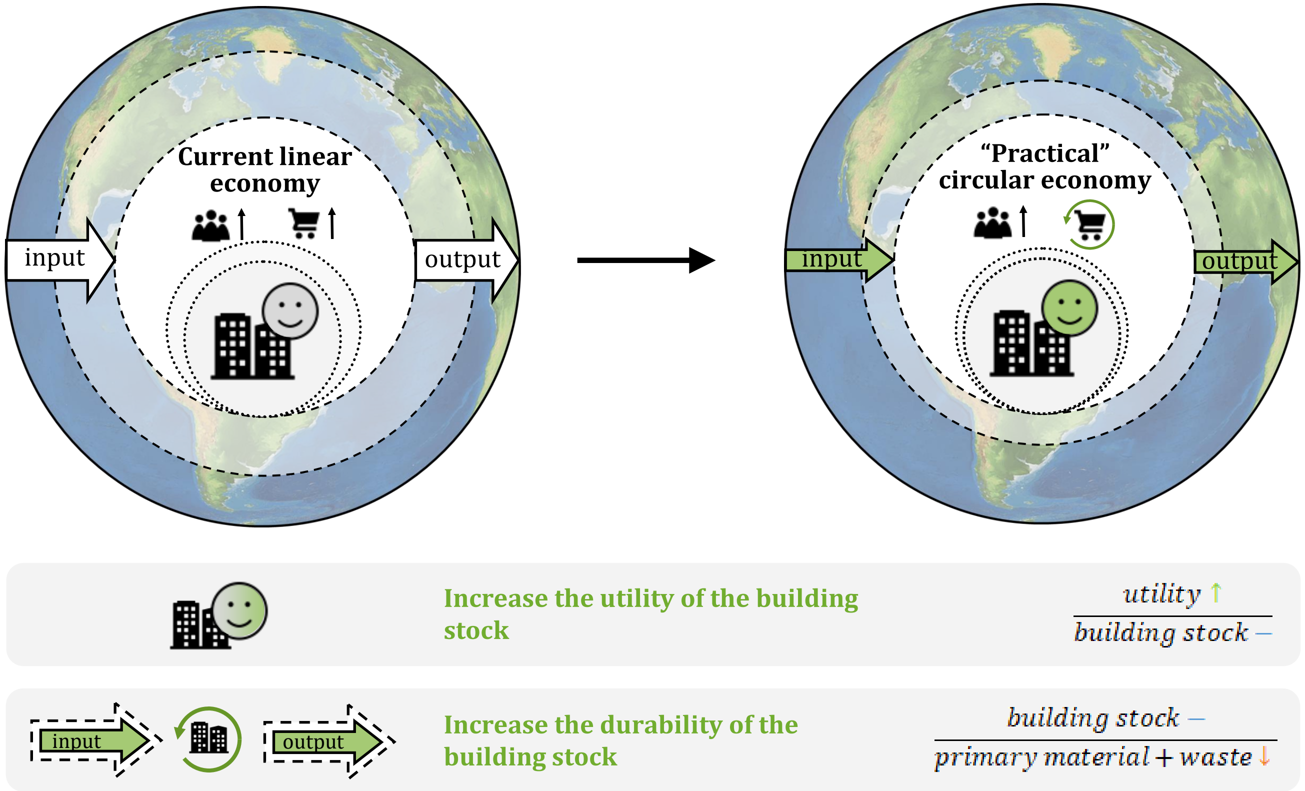


Figure 17: The place of the building stock in the transition from a linear economy of growth towards a "practical" circular economy (own figure)

A circular building stock "fits" within the objectives of a "practical" circular economy: it has a high utility and a high durability, as shown in Figure 17.

The current building stock

The building stock is often described as static; slow to respond to the dynamic changes in demand. Brand (1995) describes the characteristics of buildings as follows:

"Buildings loom over us and persist beyond us. They have the perfect memory of materiality. When we deal with buildings we deal with decisions taken long ago for remote reasons. We argue with anonymous predecessors and lose. The best we can hope for is compromise with the fait accompli of the building. The whole idea of architecture is permanence. University donors invest in "bricks and mortar" rather than professorial chairs because of the lure of a lasting monument. In wider use, the term "architecture" always means "unchanging deep structure." It is an illusion.

New usages persistently retire or reshape buildings. The old church is torn down, lovely as it is, because the parishioners have gone and no other use can be found for it. The old factory, the plainest of buildings, keeps being revived: first for a collection of light industries, then for artists' studios, then for offices (with boutiques and a restaurant on the ground floor), and something else is bound to follow. From the first drawings to the final demolition, buildings are shaped and reshaped by changing cultural currents, changing real-estate value, and changing usage" (p. 16).

In this excerpt, two extreme perceptions of buildings prevail. The one extreme is characterised by permanence, by immutable and static buildings. Most buildings are at least static in the sense that they are bound to a location, hence the term "immovable property". If the building stock indeed consisted only of static buildings as described above, it would have a high durability but a low utility.

The other extreme is characterised by temporality, by adaptable and dynamic buildings. Indeed, buildings can be renovated, transformed or demolished and built new when the utility of the building for its user drops below a certain threshold. If the building stock consisted only of dynamic buildings as described above, it would have a high utility but a low durability. In reality, the current building stock is a mixture of different types of buildings. The buildings in a circular building stock have a high utility and a high durability, as shown in Figure 18.

From the current to a circular building stock

A circular building stock "fits" within the objectives of a "practical" circular economy: it has a high durability and a high utility. In reality, durability and utility are related variables. There are several means to increase the durability and the utility of the building stock.

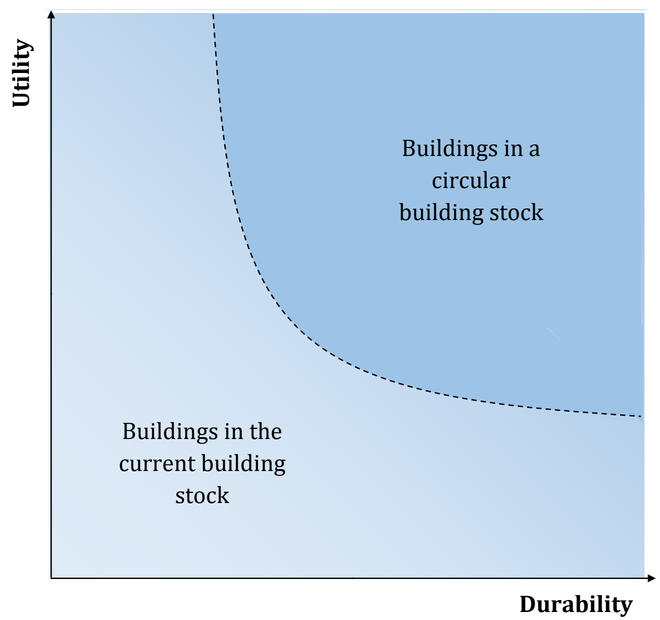


Figure 18: The difference between buildings in the current building stock and buildings in a circular building stock (own figure)

Increasing the durability of the building stock

As mentioned in "Introduction", the construction industry is said to consume more than half of the global resources and generate the greatest waste stream globally (Iacovidou & Purnell, 2016). This does not necessarily mean that the building stock has a low durability compared to the stocks of other industries — because the building stock is relatively large, it also requires a lot of materials for maintenance.

Reducing the input from primary materials

The input from primary materials can be reduced by reducing "the amount of material required to deliver each unit of service" (Allwood, 2014, p. 450). A technical measure could be to design and construct lightweight or reduce scrap rates in production. In addition, the demand for services and goods could remain the same, or even grow, by intensifying use of existing services and goods. In the built environment, the available stock could provide more service by, for example, extending opening hours, using a spare room in a house as an office, or sharing a workspace.

Reducing the amount of waste

The amount of waste can be reduced by reducing the demand for replacement. The average dwelling in the Netherlands has a lifespan of more than 75 years (Hoogers, Hoogers, & Beekmans, 2004). A long lifespan is not *synonymous* with a high durability, but one can imagine that the amount of primary materials required for and the amount of waste generated by maintenance and renovation activities is less than the alternative of demolition and new build. In other words, the amount of waste that is generated can be reduced by strategies that secure the future utility of the building stock.

Increasing the utility of the building stock

Increasing the utility of the building stock is twofold: it is about increasing the current utility of the building stock, but also about securing the future utility of the building stock.

Increasing the current utility

The utility of a building and a building stock can be expressed in willingness to pay per unit of time. For a single building this can be calculated for example by dividing the purchase price by the expected operating period. The utility of a building stock would then be the sum of the utility of a buildings in the stock. Intensifying use was mentioned as a measure to increase the durability of the stock, but it will also increase the utility of the stock. Willingness to pay is a generally accepted but imperfect measure of utility. This is especially true for the real estate market, which is an imperfect market. The *loss* of utility of buildings provides more insight into the utility of buildings and the building stock.

Securing the future utility

One could say that a building is left obsolete when it has lost its utility. There are a countless number of reasons why buildings are left by their occupants. Thomsen & van der Flier (2011) provide a useful conceptual framework, as shown in Figure 19, for building obsolescence: a quadrant matrix based on endogenous and exogenous factors and physical and behavioural factors. Endogenous factors are those related the building and the occupant itself; exogenous factors are influences from outside.

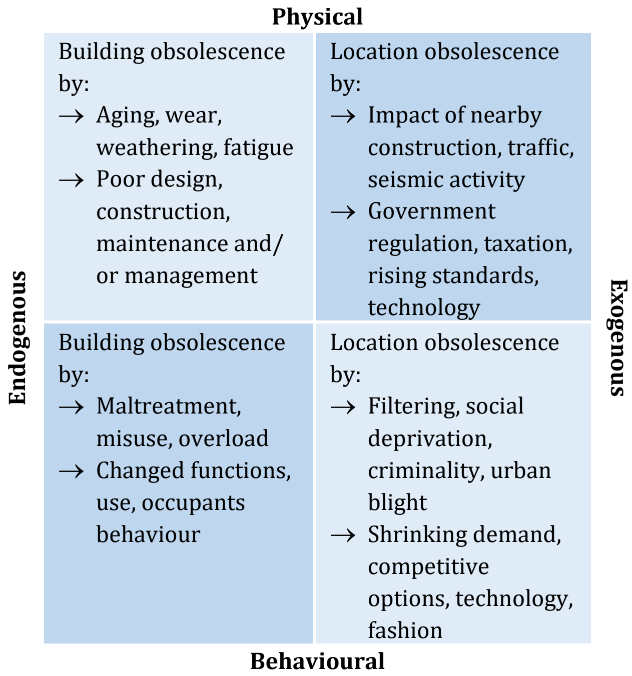


Figure 19: A matrix of factors influencing building obsolescence, edited figure of Thomsen & van der Flier (2011, p. 355)

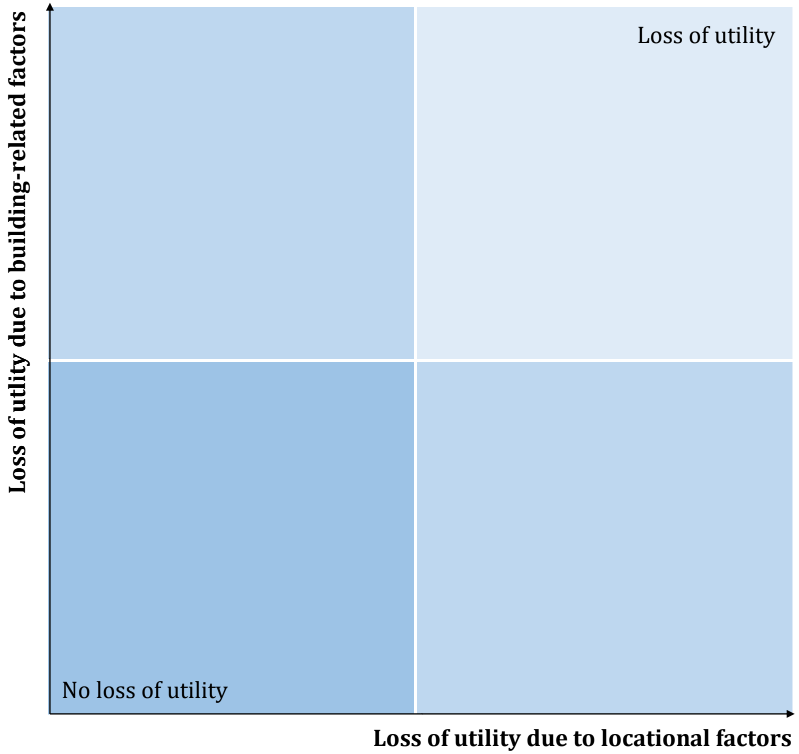
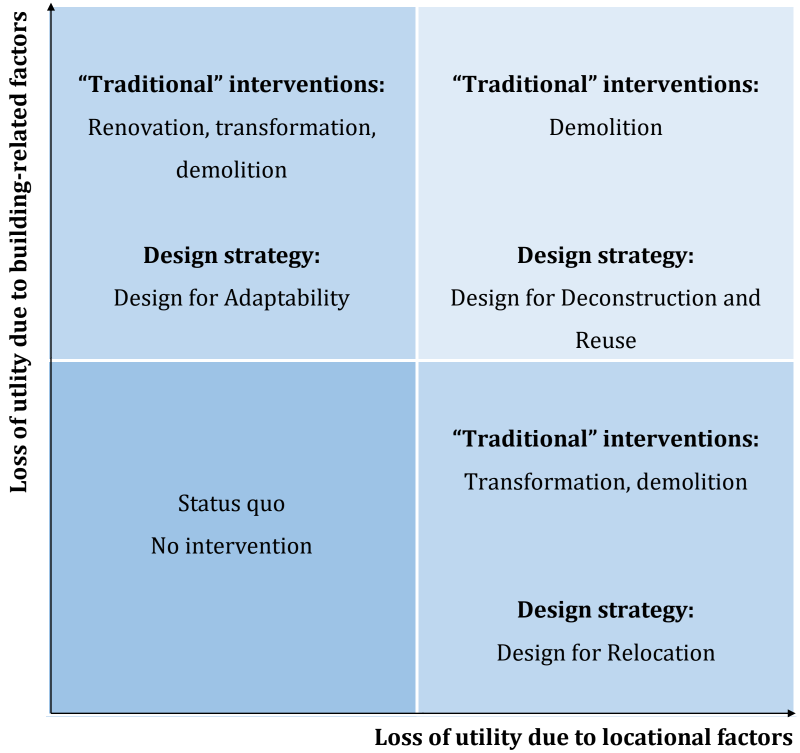


Figure 20 (left): The loss of utility of a building as a result of building-related factors, locational factors, or a combination of both (own figure)

Figure 21 (right): Strategies to secure future utility of a building (own figure)



The framework of Thomsen & van der Flier provides a comprehensive overview of factors that lead to building obsolescence, but does not provide strategies or "cures" to cope with the obsolescence. Buildings cannot be assigned into one quadrant in the matrix — a building can be left obsolete for multiple reasons, and should then be placed in more than one quadrant. Furthermore, "changed functions, use, occupants behaviour" can also be reasons for location obsolescence, and "shrinking demand, competitive options, technology, fashion" as well as "government regulation, taxation, rising standards, technology" can also be reasons for building obsolescence. Furthermore, there is an important difference between temporary and permanent building obsolescence, as elaborated in Box 5.

An alternative framework is developed, as shown in Figure 20 (on the left). Some of the factors of Thomsen & de Flier (2011) are evidently building-related, such as aging or a poor design of the building; others are clearly locational such as the impact of nearby construction. These are characteristics of the supply side. Most factors, however, do not have a distinct place in one of the quadrants of Figure 21 (on the right). These are mostly characteristics of the demand side, such as a change in the occupant's behaviour or the availability of competitive options. The aim of the framework is not to provide an exhaustive overview of factors that lead to the loss of utility of a building. The aim of the framework is to provide a simplified model, upon which strategies to secure the future utility of the building stock can be placed.

Temporary and permanent obsolescence
A building is left obsolete when it has lost its utility. However, there is no clear threshold of how much utility "should" be lost for an occupant to abandon the building. This threshold depends on the demands of the occupant — one user may accept a larger loss of utility than another user.

When the building no longer meets the demands of the original occupant, it is possible for the building to meet the demands of another potential occupant. Second-hand sales and temporary leases are common practice in the built environment. A certain percentage, usually 5%, of temporary obsolescence is required for the real estate market to perform optimally and to allow for movements.

Rather than temporary obsolescence, it is permanent obsolescence that "will eventually result in the end of the service life, generally by demolition" (Thomsen & van der Flier, 2011, p. 359). More often then not, this results in the generation of waste and the demand for replacement.

Box 5: The difference between temporary and permanent building obsolescence

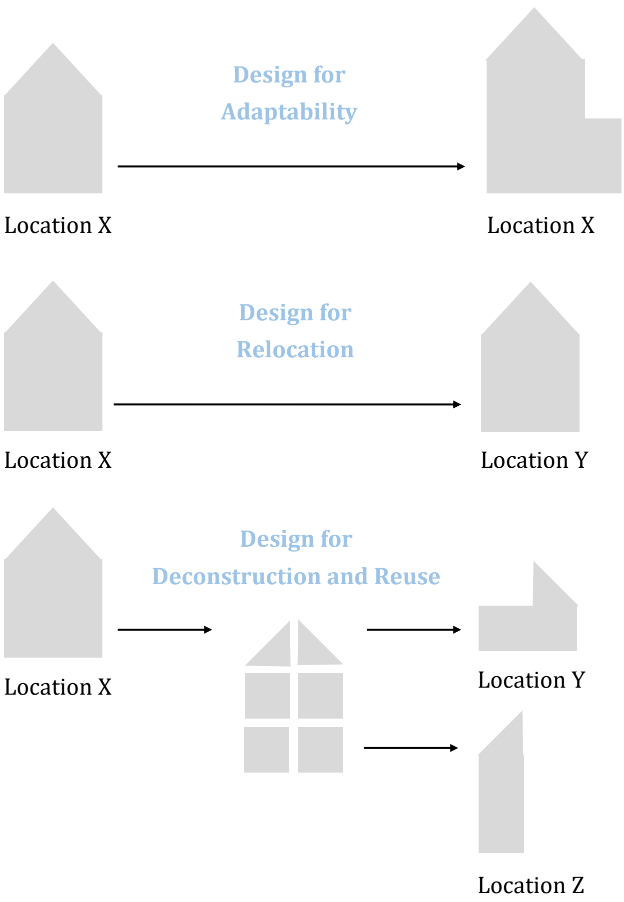


Figure 22: Design for Adaptability, Design for Relocation and Design for Deconstruction and Reuse

Strategies to secure future utility

When a building loses its utility, it is either left temporarily or permanently obsolete, or an intervention takes place, as shown in Figure 21. Depending on the reason for the loss of utility, the building is renovated, transformed, or demolished. If buildings were designed to anticipate this loss of utility, they could more easily be adapted, relocated or deconstructed and its parts reused. These design strategies can be linked to the quadrants of Figure 21, and are illustrated in Figure 22.

Design for Adaptability is a design strategy that anticipates the loss of utility due to building-related factors; Design for Relocation due to locational factors. Design for Deconstruction and Reuse is a design strategy that anticipates on the loss of utility of a building due to a combination of factors.

There are many ways to translate each of these strategies into an actual design. For example, the Dutch firm Neptunus, one of the largest providers of temporary buildings worldwide, uses a "catalogue" of elements to assemble different types of buildings:

> "We can reuse everything we make in a different configuration or in a different setting. For example, it does not matter whether we assemble a school or a sports hall; they both are made of the same elements" (Interview with Jan Heijkers, manager at Neptunus).

This type of building is sometimes referred to as "elementenbouw" in Dutch, but the term modular building is also common. Modular building seems to be a promising design strategy for adaptability, relocation, deconstruction and reuse. However, there are different interpretations possible on the concept of modular building, as will be elaborated upon in Part III.

Part III: Modular Building

In this part of the research the following research question is answered by means of a literature study and a collective case study:

→ What is modular building and what is the current practice of modular building in the Netherlands?

From craft to mass production

For a long time, the building industry has been dominated by craft production, involving "skilled workers making customized products for individual customers" (Rycroft & Kash, 1999, p. 39). The concept of mass manufacturing or industrial production was invented in the nineteenth century, involving "the division of a product into its component parts, which are standardized, and then making and assembling the parts under conditions where efficiency increases with scale" (Rycroft & Kash, 1999, p. 39). These concepts have its origins in the automotive and manufacturing industries, but are also applicable to the building industry.

Most buildings are immovable properties, and this characteristic explains why the building industry has adopted the term "prefabrication". Prefabrication means that parts of a building or complete buildings are produced off-site before (hence the preposition *pre*) they are transported to and constructed on the building site. However, prefabrication does but does not necessarily entail that the building parts or complete building are industrially or mass produced. Two contrasting dictionary definitions of "fabrication" are shown in Box 6.

Modular building, or modular construction, is closely related to the concept of prefabrication.

Modularity in the building industry

There are different interpretations of modular building in the building industry.

"Modular construction uses three-dimensional or volumetric units that are prefabricated and are essentially fully finished in factory conditions, and are assembled on site to create complete buildings or major parts of buildings" (Lawson, Ogden, & Goodier, 2014, p. 1).

Fabrication (verb, used with object):

→ To make by art or skill and labor; construct.
Source: http://www.dictionary.com/browse/fabricate?s=t

→ Construct or manufacture (an industrial product), especially from prepared components.
Source: https://en.oxforddictionaries.com/definition/fabricate

Box 6: Two contrasting dictionary definitions of the term "fabrication"

Based on the above interpretation, modular construction is a form of prefabrication, but it does not necessarily mean that the production is industrialised: the parts could be designed and manufactured for one specific application. Staib, Dörrhöfer, & Rosenthal (2008) argue that modular construction is more than just prefabrication; the production of the parts is industrialised.

"Modular construction systems are closed systems in which the elements are prefabricated by the manufacturers independent of a particular building. For a modular construction system, a particular number of elements are pre-determined which, can be organised into complete entities by combining them in a number of different ways" (Staib et al., 2008, p. 43).

Based this interpretation, the parts are designed and manufactured to be used in multiple and different configurations. These different interpretations of modular building are presented in Table 3. In this research, these interpretations will be referred to as single-configuration modular building and multiple-configuration modular building.

Modular building as interpreted by	Place of production	The module	Application	Mode of production	Term in this research
Lawson, Ogden, & Goodier (2014)	Off-site (prefabrication)	Three-dimensional or volumetric units	One type of configuration	Not specified, can be craft or mass production	Single-configuration modular building
Staib, Dörrhöfer, & Rosenthal (2008)	Off-site (prefabrication)	Pre-determined elements	Multiple possible configurations	Mass production	Multiple-configuration modular building

Table 3: Two different interpretations of modular building

Modular building to secure future utility

The different types of modularity can be linked to the strategies to secure the future utility of a building of Part II. Single-configuration modular buildings can be relocated, if the process of assembly is reversible. The same is true for multi-configuration modular buildings, but in addition, they can also be adapted or deconstructed, so that its elements can be organised into other types of entities. Multi-configuration modular building, or modular building as interpreted by Staib et al. (2008) can therefor be an effective means to a circular building stock.

The building as a system

A building can be thought of as a man-made or a technical system, and so can the building firm, the building industry and the global economy. A system is "a set of mutually related elements or parts assembled together in some specified order to perform an intended function" (Misra, 2008, p. 15). In general, a system comprises of items, attributes, and relationships (Misra, 2008):

→ Items are the operational parts of a system, they can be thought of as building blocks;
→ Attributes are the characteristics or properties of the item, for example size, color and shape;
→ Relationships are the links between the items. The relationships between the items can be an energy transfer, information and signal exchange, material exchange or physical space and alignment.

The structure of a system is the way in which elements are related to one another. A system is distinguished from its environment by a system boundary. An open system shares input and output with its environment – the elements have relationships with their environment across the system boundary. Closed systems do not have relationships with anything outside the system boundary.

A system is a hierarchical organisation: the lowest level is the fundamental element "which can be assumed indivisible in context of the problem being considered at hand" (Misra, 2008, p. 16). At one level higher, an assembly of elements to produce a functional unit is referred to as a subsystem. At the highest level, an assembly of subsystems to achieve an objective is referred to as a system. As the number of items and relationships between those items increases, the complexity of the system increases.

If a building can be thought of as the highest level of a complex system, what is then the fundamental element?

Taxonomy of a building

In the building industry, terms used to indicate a specific system level of a building such as element or component, are not well-defined. Some argue that an element is a collection of components, while others claim the exact opposite: that a component is a collection of elements. The aim of this paragraph is not to propose a rigid vocabulary for the building industry to adapt; rather it is to serve as a vocabulary within this research.

Mass products

The hierarchy as proposed by Eekhout (1997) is taken as a starting point. *Raw materials* (materials in unpurified form), such as trees or ores are mined and then purified into *materials*, such as tree trunks and iron. These materials can be combined into a *composite material*, for example plywood (thin layers of wood glued together) or steel (iron and carbon). A *'bulk material'* is a mono or composite material manufactured into shape, such as a plywood board (3 x 1,2 m), or a steel HEB180 beam (12-16, 18 or 20 m long). A bulk material is a semi-finished product from the perspective of the building industry. Up until this point in the hierarchy, products are mostly mass produced; up from this point, products are referred to as building products.

Building products

A element (or sub-element) is the smallest part of a building made from a mono or composite material, with its own characteristics (contrary to a bulk material). A part can only be broken down by using destructive techniques. This corresponds with the indivisible, fundamental element as defined in "The building as a system".

Elements (or super-elements) are further assembled in a factory or workplace into components (or sub-components). A component is an independently functioning building part, which consists of several constituent elements and/or sub-components.

The building as a unique entity

A collection of components of a building with identical technical functions is called a *building part*, such as the main supporting structure or the façade. A *building* is the sum of different building parts, assembled into a whole. This is shown in Figure 23. The *building segment* is an "artificially" separately considered part of a building, as elaborated upon in Box 7.

"Buildings are unique entities, as they are often the results of one-off projects. This feature adds to their inherent complexity (...) although buildings are made up of components which are manufactured products, when assembled together those products create an entity which no longer fits into the logic of manufacturing" (Pomponi & Moncaster, 2017, pp. 710–711).

A *building segment* is an "artificially" separately considered part of a building, consisting of disparate components of different building parts (comparable to a slice in a pie chart). In the design of a building it is important, as this is where the relations between different components are designed.

Box 7: The building segment

What is a module?

In computers science, a module is defined as "a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units" (McClelland and Rumelhart in Baldwin & Clark, 2000, p. 63). This definition can also be used to define a module in a building, but the level of the module in the taxonomy of the building is a choice.

The modules in single-configuration modular buildings are prefabricated three-dimensional or volumetric units. However, it is unclear what exactly these volumetric units are — they could be components, but could also be building parts, or even building segments.

The modules in multi-configuration modular buildings are predetermined elements. However, these elements are not necessarily synonymous with the fundamental element of the building.

Both in single-configuration and multi-configuration modular building it is unclear what level in the taxonomy of the building is considered as the module: is it the element, the component, the building part or maybe even the building segment? The chosen level of the module could influence the future utility of the building stock: the lower the system level of the module, the greater the number of combinations and configurations that can be made, and vice versa.

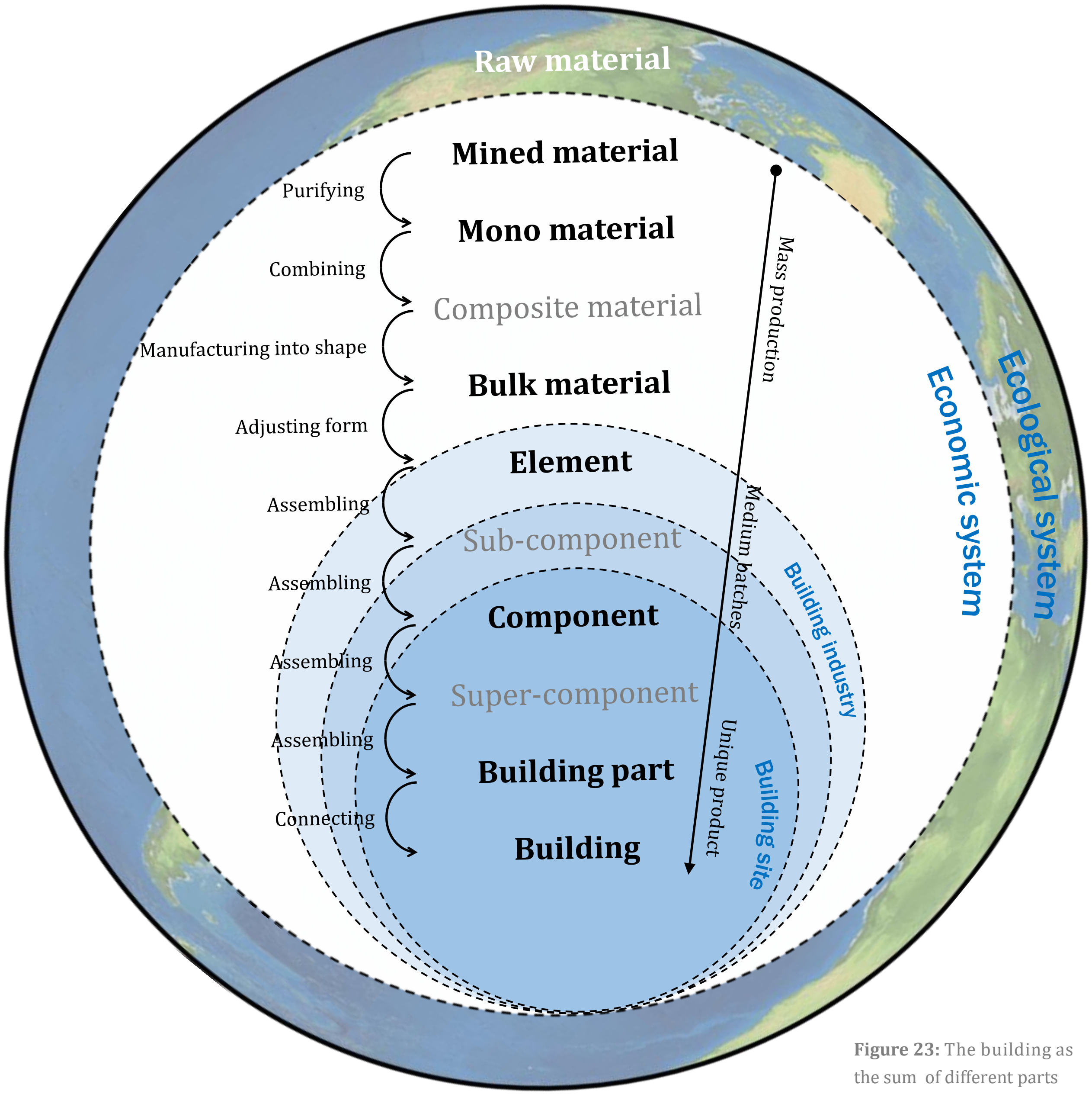


Figure 23: The building as the sum of different parts

Collective case study

In theory, modular building can be an effective means to a circular building stock. To explore whether this is holds true in practice, a collective case study is conducted, in which providers of modular buildings and their products are analysed.

Researcher's note

This collective case study was conducted simultaneously to the theory building in the previous chapters. The insights obtained from the case studies have partly determined the direction and the focus of this line of reasoning.

Sampling process

Criteria

There are no hard rules in the number of cases to include in a collective case study. However, Stake (2006) argues that any less than three will not show enough interactivity between the cases and their context; any more than fifteen will show too much interactivity for the researcher to comprehend.

Inclusion criteria for the collective cases are:

- → The number of cases to include should range from three to fifteen;
- → The firms provide modular housing solutions;
    - ♦ Housing is chosen as a focus, because of its large share in the total building stock and because of its relatively long lifespan.
- → The firms describe their product as "modular";
- → The firms mention "circular economy" or "scarcity of resources" on their website;
- → The firms are located in the Netherlands;
    - ♦ First, because the Dutch built environment is subject to the regulations laid down in the Building Decree. A research on a larger scale would include too many variables in the context.
    - ♦ Second, because of the practical limitations of the research. Face-to-face interviews in the Dutch language are preferred as it allows for natural interaction with the interviewee; in addition the researcher is also able to investigate the prototypes or products on site.
- → The firms vary in terms of materials they use in their products;

Procedure

An email was sent to thirteen firms of which nine replied. Eventually, semi-structured interviews were conducted with five firms – four by phone and one face to face. The four other firms were either unable or unwilling to be interviewed. Prior to the interview secondary data from the suppliers' websites were collected to become acquainted with the firm and the product, and to compare the data from the interview to. The researcher made detailed notes during the interviews. An example of the invitation for the interview and interviews and the interview protocol are enclosed in Appendix A.

Data collection and analysis

An overview of the firms and an excerpt from their website is provided in Figure 24. The names of the firms are replaced as the data are said to be treated with confidentiality, and are not relevant for the data analysis.

Interview topics

Introduction

- → The idea behind the firm, in other words, its reason for existence

Modular building

- → The firm's reasons for building modular
- → Interpretation of modular building, what constitutes as a module
- → The characteristics of the product: relocatable / adjustable / deconstructable and reusable

Box 8: Topics for the semi-structured interviews with firms that provide modular housing solutions

Firm A : "A permanently modular dwelling, made of a 100% sustainable and responsible materials. (…) Permanently adaptable, clean and quickly assembled, no waste on the construction site, completely renewable and non-scarce resources. (…) Product A is completely ready for a true circular economy" (Translated from supplier's website)

Firm B: "Product B is a modular, wooden, relocatable and environment-friendly building system. We build in a future-oriented and adaptable manner. (…) The modules are developed based on the circular philosophy" (Translated from supplier's website)

Firm C: "Product C is built completely modular and therefor can be custom-made for you. (…) The materials can be recycled and the components can be reused, as they can be demounted and assembled into other configurations. (….) Your Product C uses materials and resources sparingly" (Translated from supplier's website)

Firm D: "Product D is demountable, relocatable and expandable. (…) Due to circular design, the footprint of the building is minimal. Product D can be delivered in just a few days, complete with service installations, as a result of the modular construction and prefabrication methods" (Translated from supplier's website)

Firm E: "Based on our modular building system, we design and construct dwellings and offices. (…) Architecture without compromises in comfort, for every place and every budget. (…) The module is our circular building block" (Translated from supplier's website)

Figure 24: Suppliers of modular housing of the collective case study

It is important to know that the intention is not to make a value judgement about the products of the firms. The intention is to explore what modular housing solutions are available on the Dutch market, and how each single one of these solutions contributes to a circular building stock as defined in this research.

The data retrieved from the websites and the semi-structured interviews are enclosed in Appendix B.

The idea behind the firm

The specific ideas behind the concepts of the firms differ, but four out of five firms explicitly wish to provide a better product than "traditional" housing.

> "Firm E is established to make architecture more sustainable, flexible and accessible. Building can be done better, much better" (Excerpt from website of Firm E).

The firms do this by allowing the clients freedom in the design whilst being able to keep the costs low, due to the use of standardised modules.

> "We are convinced that affordable, free standing houses can be designed for a price comparable to that of row houses" (Interview with Firm C).

Some products also allow for adjustment after construction, meaning that the building can change as the demands of the client changes.

> "The housing wishes and demands of households change every seven years, Product A allows to accommodate those changes. This could not be done in "traditional" construction, where parts are often glued and sealed together" (Interview with Firm A).

Most firms also wish to limit the use of raw materials and energy.

> "Product D was designed for a competition for refugee housing, with the idea of "investing in energy"; now Firm D makes flexible, energy-neutral designer homes" (Interview with Firm D).

> "We make relocatable buildings with wood, that have as small of a CO2 footprint as possible" (Excerpt from website of Firm B).

In short, the main reason for establishing the firms include:

→ Frustration with the way things go in the building industry, the wish to offer a "better" product than traditional housing;

→ The wish to give the client freedom in the design (or even after construction) for an affordable price.

Reasons for building modular

There are multiple reasons for the firms to build modular. Most firms mention the advantages that come with prefabrication:

> "The Product A building system is developed to achieve results quickly and effectively" (Excerpt from website of Firm A).

> "[We build modular] to be able to produce a high quality product within factory settings" (Interview with Firm B).

> "Because of the modular construction and the prefabrication methods, the Product D can be assembled in just a few days. (...) Prefabrication means quality, accuracy and a reliable planning" (Excerpt from website of Firm D).

Two out of five firms explicitly mention the ability to relocate the dwelling as whole:

> "Product B is a modular, wooden, relocatable and

> environment-friendly building system" (Excerpt from website of Firm B)
>
> "In the ideal situation the building would consist of one module that can be transported as a whole" (Interview with Firm D).

In addition, some firms build modular so that the building can be customised to the wishes of the client in the design phase:

> "Product C is completely modular. As a result, can be custom-made for you" (Excerpt from website of Firm C).

> "Because of the construction of the modules of 8,65m2 (3,5x2,5), the design can be easily adapted to your wishes and allows for assembly of the dwelling within just a few days" (Brochure from website of Firm E).

Some of the firms take the customisation a step further then the design process; by means of modular building the dwelling can be adapted even after construction.

> "A Product A dwelling is made by assembling standardised modules. By means of disassembly and reassembly, adaptation of the building is simple" (Excerpt from website of Firm A).

In short, reasons for building modular include:

→ Being able to offer the client freedom to design an affordable dwelling;
→ Being able to offer the client freedom to relocate or adapt the building after construction;
→ Being able to enjoy the advantages of prefabrication: parts are made in factory conditions, transported to the site and constructed mostly within a few days.

Interpretation of modular building and the module

Even though the reasons for building modular partly overlap, the firms interpret the term "modular building" in various ways and have chosen different "modules". The interpretation of modular building and the choice of the module are linked.

Firm A

According to Firm A, modular building is building in a permanently adaptable manner, in order to meet the changing demands of the client. The module of Firm A is a standardised panel of 1500 mm by a multiplicity of 300 mm, made out of aluminium and wood. "A wall panel, a floor panel – everything is a module". The module is a standardised panel made of aluminium and wood of 1500 mm by a plurality of 300 mm. The module of Product A can be considered as an *element* in the taxonomy of a building.

Firm B

According to Firm B, modular building is an advanced form of prefabrication, "something is modular if it is a closed unit that is delivered and placed on site". The module is called the Product B standard, which is a volumetric unit made mainly out of wood, available in the sizes 25 m2, 29 m2 and 40 m2. The modules of Firm B can be considered as *building segments* or *complete buildings*.

Firm C

According to Firm C, modular building is "an industrial way of building", which this case means that "you work with a fixed grid – all components are based on this grid. You can draw Product C on a 600 x 600 mm piece of paper". The module is not defined.

Firm D

Modular building is not described in general by Firm D, but the dwelling is modular because it consist of "15 jigsaw puzzle pieces that fit into each other, with which we make a wind and waterproof building in one day". The modules are these jigsaw puzzle pieces. The modules of Firm D can be considered as *building* *segments*.

An overview of the modules of the various firms is provided in Figure 25.

Firm E

According to Firm E, modular building "means building with a module that has a standard dimension" These modules can be combined together in various different ways. There are two modules: a small one (3,5 by 2,5 m) and a large one (3,5 by 5,0 m). The modules consist of " wooden framework, a very well isolated façade and triple glazing in wooden frames". The modules of Firm E Homes can be considered as *building segments*.

In short, interpretations of modular building include:

→ Modular building is building in a permanently adaptable manner;

→ Modular building is an industrial way of building; an advanced form of prefabrication;

→ Modular building is building on a fixed grid; building with modules that have a standardised dimension.

Interpretations of the module include:

→ A module is a standardised panel or a volumetric unit, that can be assembled in a number of configurations on site (multi-configuration modular building);

→ A is a jigsaw puzzle piece, that can be assembled in a single configuration on site (single-configuration modular building).

The characteristics of the product

To assign the firms and the products into the quadrants of the framework as developed in Part II, the products are analysed – to what extent are they adjustable, relocatable, deconstructable and its parts reusable? This is based on the data from the websites and the data from the semi-structured interviews. An overview of the firms in the framework is provided in Figure 26 on the next page, and is based on the analysis below.

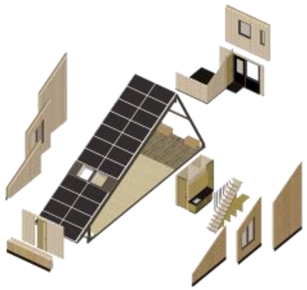
Firm A

Product A is developed to be permanently adaptable, and is adjustable to the wishes of the client in the design phase and in the operating phase. The building system resembles that of the temporary building supplier with a catalogue of elements in Part II. The standardised panels can be bolted together in various different ways. "A Firm A dwelling can be adjusted to the changing needs of the inhabitant. If you expand your family, you can add modules. If your children move, you can pass on modules or make a holiday home out of the modules".

Firm A: Standardised panel

Firm B: volumetric unit

Firm C: Elements on grid



Firm D: 15 jigsaw puzzle pieces

Firm E: volumetric unit

Figure 25: The "modules" of the suppliers

Of course, there are some constraints. The current panel cannot be used to separate for example row-houses, due to the fire safety requirements. In addition, the designed possibilities are constrained by a maximum span and a maximum height.

Product A can be relocated, but is first disassembled: “[For relocation] we would then completely demount the dwelling, including the foundation and pipework. We use a lifting method with vacuum, and as a result, we cannot transport in larger parts”.

Furthermore Product A can be deconstructed and its parts reused: “Product A modules could be bought and sold on a community. (...) Firm A could also take back the modules to refurbish them. You could make a dwelling out of second-hand modules, or save up modules”.

Firm B

Product B is developed to be adaptable. In the design phase a configuration model is use, which “allows for options in the frame (1), exterior (2), balcony (3), interior (4) and service installations (5)”. The system level of the module is relatively high: the module is a volumetric unit of 25m2, 29m2 or 40m2 floor area. These modules can be stacked or placed next to each other, but the configuration possibilities are limited as the module is a volumetric unit rather than an element.

In the operating phase, the modules can be reconfigured and the interior can be adjusted: “You could turn it into a hotel room, or an office”. The relatively large module does allow for easy relocation “Product B can be relocated in an easy and favorable manner, by means of road transport”.

In theory, the modules can be deconstructed and its parts can be reused: “After the service life, we would like to take back the modules to find a new place for them. If the module can no longer be used, we want to disassemble it into elements”.

Firm C

Firm C is developed to provide the client freedom in the design phase, as well as in the operating phase. “Product C is a completely modular and therefor can be custom-made for you”. In the design process, an architect is involved. “Our clients have a conversation with the architect about their housing wishes. The dwelling is then designed based upon these wishes. Everything consists of elements, it is almost as if you would put together an IKEA closet”.

Product C can be adapted in the operating phase: “[Modular building] allows for the client to adjust the dwelling after delivery, by reconfiguring the elements”. The constraints of Product C are as follows: “The dwelling can be enlarged to a maximum of three levels. Another constraint is the construction, as a result of the “metal box”, the footprint on the ground floor is the footprint on all levels. You can partly solve this by making a roof terrace. The height of the levels is also fixed”. Technically, the dwelling can be relocated, but it is constrained by the financial construction. “In theory it is possible to relocate the dwelling, but the bank would not allow this. The dwelling is collateral for the bank”.

The same holds true for the deconstruction and reuse of the parts, in theory “the materials can be recycled and the components can reused, as these can be disassembled and assembled into another configuration”; this would indeed be possible if the dwelling was privately funded.

Firm D

Firm D differs from the other firms, as the concept was originally developed as temporary refugee housing. It is transitioning into “flexible, energy-neutral designer homes”. Product D can be adapted in the design phase, but “it is up to the client. If a private client wishes to make one specific design, it can be done, but the one-off costs need to be taken into account. It is more profitable to make custom designs in series, for example for a housing association".

The concept is not intended to be adaptable after delivery, but it could be possible: "The wooden framework is suitable to be adapted, for example with the help of a local contractor".

The dwelling does allow for easy relocation: "It is possible to relocate Product D. The 15 jigsaw puzzle pieces would then be disassembled, transported, and assembled elsewhere".

Product D can be deconstructed and its parts could be reused: "Our ambition is to use as much dry connections as possible, so that the dwelling can be disassembled into elements".

Firm E

Firm E is "established to make architecture more sustainable, flexible and accessible". The client has freedom in the design phase, by making a configuration of the modules, which can be "be connected to one another in various different ways: in a series, in a square, or stacked on top of each other".

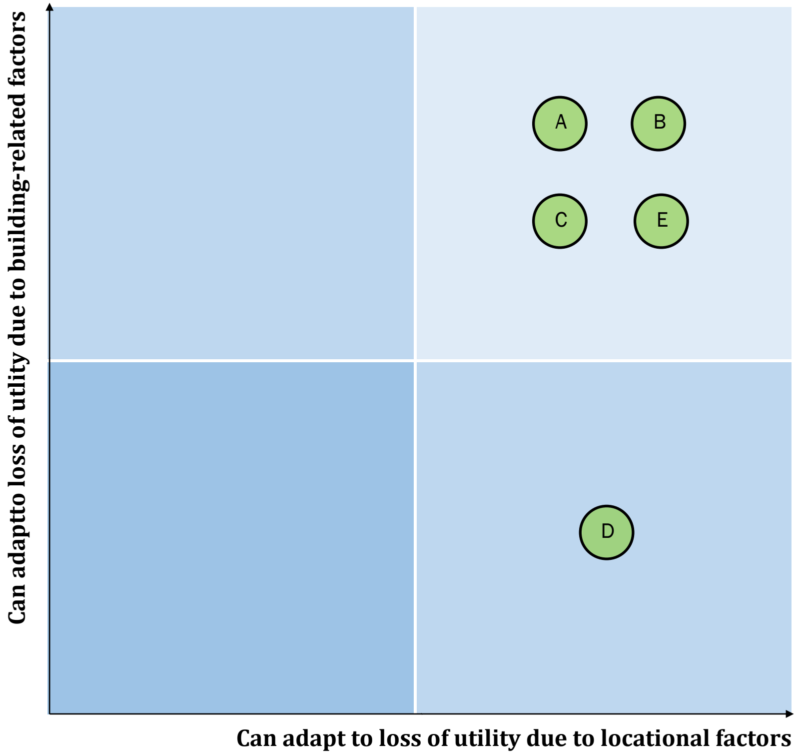


Figure 26: The products of the suppliers placed within the framework of strategies to secure the future utility of the building; there is no hierarchy within the quadrants (own figure)

Based on the website, it seems as if the buildings are not adaptable in the operating phase: "It is possible to reconfigure Product E, but it is not possible to simply add modules due to the integrated ventilation system and the foundation. Keep in mind that it is less costly to construct the dwelling at once rather than extend the dwelling at a later moment in time". However, in the interview with Firm E this is countered: "The building can be made smaller or larger after delivery. In the beams of the dwelling, perforations are made for ventilation shafts. That is a universal system. If you change the configuration, you can adjust the ventilation".

Based on the website, Product E is not designed to be relocated: "In theory Product E e is demountable and relocatable. However, this model is not designed as a relocatable home. The foundation is always calculated for a specific location and cannot simply be used elsewhere. In addition, it is not possible to close on a mortgage if you intend to relocate the dwelling". Again, this is countered in the interview: "The type of foundation depends on where you wish to build, but the biggest challenge is not to prevent the dwelling from sinking into the ground; it is to prevent the dwelling from blowing away".

As for deconstruction and reuse of the modules: "Our modules are designed to be demountable up until the "structures": the floors, the roof, the columns, the façade and the partitioning walls. One level lower, the builder often wants to screw and glue the parts together, as this results in stronger connections. So, within the system of Product E de modules can be reused, but not outside of the system".

In short, with regards to the possibility to adjust the product:
→ Most of the products can be customised by the client in the design phase;
→ Some of the products can customised by the client in the operations phase;
→ The degree of customisation is dependent on the level of module in the taxonomy of the building. If the module is an element, more options are possible then if the module is a building segment;
→ The degree of customisation is constrained by the chosen building construction, rules and regulations and integrated service installations.

With regards to the possibility to relocate the product:
→ Most of the products can be relocated;
→ A possible constraint is the financing construction: if the building serves as collateral for the bank, it can not simply be relocated.

With regards to the possibility to deconstruct and reuse the parts:
→ All products can be deconstructed, some up until the level of the element as a result of the use of dry connections; others up until the level of the component as the elements are glued together;
→ The financing construction that constrains relocation also constrains deconstruction;
→ As for reuse, the parts can be reused within the building system of the firm, but it whether these parts can be reused outside of this building system is not investigated further.

Data interpretation

This case study was conducted to explore whether modular building in practice is an effective means to a circular building stock. A circular building stock was defined as follows: a circular building stock "fits" within the objectives of a "practical" circular economy: it has a high utility and a high durability.

In theory, modular building can secure the future utility of the building stock and therefor increase the durability of the building stock. Single-configuration modular building allows for relocation, if the process of assembly is reversible. Multi-configuration modular building is an even more promising means to a circular building stock — buildings could then be relocated, adapted or deconstructed, so that its elements can be organised into entities.

In practice, the degree to which modular building can contribute to a circular building stock, greatly depends on the interpretation of the term "modular building". Modular building is often used as a means to offer the client a customised product for a relatively low price. In this way, modular building is a compromise between the current utility and the costs. The collective case study, though relatively small in size (five firms) and focus (housing), revealed different interpretations of modular building. Some interpretations allowed for the product to be relocated, some for the product to be a adapted, and some for a combination of both: for the modules of the product to be deconstructed and reused.

Recommendations for further research are provided in the conclusion of this report.

End matter

Synthesis

In this chapter the main findings of the three parts of the research are synthesised and placed within a broader context. Kingdon's (2014) multiple streams model is used to illuminate this broader context.

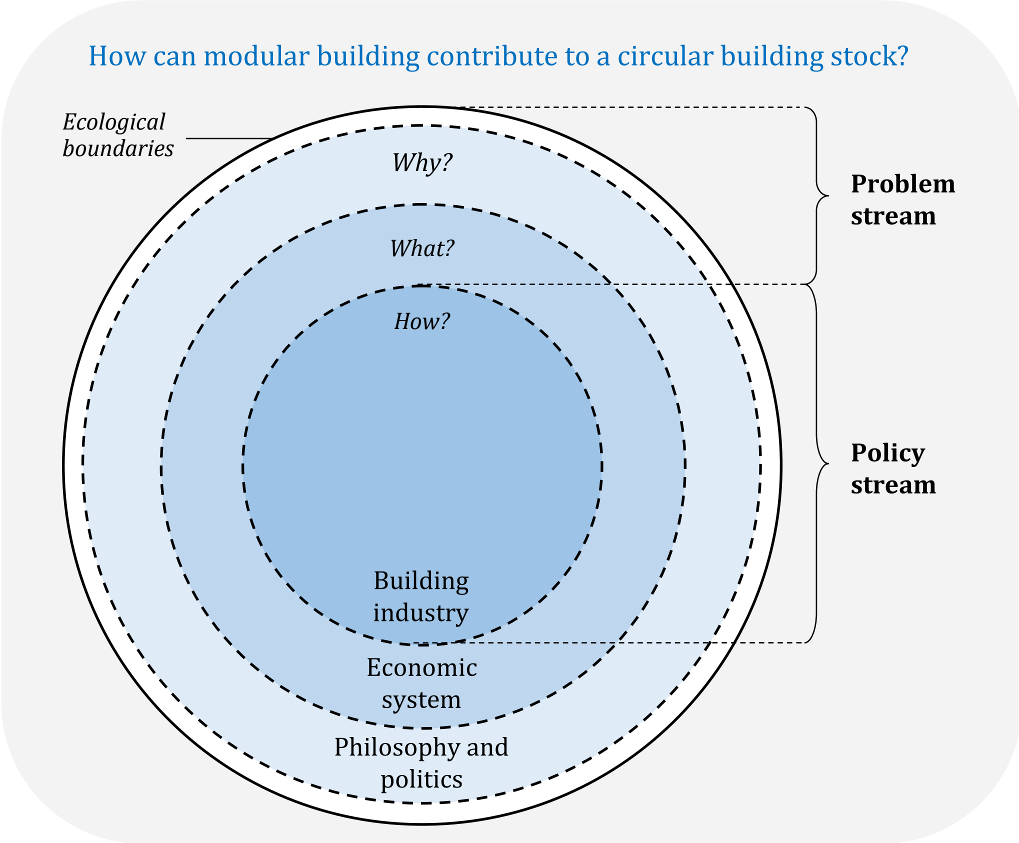


Figure 27: The place of the problem stream and the policy stream within this research

Three streams and the window of opportunity

Modular building can contribute to a circular economy, but it requires change. Kingdon (2014) argues that change, or enactment, can only occur when three streams intersect: the problem stream, the politics stream and the policy stream. This intersection is referred to as the window of opportunity. The focus of this research was on the problem and the policy stream, as shown in Figure 27.

The problem stream consists of conditions that capture the attention. This can be triggered by an indicator of the problem, an event, or feedback from current policies. What is most important is that not every condition is a problem: "conditions become defined as problems when we come to believe that we should do something about them" (Kingdon, 2014, p. 109).

A large part of this research is focuses on to the more general problem stream. This may seem odd as this research is conducted in the field of Architecture. The reason why the more general problem stream is given a great amount of attention, is because the *interpretation* of the problem is exactly what may lead to the development and adoption of one policy or another.

Defining the problem

In the past few years, the concept of a circular economy has got attention from the general public as well as from academia. A search for "circular economy" on The Guardian's homepage yields 2,470 results. A search for "circular economy" in ScienceDirect yields 238 results from 2015, 625 from 2016 and 707 results from the first half of 2017.

Common elements can be found in the different interpretations of a circular economy as a concept. It is about maximising the value of materials and eliminating waste. But to what problem is a circular economy a solution?

→ There is not enough growth in the GDP. A circular economy is a means to growth in the GDP that is less dependent on the input of raw materials. However, the goal remains to increase production.
→ There is a scarcity of resources and an expected growth in the size of the population. A circular economy is a means to keep providing services and goods to current and future generations. The goal is not to increase production, but to improve the existing stock in terms of utility and durability.

Even though some policies may "fit" both interpretations of the problem, the indicators that are used to measure intermediate goals — growth in the GDP or de development of the stock — determine the direction of the policies.

A circular economy in the Dutch building industry

In the Netherlands, it is expected that the natural growth rate will be, and will continue to be negative as of 2038 (CBS, 2016). In addition, there is no scarcity of resources in the building industry (Rijskwaterstaat, 2015). However, there are other problems that drive a circular economy in the building industry: the size of the waste stream; and the pressure on the living environment and the ecosystem (Rijskwaterstaat, 2015).

The political agenda

Whether a problem is given attention on the political agenda depends, amongst other things, on the national mood, election results and interest group pressure campaigns. Khayesi & Amekudzi (2011) argue that "a given situation has to be identified and explicitly formulated as a critical problem for it to stand a chance of attracting attention of policy makers" (p. 1548).

A circular economy has gotten the attention of policy makers, but it is linked to growth in the GDP, rather then to the development of the stock. The European Union action plan for a circular economy "Closing the loop" (European Commission, 2015) is based on a report in which a circular economy is said to "translate into a GDP increase of as much as 7 percentage points (….) [that] arise from increasing consumption" (Ellen MacArthur Foundation & McKinsey Center for Business and Environment, 2012, pp. 7-14).

Available policies

The policy stream consists of proposed solutions for the problem. Here these proposals need to be technically feasible, acceptable and future constraints need to be clear, to increase the chances of survival.

The collective case study and the interviews with suppliers of temporary buildings shows that modular building for deconstruction and reuse are not necessarily limited by technical feasibility.

The adaptable and relocatable modular product is made so that the client can adapt the product to his or her (changing) demands in the design and maintenance phase — that is the unique selling point. The suppliers of temporary buildings have made their products adaptable and relocatable, because these configurations have a relatively short lifespan. The building industry is technically capable of reusing parts of buildings,

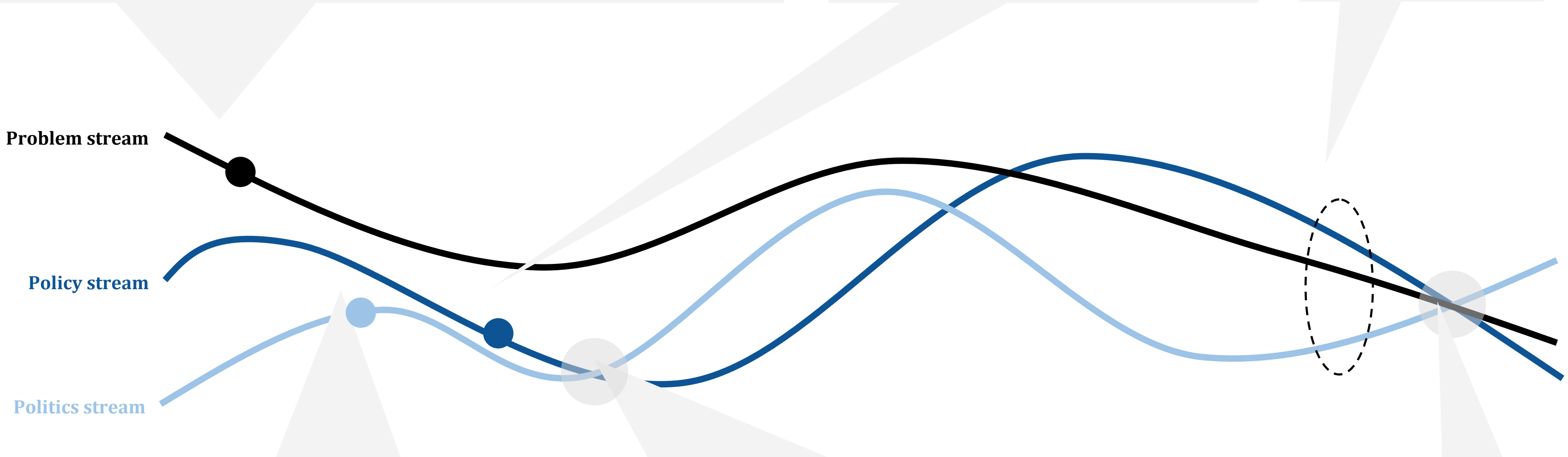
Interaction between the streams

In the past, the streams have manifested itself in isolation, or as an intersection between two streams. Currently, the three streams are close to one another, but do not intersect yet. This is shown in Figure 28 on the next page.

1973: “De Kleine Aarde”
In 1972 the Club of Rome published the report “The Limits to Growth”. One year later in the Netherlands, the bottom-up initiative “De Kleine Aarde” was set up — an experimental and educational centre for sustainable development. The centre comprised of a piece of land and an energy-efficient dwelling. Here, alternative ways of living were promoted, to spare the living environment and the earth. “De Kleine Aarde” was closed in 2010, as the concept was outdated and had a lack of funding (de Graaf, 2010).

1985: Demountable building
In 1985 an international symposium was held at Rotterdam on the topic of demountable concrete structures: “Demountable construction (...) is a question of acceptance rather than of technical constructability” (Reinhardt & Bouvy, 1985, p.1)

Status quo



1971: “Kringloopeconomie”
In 1971 two Dutch politicians argue in the Lower Chamber that it is time to transition from an economy of waste into a “kringloopeconomie” (circular economy). The concept is not further given a great amount of attention (Schouten, Grootveld, & Bureau de Helling, 2016).

1999: Industrial, Flexible and Demountable Building
In 1997 the Dutch government set up a programme to stimulate Industrial, Flexible and Demountable (IFD) building. IFD building was supposed to result in an increase the productivity of the building industry. In addition, IDF building would also lead to a decrease in the use of raw materials, due to the reuse of (parts) of the building. In 2007 the fourth and last book with examples of IFD building in practice was published (Crone, Cüsters, & SEV Realisatie, 2007).

Future: window of opportunity?

Figure 28: Examples of the three streams with regards to the concept of a circular economy in the Netherlands, and the interaction betwe en the streams (own fingure based on Kingdon (2014)). This is not intended to be an exhaustive timeline of events, but as an example of how the streams can diverge and converge

Conclusion

The concept of a circular economy has gained attention in the past few years, and could be a means to the goal of human well-being of current and future generations.

The world's population is expected to grow in the coming years, as is the demand for economic goods and services. Raw materials serve as an input for these economic goods, but the supply of raw materials is limited. In a circular economy, materials are kept in a closed loop. By increasing the durability and the utility of the economic stock of goods, the demands of current and future generation can be met.

The construction industry is said to consume more than half of the global resources and generate the greatest waste stream globally. There is a need for policies in the built environment that contribute to a more circular building stock.

A more circular building stock has a greater durability and utility than the current more linear building stock. This can be achieved by "securing" the future utility of the building stock. Buildings can lose utility as a result of building-related factors or locational factors. Buildings that are designed to be adapted or relocated can counter this loss of utility.

However, buildings can also lose utility as a result of a combination of building-related and locational factors, and more elusive, demand-driven factors such as "fashion". Buildings that are designed to be deconstructed and its piece parts to be reused in other combinations and configurations, offer the most potential to "secure" the future utility of the building stock. A quick "cure" becomes possible even in suboptimal conditions one is nowadays prepared to accept. This could be achieved by means of modular building.

In theory, there exist several definitions of modular building. In the narrowest sense, modular building is the assembly of prefabricated volumetric units into a single possible configuration on site — the building. In the broadest sense, modular building is the assembly of prefabricated elements, made by manufacturers independent of a particular building, into different configurations. It is the latter interpretation that allows for deconstruction and reuse, and thus is expected to contribute most to a circular building stock.

In practice, these different interpretations of modular building are also apparent. This is confirmed in a collective case study of five suppliers of modular housing.

The suppliers each offer a different type of modular building — ranging from the narrowest to the broadest interpretation. What these suppliers have in common though, is their ability to offer more affordable, customisable solutions that have the potential to deliver more utility compared to standardised alternatives. In this way, modular building *can* contribute to a circular building stock.

Discussion and limitations

Modular building can contribute to a circular building stock. The question remains whether this is indeed the most promising and straight-forward means, apart from reducing the overall demand for services and goods (Allwood, 2014, p.450).

Primary versus secondary materials

Within the scope of this study, but left out of the collective case study, is the question of whether primary or secondary materials are allocated in the modular buildings. If the modular buildings are made out of primary materials, this either results in an increase of the size of the building stock or a decrease in the durability of the building stock. This is an example of the compromise between the current durability and future utility.

Linkages of sustainability

In this research the focus is solely on materials, and not on energy. Furthermore, in this research no distinction is made between renewable and non-renewable materials, let alone sorts of materials. This choice was deliberately made to scope the research and to reduce the complexity of the problem. In reality, all aspects are interconnected — there exist linkages of sustainability — and a sustainable development ultimately requires a more holistic approach (Graedel, Voet, Ernst-Strüngmann-Forum, & Frankfurt Institute for Advanced Studies, 2010).

Definition of the concepts

The concepts in this research (circular economy, circular building stock, utility, durability, primary materials and waste) were not defined upfront but slowly emerged during the research process, based upon different sources of data. These concepts need to be critically reviewed and developed further. Furthermore, a norm or standard is needed to compare different solutions.

Scale levels

As mentioned in the introduction, the problem of resource scarcity has many scale levels. This research focused on the scale level Dutch building industry; in the Netherlands, it is expected that the natural growth rate will be, and will continue to be negative as of 2038 (CBS, 2016); and most materials used in the sector are not considered scarce (Rijskwaterstaat, 2015). There other drivers for a circular economy in the Dutch built environment. This nuance only became apparent at the end of the research process. Within the research there still are “jumps” between scale levels that do not take into account the scale-specific context.

Behavioural aspects

The scarcity of resources may not directly affect the “here and now”, but is expected to become a (substantial) problem in the near future. The prospect theory provides a possible explanation as to why current utility is more important than future utility (Kahneman & Tversky, 1979). Based the prospect theory, humans “are guided by the immediate emotional impact of gains and losses, not by long term prospects of wealth and global utility” (Kahneman, 2012, p. 286-287).

There is however an alternative explanation that hinders the transition from a linear to a circular economy, especially in the Dutch building industry. In the Dutch building industry, resource scarcity is not the main driver for a circular economy, rather it is the pressure on the living environment and the ecosystem (Rijskwaterstaat, 2015).

De Groot & Steg (2009) argue that three types of values are important in explaining pro-environmental behaviour: egoistic, altruistic and biospheric values: “People with a strong egoistic value orientation will especially consider costs and benefits of pro-environmental behavior for them personally: when the perceived benefits exceed the perceived costs they will behave in an environmentally friendly manner and vice versa. People with strong altruistic values will base their decision on behaving proenvironmentally or not on perceived costs and benefits for other people. Finally, people with a strong biospheric value orientation will mainly base their decision to act pro-environmentally or not on the perceived costs and benefits for the ecosystem and biosphere as a whole” (p. 62).

They suggests that, in design interventions that stimulate pro-environmental behaviour — such as the transition towards a circular economy — altruistic and biospheric values need to be strengthened, and conflict between egoistic, altruistic and biospheric values needs to be decreased. This is an opportunity to stimulate means that contribute to a circular building stock.

Case study

The collective case study can be biased in at least two ways. First, as not all firms responded to the interview invitation, this part of the research is prone to non-response bias. Second, there may be bias in the actual responses in the interviews, as the objective of the study was known to the interviewees. This bias is partly eliminated by comparing the data from the interviews to the data collected from the websites of the suppliers.

Also, one of the selection criteria was the notion of "circular economy" on the website of the supplier. However, the interpretation of the suppliers of a "circular economy" is not included in the research, and may differ from the interpretation in this research. Furthermore the focus in the case study was on suppliers of modular *housing*, whilst the findings are generalised to modular *building* in general. The findings of this research are (intended to be) an exploration, rather than a description or an explanation.

Furthermore, the inclusion criteria for the case study seem to have resulted in a misrepresentation of suppliers of modular building. The firms are all relatively small in size (number of employees and market share) and seem to have an overlap in terms of target group, though not explicitly investigated.

Recommendations

As mentioned in "Discussion", the findings of this research are of exploratory nature, rather than descriptive or explanatory. The recommendations for practice that can be made based on these findings are limited. In contrast, exactly because of the exploratory nature of this research, a lot of recommendations for future research can be made — there is a lot more to be explored, described and explained on the concept of modular building in a circular economy.

Recommendations for practice

In practice, suppliers of modular building mainly focus on the increasing current utility of the building for the user. The user can make different configurations of the modules, depending on his or her current demands. A recommendation for practice is to also take into account future utility. Suppliers of temporary buildings can prove as an example. Furthermore interfirm combinations of modules may provide even more utility to the user.

Recommendations for further research

The main focus in this research is on the supply-side of modular housing. An equally important angle is that of the demand-side. In the end, it is the user that "determines" the utility of the building. Modular building is a means to offer a affordable, customised product to the client. How does this compare to other (more traditional) alternatives, in terms of current utility? This requires research not only on the supply-side but also on the demand-side.

Modular buildings, in theory, have the ability to cope with loss of utility due to building-related and locational factors. Are modular buildings actually reconfigured and relocated in practice? Do these interventions take place frequently? What are the alternatives, drivers and barriers? Again, this requires research on the demand-side.

The assumption was made that the durability of modular building is higher than that of more “traditional” solutions. How much primary material is used as input and how much waste is created in modular building, compared to more “traditional” solutions?

Interfirm modularity is a potentially interesting subject. Interfirm modularity would allow for a greater number of possible configurations, but also has disadvantages such as the threat of technological lock-in.

Furthermore, it was not possible in this research to determine the “ideal” level of the module in a circular economy. How useful are the deconstructed parts, within (intrafirm modularity) and outside (interfirm modularity) of the building system of the firm? What system levels need to be standardised, what system levels need to be customised? There will always be a compromise between current and future utility.

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Appendices

Appendix A: Interview invite and protocol

Below an example of the email (translated from Dutch to English) that was sent to the suppliers of modular housing, as an for a semi-structured interview.

Dear,
Currently I am conducting my graduation research at the Faculty of Architecture at the TU Delft, master master Management in the Built Environment. My graduation research regards modular building, in relation to the (renewed) interest in a circular economy.

On your website I read the following: “Product D is demountable, relocatable and expandable. This makes the dwelling suitable for temporary and permanent use”.

I would like to ask you some questions on the above for my graduation research. Would that be possible?

Thanks in advance,
With kind regards,
Astrid Potemans

The research protocol is provided below (translated from Dutch to English, the interviews were conducted in Dutch).

Contact information		
Interviewee	Firm	
	Name	
	Telephone	
	Email	
	Notes	
Interviewer	Name	
	Notes	
Interview	Date [dd/mm/yyyy]	
	Time [hh:mm]	
Notes		

As mentioned in our email correspondence, I am currently graduating at the faculty of Architecture. My research is about the reuse of components. I would like to ask you some questions about Product X.

Introduction

- What is the idea of the concept behind Firm X?

Modular building system

[Quote from website on modular building system[

- What do you mean by “modular building”?
- Why do you build modular?
- What do you consider “a module”?

Characteristics of the product

- Can Product X be adjusted to the wishes of the client in the design phase? How?
    - What types of housing (or buildings) can be made from the modules?
    - What types of housing (or buildings) can not be made from the modules?
- Can Product X be adjusted to the wishes of the client in the operating phase?
    - What are the constraints?
- Can Product X be relocated?
    - What are the constraints?
- Can the modules of Product X be disassembled?
    - What are the constraints?
    - Could these parts be reused?

- Do you have any questions?

Thank you for answering these questions. I will keep you up to date on my research, and will ask for your consent in publishing the findings.

Appendix B: Data from websites and interviews

Firm	Idea behind the firm (why was it established)	Reason for building modular	Interpretation of "modular building"	Definition of the "module"
Firm A Data from website (translated)	*[not clear on website]*	"The Product A building system is developed to achieve results quickly and effectively. (…) A Product A dwelling is made by assembling standardised modules. By means of disassembly and reassembly, adaptation of the building is simple"	"Permanently adaptable, clean and quickly assembled, no waste on the construction site"	*[not clear on website]*
Data from interview (translated)	"The housing wishes and demands of households change every seven years, Product A allows to accommodate those changes. This could not be done in "traditional" construction, where parts are often glued and sealed together. Firm A was also founded out of frustration with how things go in the building industry"	"Modular housing allows for clients to be able to adapt their houses to their demands, as well as being able to control the use of materials and limit the amount of waste " "A person can live his or her whole life in a Product A dwelling. If you get children, you add some modules. If the children move out, you take off the modules and give them to your kids, or make a holiday home out of the modules"	"Modular is something that is permanently adaptable, without wasting natural resources"	"A wall panel, a floor panel – everything is a module. The module is a standardised panel made of aluminium and wood of 1500 mm by a plurality of 300 mm. "
Firm B Data from website (translated)	"We envision a world in which buildings contribute to the solving of the climate problem, are made in a sustainable manner, and are use in an environment-friendly manner. We wish for sustainable housing to be available for everybody. (…) We make relocatable buildings with wood, that have as small of a CO_2 footprint as possible. We do this without detracting from the design"	"Product B is a modular, wooden, relocatable and environment-friendly building system. We build in a future-oriented and adaptable manner"	*[not clear on website]*	"At Firm B we make buildings based on standard module. This module is called the Product B standard. There are three different frame sizes (25m2, 29m2 and 40m2 floor area) that share the same principles"

Firm	Idea behind the firm (why was it established)	Reason for building modular	Interpretation of "modular building"	Definition of the "module"
Data from interview (translated)	"The owner of the firm came up with the idea. He used to work for a supplier of modular housing, but these buildings were never actually disassembled and moved because it was financially unfeasible. There had to be a better way, also for the environment. That is how Firm B came into existence, as a better modular system"	"To be able to produce a high quality product within factory settings"	"Modular is an advanced form of prefabrication; something is modular if it is a closed unit that is delivered and placed on site"	`A volumetric unit, mainly made out of wood of 8.85 x 3.88 metres"
Firm C Data from website (translated)	*[not clear on website]*	"Product C is completely modular. As a result, can be custom-made for you"	"The elements that Product C is composed of, are easy to move. Also, the service installations are flexible and completely adaptable to a modified configuration of the dwelling"	*[not clear on website]*
Data from interview (translated)	"We are convinced that affordable, free standing houses can be designed for a price comparable to that of row houses. This means that the plot of land should be affordable. We also have a philosophy on how to use energy"	"Modular building has two main benefits: you can reduce the amount of elements that you produce industrially, and with these elements you can basically construct anything. In addition, it allows for the client to adjust the dwelling after delivery, by reconfiguring the elements"	"Modular building is an industrial way of building. For example, large components are transported to the building site, partly or fully finished. But modular building could also mean that you work with a fixed grid – all components are based on this grid. You can draw Product C on a 600 x 600 mm piece of paper"	*[not defined]*
Firm D Data from website (translated)	"Product D is an award-winning dwelling and is developed as a response to the demand for a new and innovative housing concept. Product D is suitable as a temporary and permanent dwelling and targeted at, for example, housing associations, municipalities, private clients and entrepreneurs in the leisure industry"	"Because of the modular construction and the prefabrication methods, Product D can be assembled in just a few days, complete with service installations. Product D is completely prefabricated in a production hall. (...) Prefabrication means quality, accuracy and a reliable planning. The manufacturing process takes place in ideal circumstances and is independent of the weather conditions"	*[not available on website]*	"The different parts of the dwelling are designed with a maximum width of 3,5 metres, to allow for transportation by road"

Firm	Idea behind the firm (why was it established)	Reason for building modular	Interpretation of "modular building"	Definition of the "module"
Data from interview (translated)	"Product D was designed for a competition for refugee housing, with the idea of "investing in energy"; now Firm D makes flexible, energy-neutral designer homes"	"The 15 pieces are chosen for the prototype because of transport limitations. In the ideal situation the building would consist of one module that can be transported as a whole"	"The building consists of 15 jigsaw puzzle pieces, that fit into each other on site within one day"	"A jigsaw puzzle piece of the building as a whole; these pieces are unique"
Firm E Data from website (translated)	"Firm E is established to make architecture more sustainable, flexible and accessible. Building can be done better, much better"	"Our unique building system, based on CNC [computer numerical control] milled wood modules, allows for sustainable and flexible possibilities. (…) By using new manufacturing techniques we give a new meaning to customised work. In this manner, we make the freedom in design of a private architect available to a wider audience" From brochure on website: "Because of the construction of the modules of 8,65m2 (3,5x2,5), the design can be easily adapted to your wishes and allows for assembly of the dwelling within just a few days"	From brochure on website: "The modules can easily be combined into new, original designs"	"The modules are the building stones with which almost every building can be made: inside and outside, ranging from dwellings to utility buildings" From brochure on website: "The modules of 8,65m2 (3,5x2,5) (…) consist of a wooden framework, a very well isolated façade and triple glazing in wooden frames"
Data from interview	*[not asked in interview]*	*[not asked in interview]*	"Modular building means building with a module that has a standard dimension. (…) These modules can be combined together in various different ways: in a series, in a square, or stacked upon each other"	"A module is a part with a standard dimension. We have a small and a large module. The small module is 2.5 by 3.5 metres and the large module is 5.0 by 3.5 metres"

Firm	Adaptable in the design phase	Adaptable after construction	Relocatable	Deconstructable and reusable
Firm A Data from website (translated)	"We start with your vision and ideas on how you want to live. We translate this in your programme of require-ments and wishes which is followed by a concept design. In close coopera-tion with you follows the final design, surprisingly fast and complete inclu-ding all of your desired features of your, yet to be build, property in a detailed view"	"A permanently modular dwelling, made of 100% sustainable materials. Adjust your dwelling to your wishes, needs and trends. Do you wish to make your dwelling larger, smaller or different? This is all possible with the unique building system of Firm A"	*[not available on website]*	*[not available on website]*
Data from interview (translated)	*[not explicitly asked in interview, the same principles of "adaptable after construction" apply]*	"Interviewee: A Product A dwelling can be adjusted to the changing needs of the inhabitant. If you expand your family, you can add modules. If your children move, you can pass on modules or make a holiday home out of the modules" "A constraint is to make the wall so that it can separate two dwellings, in terms of fire safety requirements. Furthermore the design possibilities are constrained in span and height"	"Interviewer: is it possible for a client to relocate his or her Product A dwel-ling? Interviewee: Yes, we would then completely demount the dwelling, including the foundation and pipe-work. We use a lifting method with vacuum, and as a result, we cannot transport in larger parts"	"Product A modules could be bought and sold on a community. The most important aspect is making the diffe-rent versions of the modules compa-tible with one another. (...) Firm A could also take back the modules to refurbish them. You could make a dwelling out of second-hand modu-les, or save up modules"
Firm B Data from website (translated)	"The basis of every Product B module consists of a fixed number of "ingredients". This is the solid wood, the great technical values, an "all-electric" approach, temporary and permanent application and the high quality finishing. The starting point for the assembly of your Product B module is our configuration model. This model allows for options in the frame (1), exterior (2), balcony (3), interior (4) and service installations (5)"	"Our buildings change with the target group, the use and the location"	"Product B can be relocated in an easy and favorable manner, by means of road transport"	*[not available on website]*

Firm	Adaptable in the design phase	Adaptable after construction	Relocatable	Deconstructable and reusable
Data from interview (translated)	"We do not offer services to private clients (yet); currently we are focused on housing corporations. (…) Interviewer: Can Product B be customised to meet the wishes of the clients in the design phase? Interviewee: That is something we are working on. Most of the time the "standard" is chosen" ** Note: at the time of the interview this was not yet possible, but at the moment of data analysis it was (as is apparent in the data from the website)*	"Interviewer: How is Product B "adaptable to change" (quote from website)? Interviewee: Product B is relocatable. In addition, the interior is modular: it is adjustable – you could turn it into a hotel room, or an office."	"Interviewer: How is Product B "adaptable to change" (quote from website)? Interviewee: Product B is relocatable. In addition, the interior is modular: it is adjustable – you could turn it into a hotel room, or an office."	"Interviewer: Why does Firm B stay involved with the delivered buildings? Interviewee: That is because of the circular philosophy – it is about maintenance and retaining the high quality. After the service life, we would like to take back the modules to find a new place for them. If the module can no longer be used, we want to disassemble it into elements"
Firm C Data from website (translated)	"Product C is a completely modular and therefor can be custom-made for you. The dimensions and the number of levels are based on your wishes. A specialised team helps and advices you to translate your wishes into an ideal Product C. Also the appearance of your Product C lies in your hands"	"Have you changed your mind over time? Not a problem: you can easily adjust your Product C to your changed circumstances or wishes without major renovation costs. The elements that are used to assemble Product C are easily relocatable. The service installations are flexible and adjustable to changes in the configuration of the dwelling. In addition, Product C can be easily enlarged by adding an extra level"	"The elements out of which Product C is assembled are easily relocatable"	"Your Product C is completely cradle to cradle and distinguishes itself from every other dwelling. The materials can be recycled and the components can reused, as these can be disassembled and assembled into another configuration"

Firm	Adaptable in the design phase	Adaptable after construction	Relocatable	Deconstructable and reusable
Data from interview (translated)	"Product C can be drawn upon a 600 x 600 mm piece of paper" "Our clients have a conversation with the architect about their housing wishes. The dwelling is then designed based upon these wishes. Everything consists of elements, it is almost as if you would put together an IKEA closet"	"Modular building has two main benefits: you can reduce the amount of elements that you produce industrially, and with these elements you can basically construct anything. In addition, it allows for the client to adjust the dwelling after delivery, by reconfiguring the elements" "The dwelling can grow with its occupants. The dwelling can be enlarged to a maximum of three levels. Another constraint is the construction, as a result of the "metal box", the footprint on the ground floor is the footprint on all levels. You can partly solve this by making a roof terrace. The height of the levels is also fixed"	"In theory it is possible to relocate the dwelling, but the bank would not allow this. The dwelling is collateral for the bank"	*[not clear from interview]*
Firm D Data from website (translated)	"Each Product D can be designed to meet the wishes of the user, based on the standard models (...) for example a single unit or a family home" "Could a private client also buy Product D? Yes, a private client could also buy Product D. In addition, a custom design is also possible, but the client should take into account the costs of transport, permits and design"	"Product D is demountable, relocatable and expandable. This makes the dwelling appropriate for temporary and permanent use"	"Is Product D relocatable? Yes, the separate parts of the dwelling are a maximum of 3,5 metres wide, so that road transport is possible" "Product D is a Dutch product and is delivered in The Netherlands. There are no piles required for the foundation; a simple subfloor will suffice. However, in polder areas, piles may be necessary"	*[not available on website]*
Data from interview (translated)	"Everything can be custom-made, but it is up to the client. If a private client wishes to make one specific design, it can be done, but the one-off costs need to be taken into account . It is more profitable to make custom designs in series, for example for a housing association"	"Interviewer: I read on your website that Product D is demountable, relocatable and expandable. How would Product D be expandable? Interviewee: You could put another Product D next to the other. The wooden framework is suitable to be adapted, for example with the help of a local contractor"	"It is possible to relocate Product D. The 15 jigsaw puzzle pieces would then be disassembled, transported, and assembled elsewhere"	"Our ambition is to use as much dry connections as possible, so that the dwelling can be disassembled into elements"

Firm	Adaptable in the design phase	Adaptable after construction	Relocatable	Deconstructable and reusable
Firm E Data from website (translated)	"The modules are the building stones with which almost every building can be made. (…) We translate your personal housing wishes into a sustainable design that suits you perfectly. (…) Ranging from a studio to a luxurious villa: the modular framework is the basis, the design is up to you. Every Product E is unique thanks to a great selection of sustainable finishing options"	"Is it possible to expand Product E after delivery with extra modules? It is possible to reconfigure Product E, but it is not possible to simply add modules due to the integrated ventilation system and the foundation. Keep in mind that it is less costly to construct the dwelling at once rather than extend the dwelling at a later moment in time"	"Is Product E relocatable? No. In theory Product E is demountable and relocatable. However, this model is not designed as a relocatable home. The foundation is always calculated for a specific location and cannot simply be used elsewhere. In addition, it is not possible to close on a mortgage if you intend to relocate the dwelling. In short, we do not advice to demount and relocate Product E"	*[not available on website]*
Data from interview	"The modules can be connected to one another in various different ways: in a series, in a square, stacked on top of each other (up until three levels). (…) The more projects we do, the more modules we can develop, so that we can offer more possibilities"	"The building can be made smaller or larger after delivery. In the beams of the dwelling, perforations are made for ventilation shafts. That is a universal system. If you change the configuration, you can adjust the ventilation" "Interviewer: Would it be possible to turn, for example, ten dwellings into one office?" Interviewee: In theory, yes. But the Building Decree has different rules and regulations for different types of functions. Turning a dwelling into an office would be easier than the other way around"	"The type of foundation depends on where you wish to build, but the biggest challenge is not to prevent the dwelling from sinking into the ground; it is to prevent the dwelling from blowing away" "The modules are connected to the foundation and each other on site with bolts"	"Interviewer: Can the modules be demounted into elements? Interviewee: Our modules are designed to be demountable up until the "structures": the floors, the roof, the columns, the façade and the partitioning walls. One level lower, the builder often wants to screw and glue the parts together, as this results in stronger connections. So, within the system of Product E the modules can be reused, but not outside of the system"