Circular Economy and
Civil Infrastructure Systems

Applying the principles of circular economy into the design and engineering process of the civil infrastructure systems

Master of Science Thesis

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Foreword

This is the graduation report for the master program of Construction Management and Engineering at the Eindhoven University of Technology. This research is conducted for the engineering company Iv-Infra and in particular department RAMS and Contract Management. Iv-Infra is a specialized engineering and design office for the civil infrastructure systems. The main activities of Iv-Infra are on the one hand drafting contracts for the civil infrastructure clients and on the other hand drawing design challenges for the contractors. In the recent years, department RAMS and Contract Management observes the increasing importance of resource efficiency or the circular economy in the society and in particular by the clients of civil infrastructure systems. Various clients, from regional to international, strive for resource efficiency since it creates more value for governments as well for the society and business. Following this, the question arose what the impact is of the circular economy on the design and engineering process of civil infrastructure systems. To gain insight into the possibilities a preliminary study in the form of master thesis was started. With great pleasure I chose this challenging topic as graduation research to complete my master. Together with the company's supervisors, the following research questions have been formulated: "How can the principles of circular economy be integrated into the engineering and design process of civil infrastructure systems?" This research is conducted under the supervision of Bauke de Vries and Qi Han(TU/e), Pieter van Gelder (TU Delft), Arno Willems and Antal Hartman (Iv-Infra) and Sten de Wit (TNO).

Finally, I want to thank my supervisors Bauke de Vries, Qi Han and Pieter van Gelder for their input and guidance during my graduation period. I am also grateful to Iv-Infra, especially to Arno Willems and Antal Hartman, for their valuable guidance for the practical side of the research. In addition, I would like to thank Sten de Wit for his contributing and his commitment. I would like to thank all the other persons who have contributed during this study. Finally, of course I would like to thank my parents, my wife and my family because of their support throughout my academic career.

Javad Alizadeh

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English Summary

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1.   Thesis Outline

This graduation research is conducted for the Engineering Company Iv-Infra. The goal of the research is to investigate whether the principles of circular economy can be integrated into the engineering and design process of the civil infrastructure systems. This chapter highlights the outline of the research. Paragraph 1.1 introduces the need for a resource efficient economic system. Paragraph 1.2 defines the research problem and the research goals which are further concretized by means of the main and sub-questions. Paragraph 1.3 describes the plan and the procedures of the research as research approach and research design. Finally, paragraph 1.4 represents a reading guide to help the reader to fathom the process and streamline the experience.

1.1 Introduction

The current economic system of industrial countries is a linear economic model of resource use (EMF, 2012). It means companies extract and transport resources from different countries, add energy and labour to manufacture a material and product and sell it to an end consumer, who then discards it when it no longer serves its purpose or because it is outdated. This model of resource use is known as the Linear Economy (LE) or ''take, make, dispose'' economy (EMF, 2012). An important characteristic of the linear economy is that economic growth is depends on input or in other words selling products. This means information, matters, energy and labour are used to make products that should be sold to make profit. The more products are sold, the more the economy growth.

In recent years, the economic growth based on linear economy is increasingly hindered due to the huge demand for resources (EMF, 2012). According to UNEP (2011), the use of natural resources such as water, energy, raw materials and fertile land is growing rapidly. Many businesses around the world feel squeezed between rising and less predictable prices in resource markets on the one hand and stagnating demand in many consumer markets on the other hand (EMF, 2012). Prices and volatility become more unstable and they are likely to remain high as middleclass populations grow and urbanize, resource extraction moves to harder-to-reach locations, and the environmental costs associated with the depletion of natural capital increases (EMF, 2012). While resource demand in the world increases, the linear economic system entails significant limits and resource losses such as: resource loss as

waste in production chain, resource loss as end-of-life waste, and resource loss as Energy. Furthermore, linear economy creates imbalances that weigh on economic growth. One of the major limitations of linear economy is that it mainly focuses on selling products and it does not maximize the benefits of resources after the product has been sold. The more products are sold, the more the economy grows. Resulting in volatility and increasing price rise of natural resources. According to McKinsey (2013) the arithmetic average of prices in four commodity sub-indices (food, non-food agricultural items, metals, and energy) stood at a higher level in 2011 than at any time in the past century [Figure 1].
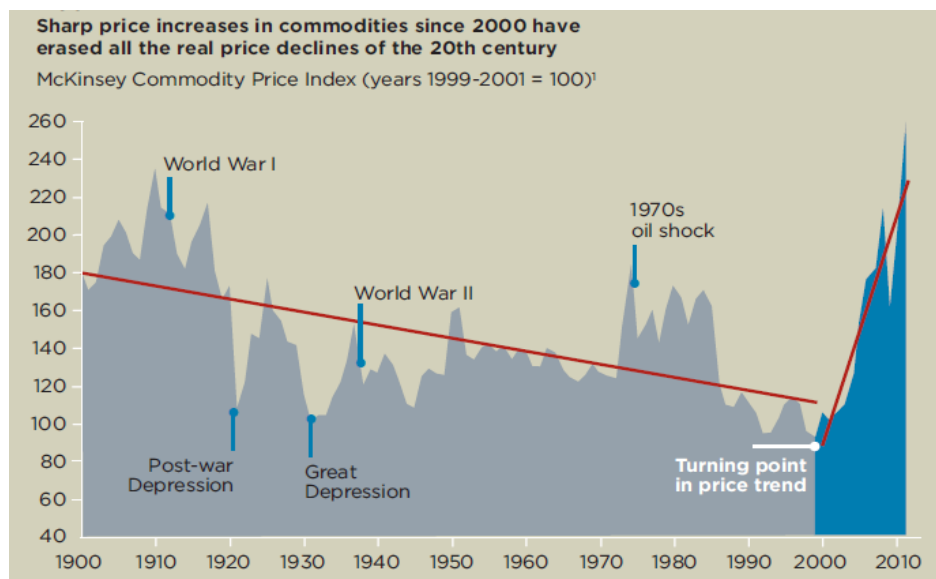
Figure 1: Increasing sharp price sins 2000

According to (EMF, 2012), current imbalances such as resource scarcity, price squeezes, and volatility are likely to get worse before they get better due to the following factors:

- Demographic trends and increasing resource demand due to growth of middle class population. It is expected that the middle-class consumers will increase with three billion by 2030, led by economic growth in India and China and other rapidly growing emerging market economies (McKinsey, 2011).
- Infrastructure needs a high investment to use newly discovered reserves. Tapping the newly discovered reserves will require heavy investment in infrastructure and new technology. According to McKinsey meeting future demands for steel, water, agricultural products, and energy would require a total investment of around USD 3

trillion per year (McKinsey, 2011), it is an amount roughly 50% higher than current investment levels (EMF, 2012).

- Political risks and limited opportunities to use remaining resources. political events can also have an impact on commodity supply as result trigger or worsen resource scarcity and push up prices and volatility levels. About 80% of all available arable land on earth lies in areas afflicted by political or infrastructural issues. About 37% of the world's proven oil reserves, and 19% of proven gas reserves, are also located in countries with a high level of political risk (EMF, 2012).

- Globalized market and awareness of local market about the material price and as result increasing higher material price.The regional price shocks can quickly become global due to the increasing ease of transporting resources globally and the rapid integration of financial markets (EMF, 2012).

- Climate and the risks of changes of ecosystem. According to the Environmental Protection Agency, changes in climate could affect snow cover, stream flow, and glacial patterns—and hence fresh water supply, erosion patterns, irrigation needs, and flood management requirements, and thus the overall supply of agricultural products (EPA, 2014).

Circular Economy

In 2010, the Ellen MacArthur Foundation (EMF) introduced the concept of Circular Economy (CE) in which the economic growth is decoupled from the resource use. In the sense of resources, decoupling means using less resources per unit of economic output for more people and reducing the environmental impact of any resources that are used or economic activities that are undertaken (UNEP, 2014) [Figure]. The mission of EMF is to accelerate the transition to the circular economy and to move the businesses and the society towards a resource efficient or circular economic system, (McKinsey, 2011).
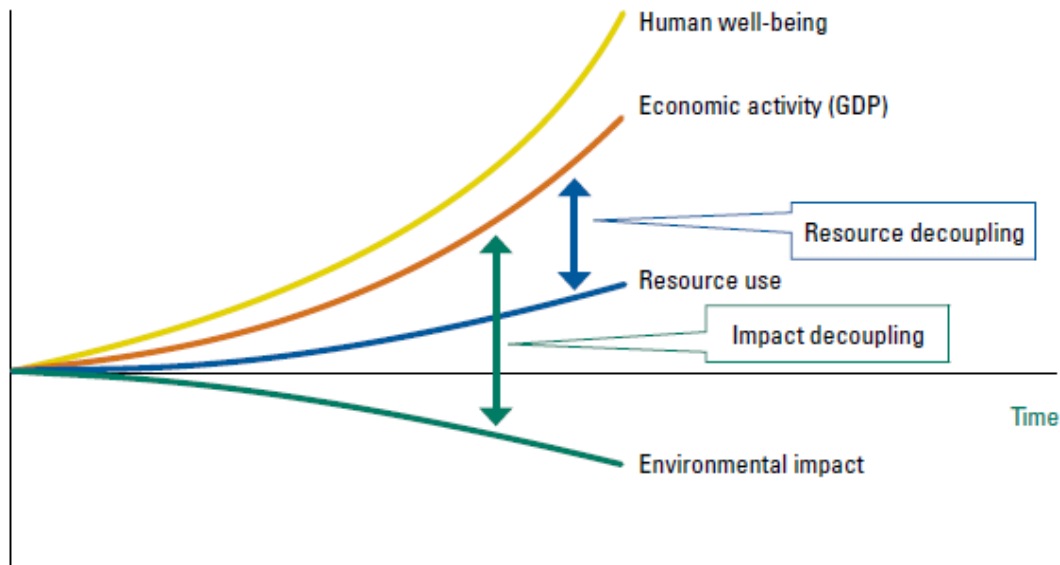
Figure 2: Decoupling natural resource use and environmental impacts from economic growth, (UNEP, 2011)

In a circular economy, the resources are used as long as possible until the maximum value from them are extracted whiles in use and then the products and materials are recovered and regenerated at the end of their life cycle (WRAP, 2012). As indicated by EMF (2012), CE can provide more value in the field of environment, economy and society or in other words the three pillars of sustainable development (Brundtland, 2010). To achieve this goal, the circular economy strategy and circular economy principles are introduced.

CE is meanwhile supported by multiple national and international governments, European Commission, Non-Governmental Organizations (NGO`S), banks, universities and the global market leaders of different sectors and industries such as Philips, the Coca Cola Company, Renault, Royal BAM Group, Royal DSM Group, Vodafone, Kingfisher, Unilever, IBM, H&M, Ikea etc. More and more regional, national and international authorities have high ambition regard circular economy. For example, in 2010, the European Commission has stated that they have the ambition to present a circular economy strategy to transform Europe into a more competitive resource-efficient economy (European Commission, 2014). Also the European Committee for Standardization (CEN) and European Committee for Electro Technical Standardization (CENELEC) have indicated that they will support the development of globally relevant standards related to the circular economy policies (CEN and CENELEC, 2015). The launch of CE signals the rise of the topic and the transition towards a circular business system.

1.2 Research problem and research questions

The transition towards a circular economy is both a political vision and an economic strategy for the global market leaders. In the circular economy governments will focus on resources and the purchasing and management of services, rather than focusing on being a supervisor of personnel and providing services directly (Eggers, 1997). For the civil infrastructure clients it means baying services instead of arranging in detail how something must be developed. For this dramatic change in the nature of government, major changes are taken in contracting system and management system of the governments in the last decade. As contracting system increasing use is made of service oriented contracting or Performance Based Contracting (PBC) in which the governments express their needs in terms of criteria, performance and quality. Furthermore, use is increasingly made of Systems Engineering (SE) as a management process in which the failures and mishaps can be minimized or avoided. For civil engineer designers and contractors it implies a shift from designing and building object to engineering resource efficient transport services. So far, civil infrastructure designers have gained practical experience with performance based contracting and systems engineering process. However, circular economy is a new subject. Circular economy introduces a new way of design systems. So, Iv-Infra is interested in the impact of the circular economy on their design and engineering process.

Research goal and research question

The goal of this research is to examine whether the circular economy principles can be integrate into the design and engineering process of the civil infrastructure systems. In particular the study is aimed to:

- Providing information about the circular economy concept, circular economy strategies and principles.
- Identifying the potential impact of circular economy in the construction sector.
- Identifying the barriers and the strategies for applying the circular economy in the design process of construction systems, in particular civil infrastructure systems.
- Identifying the ideal workflow to apply circular economy principles in to the design and engineering process of civil infrastructure systems.

Subsequently, the research objectives are expressed in the following main and sub questions to help achieve the purpose of the research.

Research question: How can the principles of circular economy be integrated into the engineering and design process of civil infrastructure systems?

Question 1:   To what extent does the current engineering process of civil infrastructure systems differs from the principles of the circular economy?

Question 2:   What is the potential impact of circular economy in the civil infrastructure sector?

Question 3:   Which circular economy criteria can be used in order to design resource efficient infrastructure systems?

Question 4:   Which strategy can be used in order to integrate these criteria into the design process?

Question 5:   What is the ideal workflow to apply circular economy in the engineering and design process of civil infrastructure systems?

1.3 Research methodology

The study is based on an analysis of relevant studies, the literature study and results from the case study. The study is structured around the steps below. The relationship between these steps, the research conclusion and recommendations are shown in Figure 3 in next page.

- **A literature review (step 1A)** which identified and reviewed relevant literature related to circular economy. This is complemented by **additional analysis (step 1B)** of the potential impact of circular economy on the construction sector including the barriers and strategies to integrate the circular economy principles in to the design process.

- **Integrating (Step 2)** circular economy principles into the design process of civil infrastructure system by Analytic Hierarchy Process (AHP), applying to a case study.

- **Creating the ideal workflow (Step 3)** that is needed in order to integrate circular principles into the design process of civil infrastructure systems.
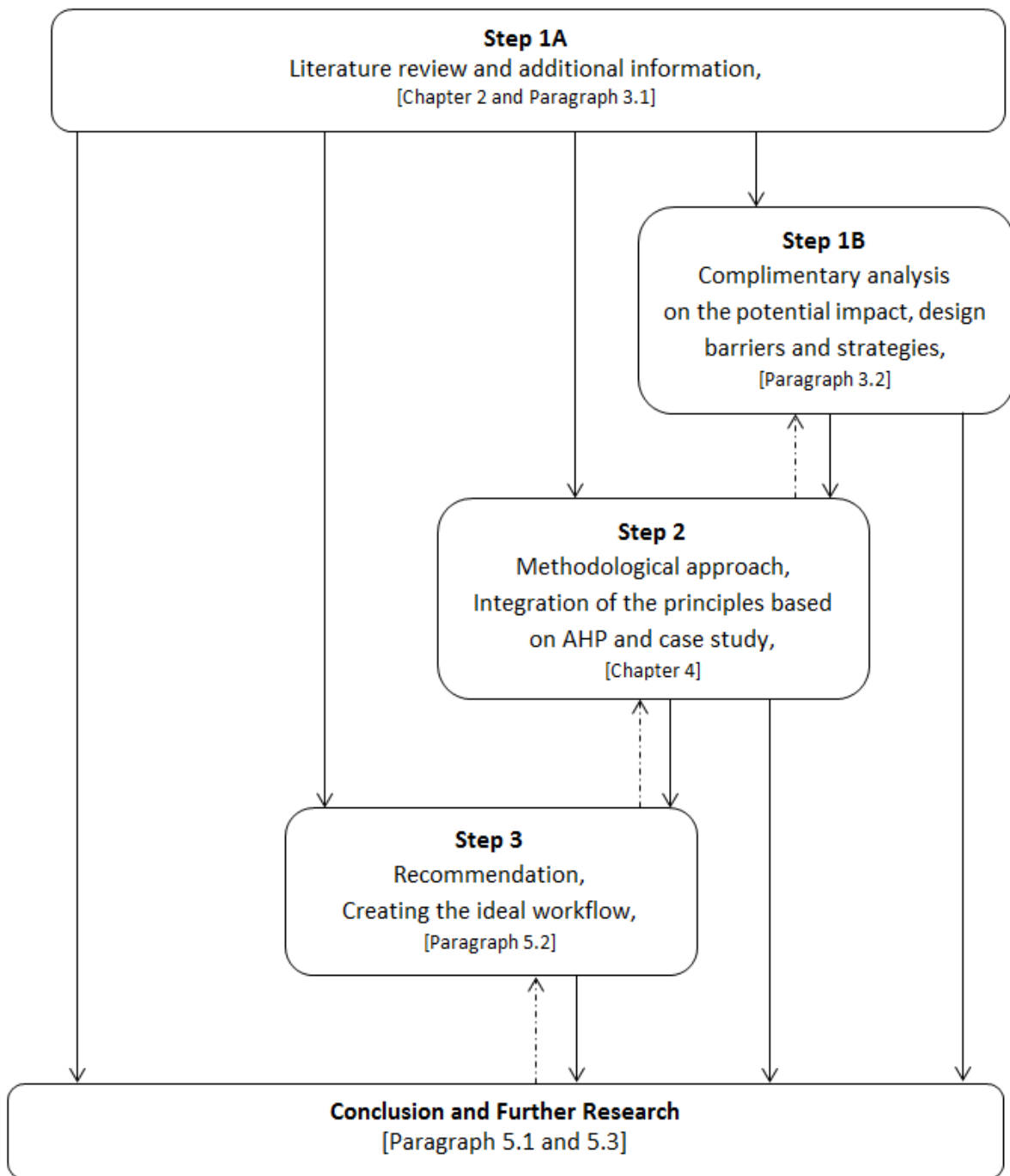
Figure 3: Relationship between project steps and the research recommendations

1.4 Structure of report

The remainder of research is structured as follows:

Chapter 2 provides a summary of the most important information related to the research problem. It represents the origin and definition of circular economy. Furthermore, it indicates the importance of developments such as systems engineering as management system and performance based contracting as contracting system in order to achieve the circular economy. Also it briefly indicates how systems engineering and performance based contract work.

Chapter 3 reviews the literature on the subject which forms a framework for the research. This chapter consists of three paragraphs including: paragraph 3.1 "Circular Economy Concept", paragraph 3.2 "Circular Economy in the Civil Infrastructure Sector" and paragraph 3.3 "Conclusion". At the beginning of first two paragraphs, the topic discussed in the paragraph is outlined. Both paragraphs end up with a brief summary. Finally, the third paragraph, "Conclusion", focusses on answering the research questions 1, 2, and 3.

Chapter 4 describes and applies the methodological approach in order to integrate resource efficient design criteria into the engineering process of civil infrastructure systems, based on decision support system the Analytical Hierarchy Process (AHP) and a case study. This chapter consists of 6 paragraphs. Paragraph 4.1 introduces the AHP method as a multi criteria decision support model. Paragraph 4.2 describes the process of AHP method. Paragraph 4.3 represents the case study which has been used in this research. Paragraph 4.4 discusses the results and the sub-conclusion that is drawn by some of the results. Paragraph 4.5 maps the identified relation between criteria based on results. the.

Chapter 5 reflects the important **conclusions, recommendation** and the **further research.** This chapter consists of three paragraphs. Paragraph 5.1 provides a concluding answer to the main question of this research. Paragraph 5.2 recommends an ideal workflow in order to achieve a resource efficient design. This is Simultaneously the answer for research question 4. Paragraph 5.3 discusses the possibilities for the further research and possible pitfalls by using AHP.

2.   Additional information relating to the research problem

This chapter provides background information on origin and definition of circular economy concept. In addition it introduces the development of instruments such as systems engineering as management system and performance based contracting as contracting system in order to achieve a circular economy. Paragraph 2.1 indicates the need for a resource efficient economy. Additionally it points out the origin, definition and the principles of the circular economy. Paragraph 2.2 describes the roll of systems engineering and performance based contract as strategic tools for the governments in order to move the society and in particular engineering community to the circular economy.

2.1 Resource efficient economic system

As indicated in the paragraph 1.1, the economic growth of industrial countries based on linear economy is hampered increasingly. While the global demand for the resources is increasing, the current economic system requires resources to produce and sell products in order to achieve growth. The more products being sold, the more the economy growth. In other words, the growth of the linear economy is mainly based on selling resources which become increasingly difficult to obtain. As a result of resource scarcity, resource prices and volatility in economic growth increase. It indicates, there is no longer balance between economic growth based on linear economy and global resource demand. In addition, at the same time the linear economy entails significant resource and energy losses. The linear economy is mainly focuses on the input (take, make and sell) and does not benefit the maximal value of resources at the output, for example by efficient recycle or reuse of resources at the end of life cycle. In 2010, Ellen MacArthur Foundation (EMF) introduced the concept of "Circular Economy" as an alternative for the linear economic system. EMF is a British registered charity and it is sponsored and supported by multiple national and international governments, European Commission, non-governmental organizations, banks, universities and more than 100 global market leaders of different sectors and industries such as Philips, the Coca Cola Company,Renault, Royal BAM Group, Royal DSM Group, Vodafone, Kingfisher,Unilever, IBM, H&M, Ikea etc. The mission of EMF is to accelerate the transition to circular economy and moving society towards the circular economic system. CE is seen as prosperous economic solution to the growing shortage of key raw materials. According to World

Economic Forum in the report "Towards a Circular Economy", about 500 billion could be earned by otherwise dealing with circularly use of raw materials in the European Union (World Economic Forum, 2014). Also TNO (2013) indicates that potential of circular economy for the Dutch economy is over 7 billion and more than 50,000 jobs could be created. Below the origin and different definitions of circular economy are indicated.

2.1.1 Origin

The idea of CE was sketched by Kenneth E. Boulding in his report "Economics of the Coming Spaceship Earth" (Boulding, 1966). Boulding was a Brits-Americans economist, systems scientist, and interdisciplinary philosopher. Boulding was president of numerous scientific institutions such as "American Economic Association", "Society for General Systems Research" and "American Association for the Advancement of Science". He was also the founder of numerous ongoing intellectual projects in economics and social science and cofounder of "General Systems Theory" (Keyfitz, 1996). After the creation of the idea of circular economy by Boulding, it was further refined by Walter Stahel. In 1976, Walter Stahel and Genevieve Reday sketched the vision of an economy in loops (or circular economy) and its impact on job creation, economic competitiveness, resource savings, and waste prevention in their research report to the European commission "The Potential for Substituting Manpower for Energy"[1]. In 2006 the promoting plan of circular economy as a five-year plan as national policy in China started (Zhijun et al. 2007). In time, circular economy concept has been mainly developed and refined by the following schools of thought:

1- "Regenerative design" (1970), by John T. Lyle an American professor of landscapearchitecture**. In 1970, Lyle creates the idea that all systems, from agriculture onwards, could be orchestrated in a regenerative manner. In other words, that processes themselves renew or regenerate the sources of energy and materials that they consume (EMF, 2012). This idea is described in his book "Regenerative design for sustainable development".

2- ''Permaculture''(1970), by Bill Mollison, Australian biologist and ecologists, and David Holmgren, an Australian environmental designer, ecological educator and writer**. In 1970 they coined the term ''permaculture'', defining it as 'the conscious design and maintenance

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[1] _"Cradle to Cradle | The Product-Life Institute"_. _Product-life.org. 2012-11-14. Retrieved 2013-11-20._

of agriculturally productive ecosystems, which have the diversity, stability and resilience of natural ecosystems'. Permaculture draws elements from both traditional sustainable agriculture and modern innovations and principles (EMF, 2012).

3- "Performance Economy" (1976), by Walter Stahel Swiss architect and industrial analyst. In 1976 he sketched the vision of an economy in loops and its impact on job creation, economic competitiveness, resource savings, and waste prevention in his research report to the European Commission, "The Potential for Substituting Manpower for Energy" (EMF, 2012). This research was co-authored with Genevieve Reday-mulvey. In 1982, Stahel published the book "Jobs for Tomorrow, the Potential for substituting manpower for energy". In 2010, he introduce the second edition of his book *performance economy* (first edition was introduced in 2006)[2]. In this book circular economy is seen as part of performance economy and *performance* refers to the quality and quantity of stocks (resources). Measuring the quantity and quality of resource (resource management) is seen as important key factor for a CE policy (Stahel, 2006).

4- "Cradle to Cradle" (1990), by Michael Braungart, a German chemist and visionary, in association with an American architect Bill McDonough**.** They develop the ''Cradle to Cradle'' concept and certification process in 1990. The phrase "cradle to cradle" itself was coined by Walter R. Stahel in the 1970s. The Cradle to Cradle framework focuses on design for effectiveness in terms of product flows with positive impact, which fundamentally differentiates it from the traditional design focus on reducing negative impacts. This concept addresses not only materials but also energy and water inputs, and builds on three key principles: "Waste equals food"- "Use current solar income" – "Celebrate diversity" (EMF, 2012). In 2002 they published the book "*Cradle to Cradle: Remaking the Way We Make Things*".

5- "Biomimicry" (1997), by Janine Benyus, an American natural sciences writer and innovation consultant**.**, she published the book "*Biomimicry: Innovation Inspired by Nature*" in 1997. She defines her approach as 'a new discipline that studies nature's best ideas and then imitates these designs and processes to solve human problems'. Studying a leaf to invent a better solar cell is an example. She thinks of it as 'innovation inspired by nature'. Biomimicry relies on three key principles: (1) Nature as model, study nature's models and

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[2]http://www.product-life.org/en/major-publications/performance-economy

emulate these forms, processes, systems, and strategies to solve human problems; (2) Nature as measure, use an ecological standard to judge the sustainability of our innovations;(3) Nature as mentor: view and value nature not based on what we can extract from the natural world, but what we can learn from it (EMF, 2012). She also has authored 5 other books on "Biomimicry" during 1983 – 1990.

6- "Industrial Ecology" is the study of material and energy flows through industrial systems. Focusing on connections between operators within the 'industrial ecosystem', this approach aims at creating closed-loop processes in which waste serves as an input, eliminating the notion of an undesirable by-product. Industrial ecology was popularized in 1989 in a Scientific American article by Robert Froschand Nicholas E. Gallopoulos. Frosch and Gallopoulos' vision was "why would not our industrial system behave like an ecosystem, where the wastes of a species may be resource to another species (EMF, 2012). Industrial ecology is concerned with the shifting of industrial process from linear (open loop) systems, in which resource and capital investments move through the system to become waste, to a closed loop system where wastes can become inputs for new processes (Allenby , 2006)

7- "Blue Economy" (2010), by Gunter Pauli, a Belgian businessman. He published the book ''the Blue Economy'' which was originally a report to the Club of Rome that became a commercial book in 2010. The report, which doubles up as the movement's manifesto, describes '100 innovations that can create 100 million jobs within the next 10 years', and provides many examples of winning South-South collaborative projects—another original feature of this approach intent on promoting its hands-on focus (EMF, 2012).

2.1.2 Definition

There are different definitions for the circular economy. Following, a number of definitions: **Ellen MacArthur Foundation**: "The circular economy refers to an industrial economy that is restorative by intention and design. It aims to enable effective flows of materials, energy, labour and information so that natural and social capital can be rebuilt. It seeks to reduce energy use per unit of output and accelerate the shift to renewable energy by design, treating everything in the economy as a valuable resource" (EMF, 2012).

Waste and Resource Action Plan[3]: "A circular economy is an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life".

Report to the European Commission regard circular economy: "A circular economy represents a development strategy that enables economic growth while optimizing the consumption of natural resources, deeply transforming production chains and consumption patterns and re-designing industrial systems" (European Commission, 2014).

Wikipedia: "The circular economy is a generic term for an industrial economy that is, by design or intention, restorative and in which material flows are of two types, biological nutrients, designed to re-enter the biosphere safely, and technical nutrients, which are designed to circulate at high quality without entering the biosphere".

EMF defines circular economy as an "industrial economy". However, a transition to a circular economy affects not only the economic system of an industrial country but also it the society and environment. In this respect the definition used in the report to the European commission is more appropriate that indicates that circular economy introduces a 'development strategy'. In addition the definition used by WARP is more focused on material use. In this research the following definition is used: "Circular economy introduces a development strategy that optimizes natural and social capital by creating an effective closed system for materials flow, energy flow, labour flow and information flow". In the sense of natural capital, it enables an economic growth while optimizing the consumption of natural resources by: reducing energy use per unit of output, reusing energy by means of cascading, using more renewable energy, reducing material use, using materials as long as possible until the maximum value from them is extracted whilst in use and by reusing, recovering, regenerating and recycling materials to make products and materials at the end of each service life.

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[3] http://www.wrap.org.uk/content/wrap-and-circular-economy

2.2 Moving towards a resource efficient construction sector based on SE and PBC

Today's governments will shift their focus to resources and the purchasing and management of services based on circular economy. For this dramatic change in the nature of government, major changes are taken. For example use is creasing made of a contracting system that is outcome based with clear performance standards. This state-of-the-art contracting system refers to the Performance Based Contracting (PBC). In addition, use is made of a management process that avoids failures and mishaps. This management process refers to Systems Engineering (SE).

2.2.1 Performance Based Contracting (PBC)

Since the 1990s, PBC has been heralded as one of the most effective instruments for moving the society towards a resource-efficient or circular economy and creating a much needed resource revolution (Tukker, 2013). For the governments, PBC makes possible in order to express their needs in terms of requirements, performance and quality. Another terms for PBC are Performance Based Acquisition, Product Service System, Performance Contracts, Performance Based Agreements and Outcomes or Output Based Contracts. "A performance-based contract is a contract that focuses on the outputs, quality and outcomes of service provision and may tie at least a portion of a contractor's payment as well as any contract extensions to their accomplishment" (Martin, 1997; CIPS and NIGP, 2012).This contracting system clearly spells out the desired end result expected of the contractor, but the manner in which the work is to perform is left to the contractor's discretion. In these contracts, contractors are given as much freedom as possible in figuring out how to best meet clients' performance objective (CIPS and NIGP, 2012).

PBC holds great promise to reduce costs while increasing service quality. These contracts ensures the clients that system is designed, built and operated so that it accomplishes its purpose safely in the most cost-effective way possible, considering functional and operational performance, cost, schedule, and risk. PBC is a preferred contracting system in capital-intensive industries such as civil infrastructure where the systems and subsystems require high availability and are expensive to maintain

(Mirzahosseinian, et al., 2011). To achieve high system functionality use is made of RAMS functional performance criteria. Below RAMS is described.

RAMS requirements

Reliability, Availability, Maintainability and Safety (RAMS) are the most important quality and functional performance crietria which are used to define, to determine, to measure, to asses and to monitor the functional performance of systems (Rijkswaterstaat, 2010). However, in recent years RAMS has been expanded by aspects such as: Security, Health, Environment, Economic and Politic (RAMSSHEEP). RAMS engineering is an enlarged engineering discipline that was originated from the concept of safety and reliability. RAMS engineering was firstly introduced by the aerospace industry to evaluate the reliability and safety of aircrafts in the 1930s (An, 2005; Ebeling, 2010). Since the 1980s, with the rapid development of systems engineering, RAMS management has been widely adopted to effectively define, identify, assess and control all potential threats affecting the achievement of the functional and operational objectives of a system. RAMS management has developed as a distinct discipline of systems engineering since the early 1990s with the established engineering concepts, methods, techniques, measurable parameters and mathematical tools (Villemeur, 1992; Park, 2013). RAMS engineering is a significant disciplines and decision making factor in engineering systems, since system functionality and operation performance are the primary requirements interest of systems.

RAMS management is an engineering discipline that integrates reliability, availability, maintainability and safety characteristics appropriate to the operational objectives of a system into the inherent product design property through systems engineering (Park, 2013). The goal of RAMS is to achieve the systems safety, availability and cost-effectiveness in the management aspect of system's long term operation (Park, 2013). In long term operation systems such as civil infrastructure systems, RAMS analysis can be used in different life cycle stage of the infrastructure system in order to define, to measure, to asses and to monitor the functional and operation performance of systems. A decreasing of functional and operational performance of the infrastructure systems can lead to for example: the frequent delay of the transport service, the increase of total ownership cost, and even the continuous increase of the potential damage for humans and environments caused transport accidents. To avoid such effects in the civil infrastructure systems, RAMS management is applied (1) to defining RAMS characteristics, such as reliability, availability, maintainability and safety,

proper to RAMS requirements and operational contexts, (2) to assessing and controlling the potential threats, such as faults, failures and errors, that affect the quality of infrastructure services and (3) to provision the controlling means, such as failure prevention, fault tolerance, fault removal and fault prediction (Park, 2013). Since the infrastructure systems are originally developed to function and operate properly, much attention has been paid to RAMS management from the early development phase.

Resource efficient requirement

In addition to RAMS performance, the government can require performance with respect to resource efficiency by optimal use of materials or reducing waste. For example, to stimulate reuse and recycling of materials in the construction sector, Waste Framework Directive (WFD)[4] requires member states to take any necessary measures to achieve 'a minimum target' of 70% (by weight) of C&D waste by 2020 for preparation for re-use, recycling and other material recovery, including backfilling operations using non-hazardous C&D waste to substitute other materials. By using such regulations, the governments stimulate the contractors to take into account waste reduction by optimal use of materials in construction projects. Chapter 3, discusses more about the resource efficiency in the construction sector.

2.2.2 Systems Engineering (SE)

As mentioned before, governments will increasingly use of SE to avoid failures and misshape by developing systems by contractors. For example, Rijkswaterstaat (a part of the Dutch Ministry of Infrastructure and the Environment) has introduced three guides in 2007s, 2009s and 2013s to introduce SE to the market and to stimulate the use of SE in civil infrastructure sector (Rijkswaterstaat, et al., 2013). There are many definitions for the term "Systems Engineering". As defined by Defence Acquisition University "Systems Engineering is an interdisciplinary engineering management process that evolves and verifies an integrated, life-cycle balanced set of system solutions that satisfy customer needs" (Department of Defence, 2001). The holistic view of SE is a process which focuses on analyzing and eliciting customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem, the system lifecycle (Oliver, et al., 1997).

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[4]Directive 2006/12/EC revised by Directive 2008/98/EC

Originally, the need for systems engineering arose with the increase in complexity of systems and projects, in turn increasing the possibility of component friction, and therefore the unreliability of the design (Yassin et al., 2003; Braha et al., 2007). There are three kinds of systems engineering: Product Systems Engineering, Enterprise Systems Engineering, Service Systems Engineering (Cheeckland, 1999). Civil infrastructure has to do with the engineering of service systems. Cheekland (1999) defines service systems as a system which is conceived as serving another system (Cheeckland, 1999). According to the International Council on Systems Engineering (INCOSE) "a system is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce systems-level results. The results include system level qualities, properties, characteristics, functions, behavior and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected" (INCOSE, 2010). However, the way in which s system is defined dependent on the interests and responsibilities of the observer.

In general, SE is divided to the management and technical process. The goal of the management process is to organize the technical effort in the lifecycle, while the technical process includes assessing available information, defining effectiveness measures, to create a behavior model, create a structure model, perform trade-off analysis, and create sequential build & test plan (Oliver, et al., 1997). The most important element in systems engineering is the explicit documentation of information. In this process, the communication of the documented information is absolutely essential to prevent errors and the cost of failure. Due to this, transparency and explicit methods of working are absolutely essential (Rijkswaterstaat, et al., 2007). Systems thinking is the fundamental principle of systems engineering. System thinking provides a potential solutions to a complex problems from a holistic perspective in which the problem is viewed in the context of the larger whole. This fundamental principle ensures a structured way of developing and managing a project in a repeatable and transparent way.

2.2.2.1 Systems Engineering Process

The Systems Engineering Process (SEP) is a comprehensive, iterative and recursive problem solving process which applied sequentially top-down by integrated teams (Department of Defence, 2001). The goal of SEP is to transform needs and requirements into a set of system product and process descriptions, to generate information for decision makers and to provide input for the next level of development (Department of Defence, 2001). The design process based on SE progresses through distinct levels or stages:

- "Concept level: which produces a system concept description (usually described in a concept study),
- System level, which produces a system description in performance requirement terms; and
- Subsystem/Component level, which produces first a set of subsystem and component product performance descriptions, then a set of corresponding detailed descriptions of the products' characteristics, essential for their production" (Department of Defence, 2001).

According to Department of Defence (2001) the configuration baselines are called the functional baseline for the system-level description, the allocated baseline for the subsystem/ component performance descriptions, and the product baseline for the subsystem/component detail descriptions [Figure 4].
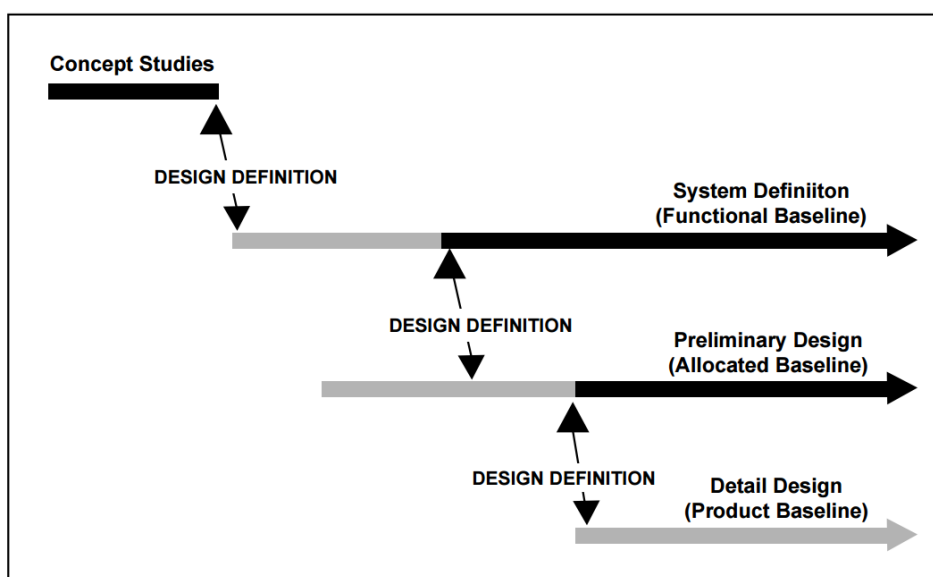

Figure 4, System Engineering development phase, (Department of Defence, 2001)

Systems Engineering Activities

Systems engineering process has three fundamental activities: Requirements Analysis, Functional Analysis and Allocation and Design Synthesis (Department of Defence, 2001). Figure 5 maps the relation between three activities. Following the three activities are explained.
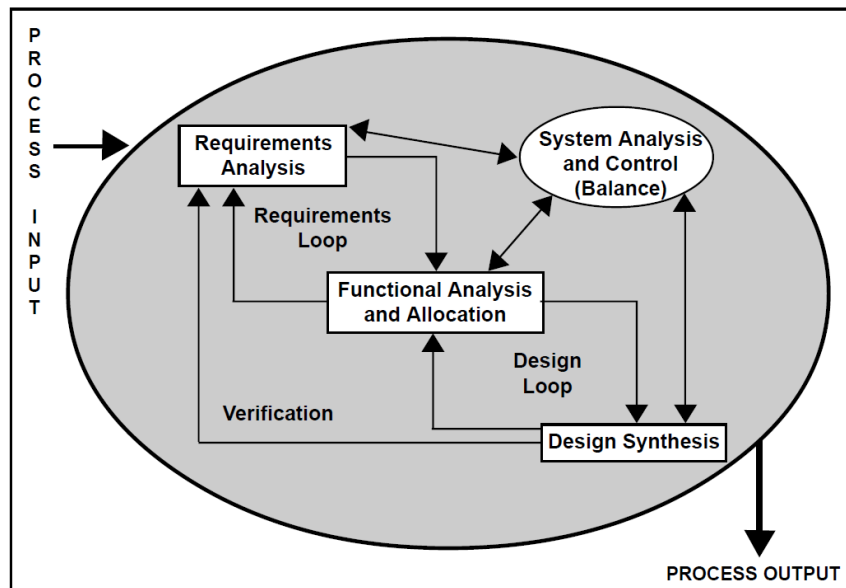
Figure 5: The Systems Engineering Process (Department of Defence, 2001).

Requirements analysis is the he first step of the systems engineering process. Requirement analysis is a process to analyze the customer requirements or process inputs that define what the system must do and how well it must perform. In this stage the engineering team must ensure that requirements are understandable, unambiguous, comprehensive, complete and concise. "Requirements analysis must clarify and define functional requirements and design constraints. Functional requirements define quantity (how many), quality (how good), coverage (how far), time lines (when and how long), and availability (how often)" (Department of Defence, 2001).

Functional Analysis and Allocation (FAA*)* plays an important role in the systems engineering process. As given by Department of Defence(2001) "Functional Analysis and Allocation facilitates traceability from requirements to the solution descriptions that are the outcome of Design Synthesis". This activity transform the functional, performance, interface and other requirements that were identified through requirements analysis into a coherent description of

system functions that can be used to guide the 'design synthesis activity' that follows. (Department of Defence, 2001). FAA translate the customer requirement in function and it allow better understanding of what the system has to do, in what ways it can do it, and to some extent, the conflicts associated with lower-level functions (Department of Defense, 2001). In this stage, functions are analyzed by decomposing higher level functions identified through requirements analysis into lower-level functions (Department of Defence, 2001).

Design synthesis "is the process of defining the product or item in terms of the physical and software elements which together make up and define the item. The result is often referred to as the physical architecture (Department of Defence, 2001). Each part must meet at least one functional requirement, and any part may support many functions. The physical architecture is the basic structure for generating the specifications and baselines" (Department of Defence, 2001).

Systems Engineering Process

Systems engineering is based on the three important aspects including: separation of specification and design; verification and validation; the life cycle approach (Rijkswaterstaat et al., 2007). Following these three aspect are explained briefly.

Separation of Specification and Design

The starting point for developing a system is the problem definition and preparation of specifications includes the survey and analysis of requirement and functions (Rijkswaterstaat, et al., 2007). The goal of the project is to find a solution for the problem, for example resolving the traffic congestion between two area. The problem statement is described in the project's primary requirement. To achieve the project objective, the systems engineering process subsequently proceeds on the basis of two processes running in parallel: the specification process and the design process (Rijkswaterstaat, et al., 2007) [Figure 6].
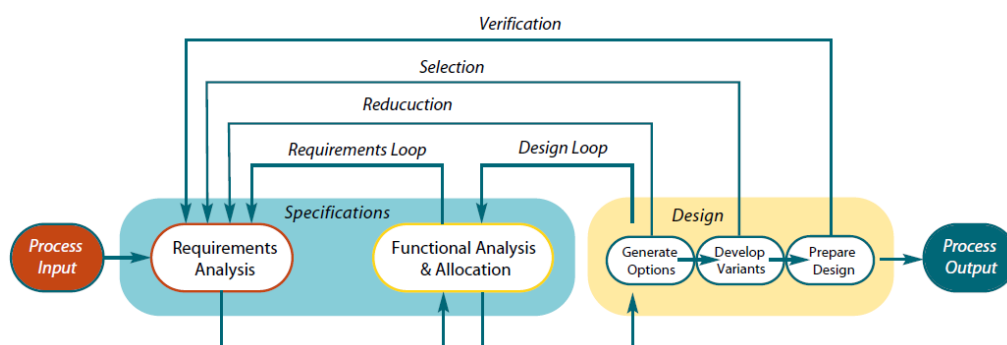

Figure 6: The engineering process in public works and water management (Rijkswaterstaat, et al., 2007).

As indicated by Rijkswaterstaat,(2007) , "the goal of the requirements analysis process is to translate the stakeholders' requirements into measurable system requirements and functions. The functions are therefore transformed into requirements during this phase and, where necessary, requirements are translated into more detailed requirements on the basis of the design choices made" (Rijkswaterstaat, et al., 2007). In addition to the functional requirements, the system is expected to meet other requirements as well such as environmental requirements as a part of the performance requirements. Reducing waste and optimal use of resources can be a part of this requirement. After analyzing the requirements the functions of system are, on the basis of functional analysis and allocation, transformed into subsystems and to prepare a specification that documents the requirements that the relevant subsystem is expected to meet (Rijkswaterstaat, et al., 2007). The functional analysis and allocation process is done by following the next steps (Rijkswaterstaat, et al., 2007):

- the detailed specification of all of the system's functions
- derive the subsystems (function enablers) from these functions
- create structure and coherence among these subsystems
- link the requirements from the requirements analysis to these subsystems

The inputs into the functional analysis and allocation are the system functions that has to be designed, determined on the basis of the contracting authority and/or stakeholders' needs. These main functions can be further decomposed or used for deriving sub functions. (Rijkswaterstaat, et al., 2007). After the functional analysis and allocation of system and subsystems, the functions of each solution-independent subsystem is transformed into a physical solution-based subsystem (Rijkswaterstaat, et al. 2007). In this process, design is derived from the described requirements and (sub)system functions (Rijkswaterstaat, et al. 2007). In this stage, the design process produces the design choices that best meet the client's requests and objectives, and therefore provides the transition from problem to solution. In order to achieve the best design solution, the design process is subdivided into a the following steps (Rijkswaterstaat, et al., 2007):

Generate options: " the objective of the options generation and reduction process is to determine the possible solutions for a system and to produce a limited number of feasible options on that basis that will be subjected to further investigation. The generation of options is defined as the consideration of all possible solution directions for the system. In order to be able to produce a comprehensive list that does not 'overlook' any potentially acceptable

solutions, it is important that the initial survey of options be determined without any consideration of value whatsoever and to stimulate out of-the-box thinking during the options generation phase. This can be accomplished on the basis of brainstorming sessions, for example. The generated options are subsequently reduced to a limited number of feasible solutions that are then developed further into variants. The reduction of the collection of conceivable options into a set of feasible options is accomplished by way of an elimination process based on one or more requirements and preconditions. Put another way: only those options that are inherently capable of meeting all of the requirements are transformed into variants. The entire process is documented" (Rijkswaterstaat, et al., 2007).

Develop variants: " the objective of the variant development phase is to be able to make a design choice for the system under consideration that best meets the requirements and other criteria. Further development of the variants is necessary in order to bring the options judged as being feasible to a level of detail that allows the variants to be mutually compared on the basis of the specified requirements and criteria. It is important that, in addition to the specified requirements, other criteria such as environmental impacts or costs are allowed to play a role as well as part of the assessment. This is where the 'value' concept comes in. Value is an abstract concept and essentially represents a measuring stick that allows the specified requirements and 'requests', and the required financial resources to be correlated. Once the variants are developed in further detail, it becomes possible to calculate the impacts of the variants in relation to the assessment criteria. A score matrix or a trade-off matrix is used to allow the variants to be compared. The different assessment criteria are assigned a weighting factor. The variant with the best score (or that represents the highest value) is ultimately selected as the solution for the system" (Rijkswaterstaat, et al., 2007).
Prepare design: "In this stage the design selected as the solution of the system is developed in further detail during this phase. The requirements or functions attributed to the subsystem is developed in further detail during this phase. The requirements or functions attributed to the subsystem or process are defined in specific terms at the desired level of detail" (Rijkswaterstaat, et al., 2007).

In order to work out the design in further detail, sub requirements and sub-functions are derive from the main requirements and main functions. This process is repeated until a design emerges that is suitable for production(construction). The specifications and the design often merge at the lowest level. In that case the specification and design chunks can also be considered as a combined chunk" (Rijkswaterstaat, et al., 2007). Figure 7 shows the

combination of the specification, design and production processes based on the system engineering V-model. This model indicates the process flow with a descending line representing the further detailing of the specification and design process and an ascending line representing the production process. It also illustrates the relationship between the contracting authority's requirements, the stakeholders' and client's requests and the system to be designed and produced.
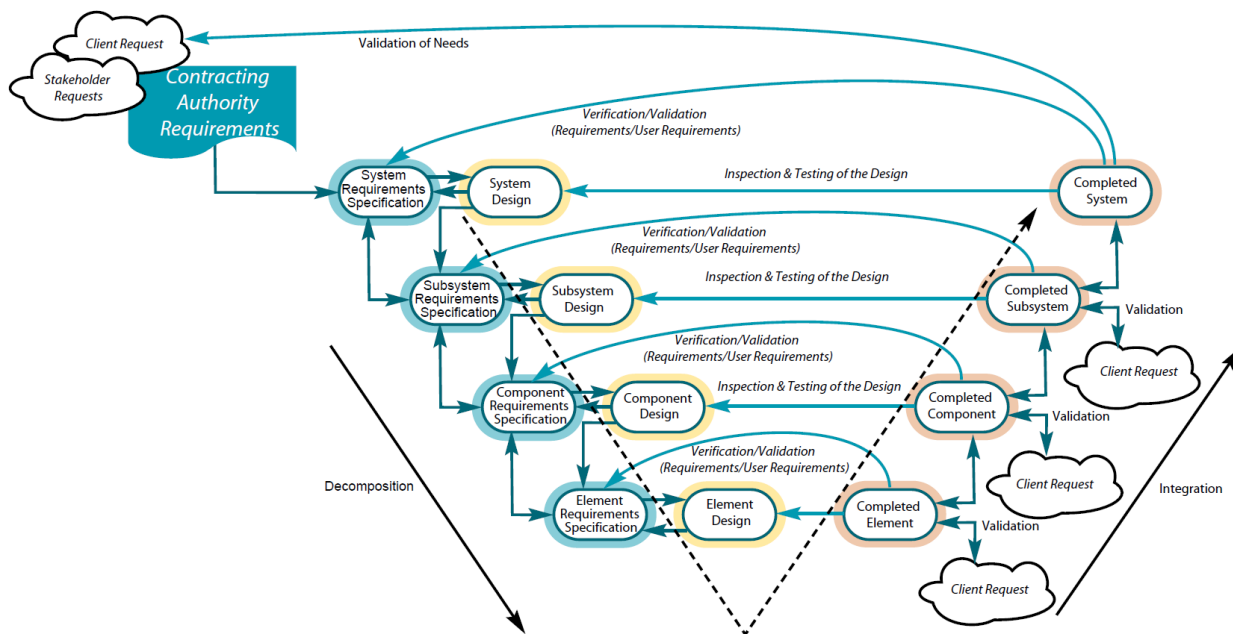
Figure 7: Integrated V-model of systems engineering process, (Rijkswaterstaat, et al., 2007).

Verification and validation

Since a system design is prepared on the basis of the specified requirements, the design is verified and validated to determine whether the design meets these requirements and the client's. Validation express the act of proving and monitoring whether the produced system meet the client's requests on system, subsystem and component level. Verification means the act of showing or checking whether the produced system respect the design (Rijkswaterstaat, et al., 2007). Inspection and testing are the commonly used terms for verification and validation. "In this respect, inspection and testing are carried out on the basis of the design, while the requirements must ultimately be verified" (Rijkswaterstaat, et al., 2007), [Figure 7].

The Life Cycle approach

Systems engineering is based on life cycle approach. "First, because the systems engineering approach applies to all phases of the system life cycle. Second, this comes to the fore in the way in which life cycle considerations are included in advance and explicit in the design process as a mandatory element" (Rijkswaterstaat, et al., 2007). The repetitive execution of specification, design and production during the life cycle is graphically depicted in figure 8.
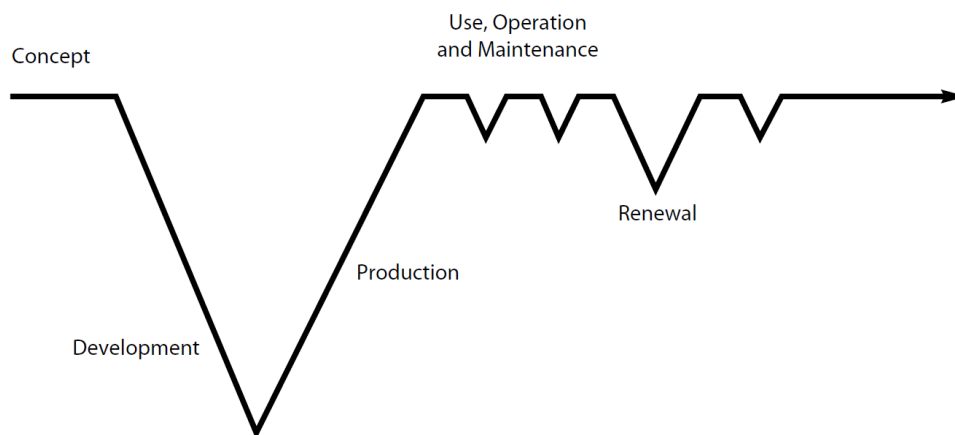
Figure 8: Execution of specification, design and production during the life cycle (Rijkswaterstaat, et al., 2007).

During design stage, the RAMS requirements play a key role in order to make a making life cycle trade-offs, hence RAMS requirements refers to the functionality of the system. Due to this, it is important to devote a great deal of attention to the system's RAMS requirements during the specification and design phases by analyzing the matters that can affect the functionality of the system (Rijkswaterstaat, et al., 2007). Figure 9 positions the RAMS requirements.
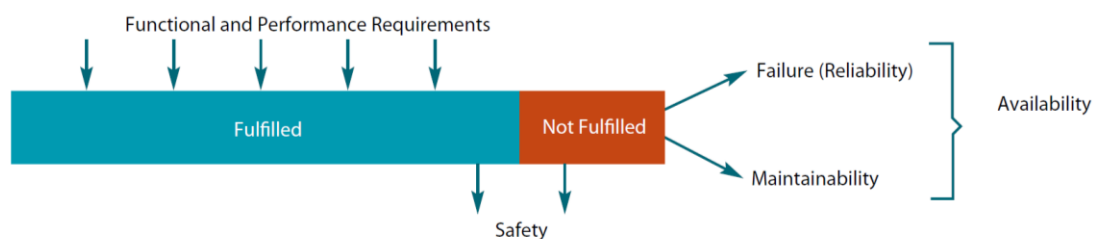
Figure 9: RAMS requirements, (Rijkswaterstaat, et al., 2007).

The overall bar in figure 9 represents the system during use. As indicated by Rijkswaterstaat, "the blue portion represents the system operating in accordance with all requirements and the red portion represents where this is not the case. The "not fulfilled" status during the user phase could be the result of a failure (lack of reliability) or because maintenance is required. Both situations can lead to reduced availability of the system (Rijkswaterstaat, et al., 2007). By using design alternatives and materials that require low maintenance, the unavailability can be reduces.

3.   Theoretical framework

This chapter reviews the literature on the research subject which forms a framework for the research. This chapter consists of three paragraphs. Paragraph 3.1 "Circular Economy Concept" important aspects of the circular economy including circular economy principles, circular economy strategy and circular economy loops. In addition, it indicates how circular economy can be measured. Paragraph 3.2 "Circular Economy in the civil infrastructure sector" highlights the importance of construction sector in the transition to a circular economic system. Also it indicates the barriers and strategies for the designers in order to design according to the circular economy principles. Finally, paragraph 3.3 "Conclusion" gives an answer to the research questions 1, 2, and 3.

3.1 Circular Economy Concept

This paragraph highlights the circular economy concept including the fundamental principles, strategies deployed to date as well as the concept of 'circular economy loops. Section 3.1.1 introduces the circular economy principles. Section 3.1.2 describes the strategy and the way in which circular economy will work. Section 3.1.3 indicates the concept of ''circular economy loops'' which is needed for a successful transition to a resource efficient economy. Section 3.1.4 shows 4 ways in which circular economy create value. 3.1.5 indicates how the circular economy can be measured.

3.1.1 Circular Economy Principles

As indicated by EMF (2013), the circular economy is based on few fundamental principles. These include: design out waste, build resilience through diversity, rely on energy from renewable sources, think in systems and waste is food. Below a brief explanation of the principles is indicated.

Design out waste
According to this principle, products should be designed by intention to fit within a material loop (EMF, 2013). As stated by EMF(2013) waste does not exist when the biological and technical components (or 'materials') of a product are designed by intention to fit within a biological or technical materials cycle, designed for disassembly and re-purposing. Design

for assembly, design for reuse and design for refurbishment are examples of design waste out principle.

Build resilience trough diversity

Modularity, versatility and adaptively are the most important features of this principle (EMF, 2013). This principle ensure the flexibility of systems for the future changes and needs. According to EMF (2013), diverse systems with many nodes, connections and scales are more resilient in the face of external shocks and changes than systems built simply for efficiency.

Shift to renewable energy sources

This principle aims to use renewable energy such as solar energy, energy from soil and or wind power for producing materials or systems through the supply chain. According to EMF (2013), using renewable energy reduces the need for fossil-fuel based inputs and capture more of the energy value of by-products and manures.

Think in systems

System thinking is a process of understanding and it has roots in the 'General Systems Theory' that was advanced by Ludwig von Bertalanffy in the 1940s and furthered by Ross Ashby in the 1950s (Senge et al. 1990). According to Senge (1990), " Systems thinking is a discipline for seeing wholes. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshot." In the context of circular economy, 'Systems thinking' refers to the system theory and in particular self-regulating systems or systems self-correcting through feedback that can be found in nature, including the physiological systems of our body, in local and global ecosystems, and in climate—and in human learning processes (Biel et al., 200). Self regulating is the property of systems in which variables are regulated so that internal conditions remain stable and relatively constant. Self regulating comes back in living organism for example the self regulating process of human body that maintains the body-stability of the internal environment in response to changes in external conditions. In this process all body internal processes, from cell to body organ, operate as a whole to keep the conditions within tight limits to allow these reactions to proceed. This automatic control system is done through feedback in which the system feed back into itself or in other words outputs of a system are routed back as inputs as part of a chain of cause-and-effect that forms a circuit or loop (Frod, 2010). According to " Self-

regulating mechanisms have existed since antiquity, and the idea of feedback had started to enter economic theory in Britain by the eighteenth century, but it wasn't at that time recognized as a universal abstraction and so didn't have a name" (Mayr, 1989). Systems engineering is partly an example of application of system theory in the field of engineering that integrates more disciplines and specialty groups into a team effort in order to function as a whole. EMF (2013) defines system thinking as " the ability to understand how parts influence one another within a whole, and the relationship of the whole to the parts". According to EMF (2013), " Systems' thinking usually refers to the overwhelming majority of real-world systems which are non-linear, feedback-rich, and interdependent. In such systems, imprecise starting conditions combined with feedback lead to often surprising consequences, and to outcomes that are frequently not proportional to the Such systems cannot be managed in the conventional, 'linear' sense, requiring instead more flexibility and more frequent adaptation to changing circumstances''(EMF, 2012).

Waste is food

The phrase 'waste is food', coined by Braungart and McDonough, summarizes the circular philosophy and design out waste principle (EMF, 2012). According to this principle the biological nutrient can be cascaded for products of materials. It express the ability to reintroduce products and materials back into the biosphere through non-toxic, restorative (EMF, 2013). On the technical nutrient side, materials can be up cycled, recycled and reused for the same of other products or systems (EMF, 2012).

3.1.2 Circular Economy Strategy

In the circular economy the economic growth is decoupled from the resource use. In the sense of resources, decoupling means using less resources per unit of economic output for more people and reducing the environmental impact of any resources that are used or economic activities that are undertaken (UNEP, 2011), [Figure 10]. Another term for recourse decoupling is ''recourse efficiency'' (UNEP, 2011). Circular Economy is a practical and proven implementation of resource efficiency. In different literatures such as UNEP (2011) and WRAP (2012), the term resource efficiency is used as a substitute term for circular economy. Also in this report both circular economy and resource efficiency are used.
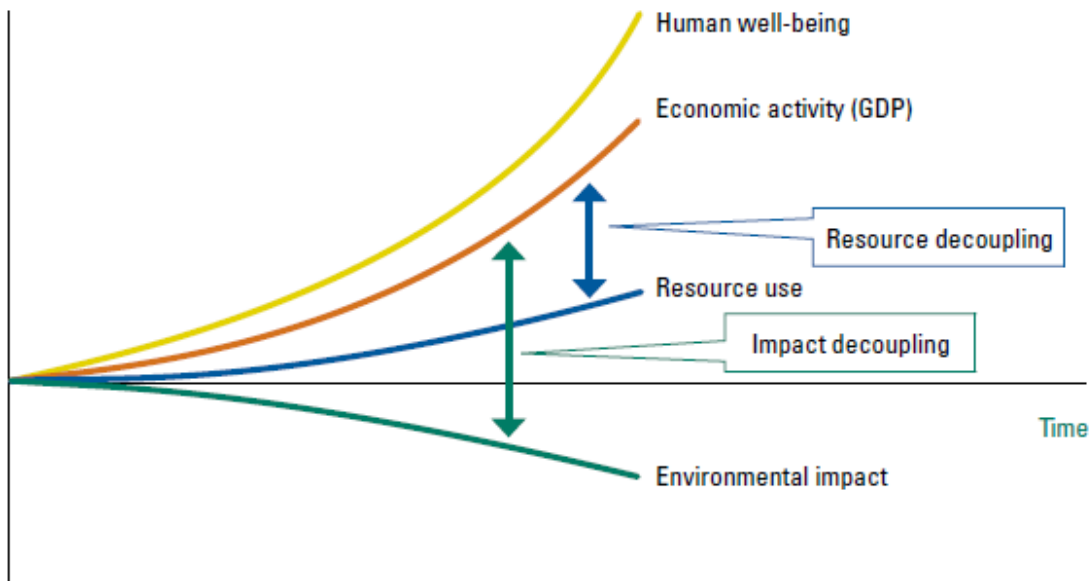
Figure 10: Decoupling natural resource use and environmental impacts from economic growth [UNEP, 2011]

In the circular economy the economic growth is based on renting resources or selling service rather than selling products. "This idea refers to as the 'functional service economy' and sometimes put under the wider notion of 'performance economy' which also advocates more localisation of economic activity" (Clift et al., 2011). According to report done for the european commission, *"Circular economy strategies are schemes ensuring that upstream decisions in the value chain are coordinated with downstream activities and actors"* (EU, 2014). Circular economy strategy connect producers, distributors, consumers and recyclers, link incentives for each of these actors, with an equal distribution of costs and benefits. It aims to inspire innovation throughout the whole value chain, rather than relying solely on waste recycling at the end of value chains. According to the report to the European Commission (2014), circular economy strategy is based on two pillars including the 'the cradle to cradle ' principle and industrial symbiosis. The cradle to cradle principle refers to the product design for durability , disassembly and refurbishment. It express that that businesses should apply the principles of eco-design to all their products, i.e. use as little non-renewable resources, eliminate as many toxic elements and hazardous materials as possible, use renewable resources (at or below their rates of regeneration), increase the life and reuse potential of products, and facilitate, at the conception stage, the sorting and final recovery of products (EU, 2014). Furthermore, it change the model of consumption from buyer to user (EU, 2014). Industrial symbiosis express a cross-sector approach and cooperation between actors unaccustomed to cooperate (e.g. between product designers and recyclers), along the whole supply chain of a product, in order to optimise its life-cycle (Eu,

2014). It is the sharing of services (e.g., transport) (EMF et al., 2012), utility, and by product resources among industries in a territory, creating synergies between businesses for economies of scale. The spatial clustering of collaborating companies is highly important as it makes the interconnecting of links in the supply chain and the exchange of residuals between links easier (TNO, 2013).

3.1.3 Circular Economy Loops

Circular economy distinguishes the resources into two categories. Firstly, biological materials from biological origin such as agricultural and forestry goods/commodities, bio-based wastes and residues, which are generally non-toxic and renewable to an extent as they are limited by the availability of land, water and nutrients and can be returned to the biosphere, where they act as nutrients (EMF et al., 2012). Secondly, technical materials like minerals, metals, polymers, alloys and hydrocarbon derivatives (e.g. plastics), which are not biodegradable and are based on finite resources (EMF et al., 2012). As seen in the figure 11, each kind of material between these twee resource categories comes in a material loop. Each category has its own loops. Below the loops belong to each categories are mapped.
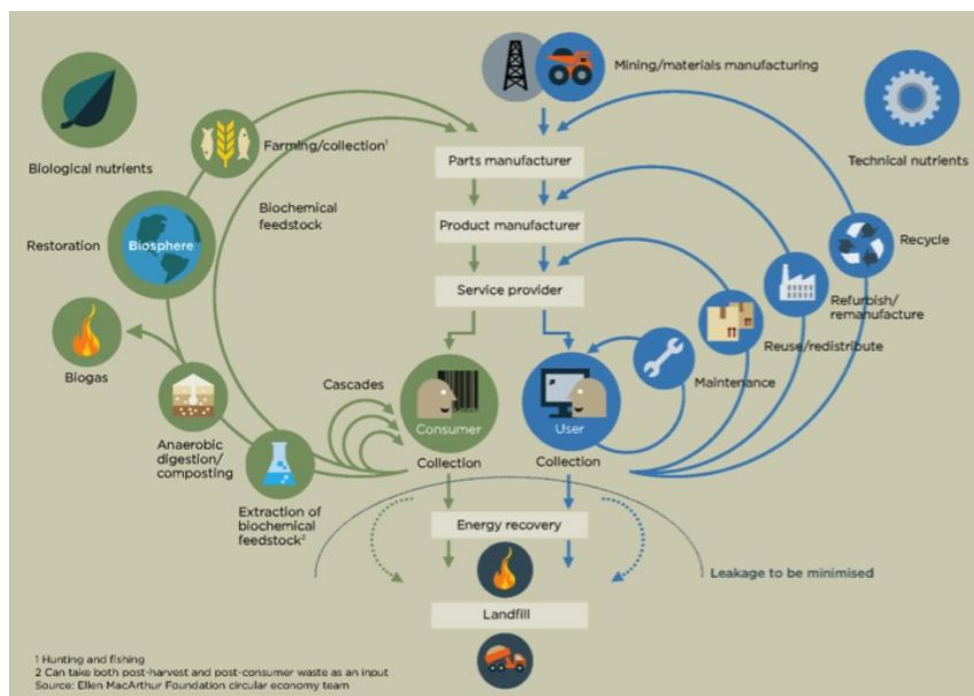

Figure 11: The circular economy loops, (EMF et al., 2012).

Circular economy loops for technical nutrients

According to Ellen MacArthur Foundation and others (2012), there are four ways of achieving a circular economy for technical nutrients which are set out below in descending order of the value of the outcome:

1- Reuse of goods:

- Reuse of a product again for the same purpose as in its original form with little enhancement or change. In this, the reused product is "as-good-as-new".
- Reuse of a productagain for a different purpose than its original form with few or negligible improvements (e.g. using tires as boat fenders).

2- Product refurbishment or component remanufacturing:

- Product refurbishment: returning a product to good working condition by replacing or repairing major components that are faulty or close to failure, and making changes to update the appearance of a product, such as cleaning, changing fabric, painting or refinishing.
- Component remanufacturing: A "process of disassembly and recovery at the subassembly or component level. Functioning, reusable parts are taken out of a used product and rebuilt into a new product (EMF et al., 2012).

3- Cascading of components and materials:

As stated by EMF and others (2012) cascading is successive uses of a material across different value streams. It refers to user-friendly, cost-effective, and quality preserving collection systems; as well as treatment/extraction technologies that optimise volume and quality.

4- Material recycling:

Material recycling point out any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. " It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations" (EMF et al., 2012). As reported by EMF and otehrs (2012), recycling can be divided into the following types:

- Upcycling: " converting materials into new materials of higher quality and increased functionality" (EMF et al., 2012).

- Functional recycling: " recovering materials for the original purpose or for other purposes, excluding energy recovery" (EMF et al., 2012).

- Downcycling: " converting materials into new materials of lesser quality and reduced functionality" (EMF et al., 2012).

Circular economy loops for biological nutrients

Next to the technical nutrients, EMF report (2012) highlights the following means available to create a more circular economy in the field of biological nutrients:

1- Cascading of components and materials:

As with cascading use of technical materials, it involves using materials for other, higher value, uses for constituent materials than material recycling of raw materialsIt refers to user-friendly, cost-effective, and quality preserving collection systems; as well as treatment/extraction technologies that optimise volume and quality.

2- Extraction of biochemical:

"Applying biomass conversion processes and equipment to produce low-volume but high-value chemical products, or low-value high-volume liquid transport fuel—and thereby generating electricity and process heat fuels, power, and chemicals from biomass. In a 'biorefinery' such processes are combined to produce more than one product or type of energy" (EMF et al., 2012).

3- Anaerobic digestion:

"process in which microorganisms break down organic materials, such as food scraps, manure, and sewage sludge, in the absence of oxygen (EMF et al., 2012)." This process generates biogas (methane and carbon dioxide) and a solid residual. The solid residual can be applied on the land or composted and used as a soil amendment, while biogas can be used as a source of energy similar to natural gas''(EU report, 2014).

4- Composting:

"Biological process during which naturally occurring microorganisms (e.g., bacteria and fungi), insects, snails, and earthworms, break down organic materials (such as leaves, grass clippings, garden debris, and certain food wastes) into soil-like material called compost.

Composting is a form of recycling, a natural way of returning biological nutrients to the soil"
(EMF et al., 2012). Compost can be used as a non-toxic ingredient in agricultural fertilizers,
(EU report, 2014).

Energy recovery and landfilling

Energy recovery and landfilling is the final option in material loop in which products would
consist of energy recovery, after options with cost and resource savings have been exhausted
or can no longer be chosen by economic actors due to the quality degradation constrains.
Energy recovery can be defined as a process in which "waste materials can be converted into
useable heat, electricity or fuel" (EMF, 2012), " through combustion, gasification, pyrolysis,
combustion of biogas from anaerobic digestion, or landfill gas recovery. Finally, landfilling
(i.e. disposing of waste in a site used for the controlled deposit of solid waste, onto or into
land1) is considered as the last end-of-life solution for non-recyclable waste". According to
EMF, " circular economy would try to extract the maximum value from used products and
materials", because landfilling creates negative externalities such as its impact on land use—
including the societal burden associated with siting choices—and greenhouse gas emissions"
(EMF, 2012) .

3.1.4 Creating value by circular economy loops

As indicate by EMF and others (2014) the circular economy loops are the sources of value
creation that offer arbitrage opportunities, i.e. ways to take advantage of the price difference
between used and virgin materials. This can be done in four ways including: the power of
inner cycle, the power of circling longer, the power of cascading use and the power of pure
inputs (EMF et al., 2014). Below the sources of value creation are briefly described.

The power of the inner circle

"The power of the inner circle refers to minimising comparative materials use
vis-à-vis the linear production system. The tighter the circle, i.e. the less a product has to be
changed in reuse, refurbishment and remanufacturing and the faster it returns to use, the
higher the potential savings on the shares of material, labour, energy and capital still
embedded in the product, and the associated externalities (such as greenhouse gas (GHG)
emissions, water and toxicity)" (EMF et al, 2014).

The power of circling longer

"The power of circling longer refers to maximising the number of consecutive cycles (be it repair, reuse, or full remanufacturing) and/or the time in each cycle. Each prolonged cycle avoids the material, energy and labour of creating a new product or component" (EMF et al, 2014), [Figure 12].

The power of cascaded use

"The power of cascaded use refers to diversifying reuse across the value chain, as when cotton clothing is reused first as second-hand apparel, then crosses to the furniture industry as fibre-fill in upholstery, and the fibre-fill is later reused in stone wool insulation for construction—substituting for an inflow of virgin materials into the economy in each case— before the cotton fibres are safely returned to the biosphere" (EMF et al., 2014).

The power of pure inputs

"The power of pure inputs, finally, lies in the fact that uncontaminated material streams increase collection and redistribution efficiency while maintaining quality, particularly of technical materials, which in turn extends product longevity and thus increases material productivity" (EMF et al., 2014).
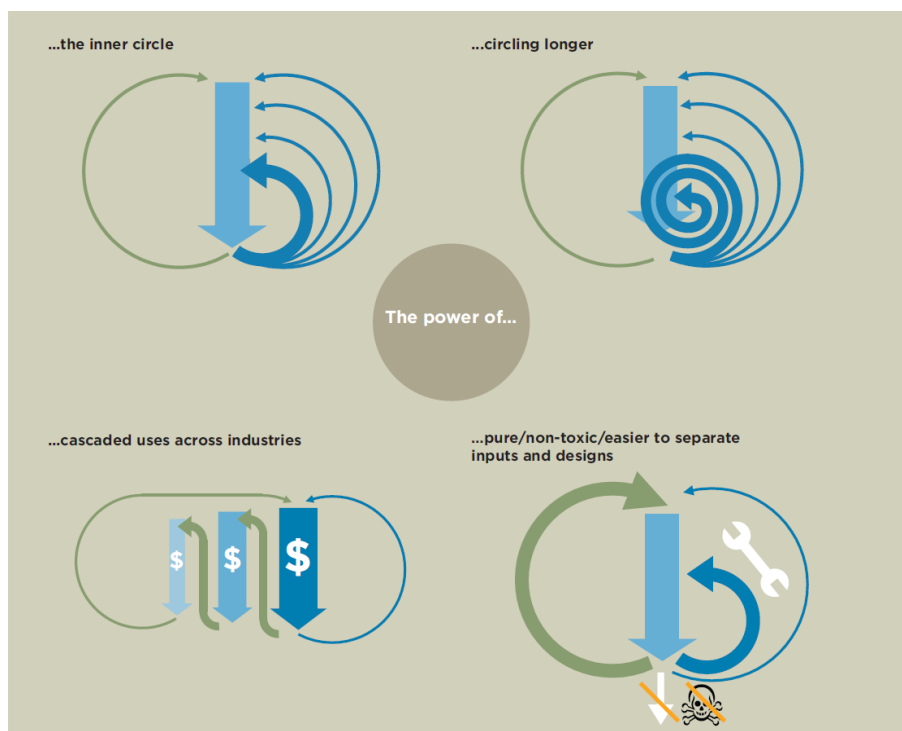

Figure 12: Sources of value creation for the circular economy, (EMF, 2014)

3.1.5 How to measure

In 2015, EMF in cooperation with Granta Design and LIFE introduced the report "Circularity Indicators" . In this report a methodology is developed based on indicators that assess how well a product or company performs in the context of a circular Economy. The developed indexes consist of a main indicator, the Material Circularity Indicator (MCI), measuring how restorative the material flows of a product or company are, and complementary indicators that allow additional impacts and risks to be taken into account (EMF et al., 2015). MCI can be used as decision-making tool for designers, but might also be used for several other purposes including internal reporting, procurement decisions and the evaluation or rating of companies (EMF et al., 2015).

MCI methodology focuses exclusively on technical cycles and materials from non-renewable sources and on the product level it can be used in the design of new products to take Circularity into account as a criterion and input for design decisions. The indicators allow for comparing different versions ('what if' scenarios) of a product regarding its circularity at the design level. They could also be used to set minimum circularity criteria for designers. This can apply to new products as well as the further development of products with the aim to make them more circular. Aspects of product design that can influence the circularity scores range from material choices to new business models for the product (EMF et al., 2015). In addition, MCI focuses on the restoration of material flows at product and company levels and is based on the following four principles:

i) using feedstock from reused or recycled sources,
ii) reusing components or recycling materials after the use of the product,
iii) keeping products in use longer (e.g., by reuse/redistribution),
iv) making more intensive use of products (e.g. via service or performance models) (EMF et al., 2015). Based on MCI it should be possible to measures the extent to which linear flow has been minimized and restorative flow maximized for its component materials, and how long and intensively it is used compared to a similar industry-average product.

" The MCI is essentially constructed from a combination of three product characteristics: the mass V of virgin raw material used in manufacture, the mass W of unrecoverable waste that is attributed to the product, and a utility factor X that accounts for the length and intensity of the product's use" (EMF et al., 2015) . Figure 13 indicates the associated material flows. As

stated by EMF and others (2015) " any product that is manufactured using only virgin feedstock and ends up in landfill at the end of its use phase can be considered a fully 'linear' product. On the other hand, any product that contains no virgin feedstock, is completely collected for recycling or component reuse, and where the recycling efficiency is 100% can be considered a fully 'circular' product. In practice, most products will sit somewhere between these two extremes and the MCI measures the level of circularity in the range 0 to 1" (EMF, et al. 2015).
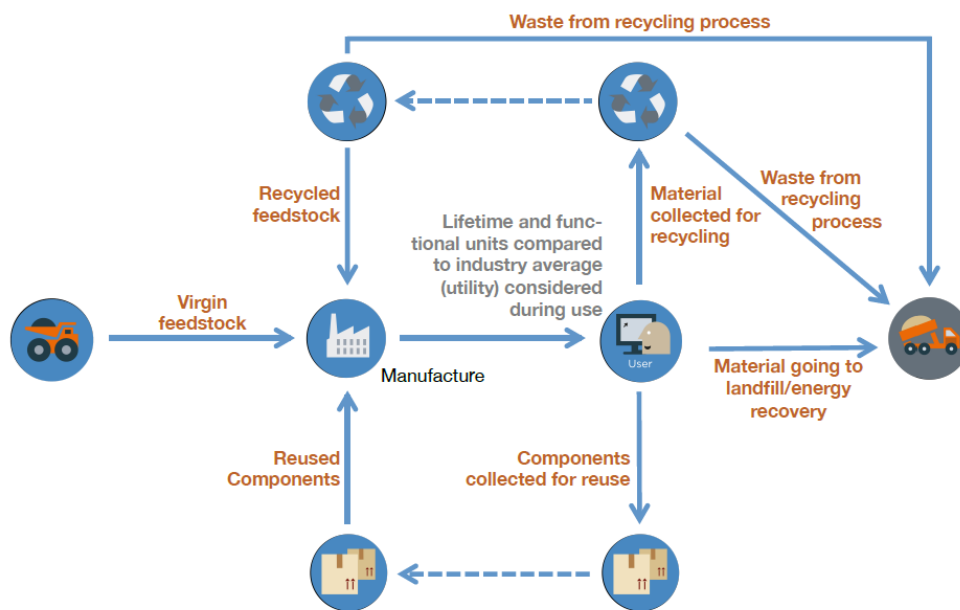

Figure 13 : Diagrammatic representation of material flows (EMF et al., 2015)

3.2 Circular Economy in civil infrastructure sector

This paragraph highlights the potential impact of the circular economy in the construction sector including design barriers and strategies. Paragraph 3.1 introduces the significant role of the construction sector in the transition into the circular economy. The literature discussed in this paragraph show that the construction sector is a priority sector for this transition. Paragraph 3.2 indicates the potential impact of circular economy in the construction sector. According to the literature review covered in this section, by effective and efficient use of construction materials different value such as reduction of life cycle costs van be created. Paragraph 3.3 describes the circular economy design strategy and design principles for the engineering of civil infrastructure systems. According to the literature discussed in this paragraph, the main barriers in order to transit the construction sector into the circular economy and to achieve the maximal value form resources is the lack of resource efficient design principles and involvements of stakeholders in the design process. As a solution, the use of resource efficient design criteria during the design stage and the use of an integrated design process, in which all stakeholders can be involved, is advised. Finally, paragraph 3.3.4 summarizes the literature discussed in paragraph 3.2 as whole.

3.2.1 Introduction

The construction sector is an important economic engine with one of the largest users of raw materials and energy. For example, Dutch construction and demolition sector represents an important share, 4.8% in 2013, of the added value within the Dutch economy with building production of 72 thousand million euros (ABN-AMRO et al., 2014). Dutch constructions sector is more than 90% dependent or raw materials such as iron, aluminium, copper, sand, clay, limestone and wood,together accounting for an about 260 million tons in 2010 ABN AMro et al, 2014). From this, 23 million tons of these materials ended up as waste, which is responsible for 37% of the total waste stream in the Netherlands (ABN AMRO et al., 2014).

While Netherlands is one of the European countries with the highest reuse and recycling rate of construction and demolition waste with more than 95%, the recycling of it is suboptimal (ABN AMRO et al., 2014).The recycling processing of this fraction is very energy intensive, and the most of this waste is 'downcycled'. In other words, the current recycling is not a

valuable form of recycling. As pointed out by ABN AMRO and Circle Economy (2014), "more than 75% of construction waste is stony rubble, of which only 2% will be re-used as a replacement for gravel in new concrete. The vast majority of the gravel ends up in roads. Nevertheless, as much as 15% of all the Dutch waste that will be dumped or burned originates in the sector. Nearly 20% of this share is 'hazardous' ".

In addition, the construction sector is highly dependence on fossil fuels and energy and it produce large amount of CO_2 emission. The necessary energy and CO_2 emissions per kilogram of most of these new and raw materials are relatively high, since the extraction and processing of these materials are so complex. For example, Dutch construction sector,between materials extraction and the End of Life phase (EoL), is responsible for 4.5% of the total energy use in the Netherlands, excludes energy use during the use phase (USI, 2014). The climate impact of the sector is 9.6 million tons CO_2, it is about 5% of the national greenhouse gas emissions. From this amount 70% are released in the harvesting and production phase for construction materials (ABN AMRO et al., 2014). This amount is exclusive CO_2 emission during transportation of heavy building material which contributes significantly in Dutch CO_2 emissions (ABN AMRO et al., 2014). The current construction method has also other negative impacts such as noise, dust, waste (healthy) and contamination (toxins and chemicals) (ABN AMRO et al., 2014).

3.2.2 Potential impact of circular economy on the civil infrastructure systems

Construction sector, buildings and infra, is a priority sector for the circular economy (EU, 2014), because of the large amounts resource use that are generated and the high potential for re-use and recycling embodied in these materials. Due to this, European commission has set high ambitions to stimulate the transition to a circular construction sector (EU, 2014). In Europe, only 20% to 30% of all construction and demolition waste is ultimately recycled or reused efficiently, often because construction objects are designed and built in a way that is not conducive to breaking down parts into recyclable, let alone reusable components (EPA, 2009) [Figure 9]. To stimulate reuse and recycling in the construction sector, Waste Framework Directive (WFD)[5] requires member states to take any necessary measures to achieve "a minimum target" of 70% (by weight) of C&D waste by 2020 for preparation for re-use, recycling and other material recovery, including backfilling operations using non-hazardous C&D waste to substitute other materials.

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[5]Directive 2006/12/EC revised by Directive 2008/98/EC
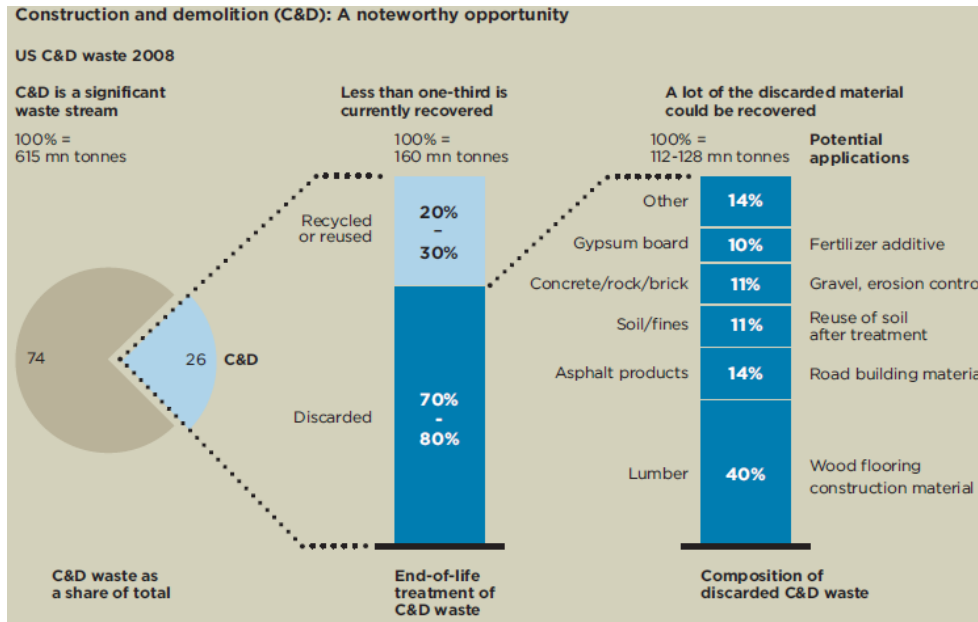
Figure 14: Construction and Demolition waste (C&D), (EPA, 2009)

The current C&D waste quantities are ranged between a total of 310 and 700 million tonnes per year in the EU-27 (0.63 to 1.42 tonnes per capita per year). Due to a lack in the available C&D waste data, it is difficult to estimate the total waste quantities generated in Europe (EU, 2014).

Generally, civil infrastructure systems are owned by the governments. In other words, civil infrastructure systems are the natural capital or physical assets of governments that requirea major investment regarding raw materials and energy. To meet the huge need of materials and energy, governments have been increasingly importing natural resources from other countries, and exporting the negative consequences of their overconsumption abroad. By applying the principles of circular economy, different types of value (expressed as economic, environmental and social benefits) can be created. In the case of design and engineering process of civil infrastructure systems, applying circular economy principles provide more value or a higher service quality for the clients.

This value can be expressed, for example by:

- *Reducing CO₂ emission.*
- *Reducing life cycle costs,*
- *Reducing energy use of system during its life cycle*
- *Reducing waste as output.*
- *A more robust system.*

Several studies indicate the economic, environmental and social benefits by efficient reusing of recycling of construction materials. Below two initiatives as an example has been displayed.

Ferrara LOWaste GPP Initiative, Italy

LOWaste (Local Waste Market for Second Life products) program was launched in September 2011, in the municipality of Ferrara (estimated population of 135,000), in Italy. The programwas focused on the applying of lifecycle thinking, eco-design and local recycling markets including construction market. This initiative has provided important results over the past three years in terms of saved carbon dioxide emissions based on reused materials. In this 11,200 tons of recycled construction and demolition waste materials used for the construction of roads and cycling lanes, resulting in up to 593 tons of avoided CO_2 emissions from reuse of materials.

Waste & Resources Action Program (WRAP), United Kingdom

WRAP is established in 2000 as a not-for-profit company to identify the benefits and opportunities to reducing waste, developingsustainable products and using resources in an efficient way. WRAP is funding fromDefra (Department for Environment, Food and Rural Affairs), Scottish Government, the WelshGovernment, the Northern Ireland Executive, and the European Union. In 2008, WRAP developed and launched a voluntary agreement ''the Halving Waste to Landfill (HWTL)'' to support the joint Government and Industry Strategy for Sustainable Construction. The goal was a 50% reduction in construction, demolition and excavation waste to landfill by 2012, compared to 2008 and before. After implementation of initiative, following results is quantified:

Environmental impacts: to 2011, reusing and recycling of 5 million tons per year of waste diverted from landfill has result to 1 million tonsCO_2reduction per year.

Economic benefits: this initiative provided a cost saving of £400 million per year to organizations involved in this project. Also, £38 billion of procurement value (including public procurement projects) was influenced through HWTL by influencing procurement projects in progress. The key projects include: the London 2012 Olympics, the Shard building (UK's tallest building) and Crossrail (thought to be Europe's biggest infrastructure project).

Social benefits: employees from participating companies improved their skills in planning design, designing out waste and waste management during delivery of the agreement, through the attendance at workshops, training sessions and using online tools.

3.2.3 Barriers and strategies

International Council for Research and Innovation in Building and Construction (CIB) introduced in 2014 an overview-report that maps the most global technical barriers and strategies for re-use and recycling of construction materials in both building and infrastructure sector (Nakajima et al., 2014). This report represents an overview of the most frequent barriers in countries such as: Canada, Germany, Netherland, Singapore, US, Japan and Norway. The main barriers in the construction sector are lacks in resource efficient design principles during the design stage (namely design methodology) and lacks in the cooperation of all stakeholders to the design process (Nakajima et al., 2014).

Design lack and strategies

The most important factor that limits the reuse and recycling construction materials is a lack in current design methodology (Nakajima et al., 2014). Current construction structures are designed to construction and not deconstruction. Construction components are not designed to be reused and reconfigured, and the applied materials are often composed of composites, which are not designed to be recycled (Nakajima et al., 2014). For examples metals such as copper, aluminium and steel are usually contaminated with concrete. Furthermore, the complex recovery process is more expensive than raw materials and new materials. As stated by EMF (2012), circular economy is restorative by intention and design. Design is at the heart of a circular economy. According to EMF (2012) "in a circular economy, products are designed for ease of reuse, disassembly and refurbishment, or recycling, with the understanding that it is the reuse of vast amounts of material reclaimed from end-of-life products, rather than the extraction of resources, that is the foundation of economic growth".

Since construction objects have a long life cycle, designers need to consider systems as a whole rather than focus on individual components or products (RSA, 2012). As indicated by WRAP (2012), "designers and engineers have a key role in optimizing materials used in construction as their decisions directly influence what gets constructed and how. The best opportunities for improving resource efficiency in construction projects occur during the design stage". Construction designers have to create design solutions that minimise waste and

use resources efficiently. Also, they have to identify for clients and contractors the best opportunities to reduce waste anduse more recovered material (WRAP, 2012). This can be done by the use of resource efficient design criteria. Resource efficient design criteria are the main technical strategies to enable reuse and recycling in construction sector. 'Design for deconstruction' and 'design for reusability/recyclability' are some examples of resource efficient design criteria.

WRAP has carried out several researches, applied to different case studies, to identify opportunities to optimize resource efficiency in the construction projects. As result, WRAP launched in 2012 a design guide for builders and civil engineering design teams. This report indicates applying resource efficient design criteria as the key factor to enable reuse and recycle in the construction sector (WRAP, 2012). In addition, ABN AMRO and Circle Economy emphasizes the importance of using design principles such as designing for dismantling, reuse and adaptability as one of the most important opportunities (factors) to enable reuse and recycle in the construction sector (ABN AMRO et al., 2014). Table 1 indicates the recommended design principles according to WRAP (2012), CIB (2014) and ABN AMRO (2014).

Lack and strategies in cooperation of stakeholders

According to CIB (Nakajima et al., 2014), integrated design process allows all members of the construction team to be in on the decision making processes from the very beginning of a project that leads to greater understanding of project goals and resource efficiency. As result this process would help improve recycling and reuse because of its inclusive approach and the awareness of the important issues throughout the decision process. Also WRAP (2012) recommends an integrated design process in order to ensure that perspectives of the stakeholders are included before that final design is determined. As stets by WRAP (2012), it is important that resource efficient design principles are considered from an early stage in the project cycle, and that designers follow this through the ground investigation, detailed design specification and procurement stages, in conjunction with other members of the project team, to ensure that design solutions identified at an early stage are embedded into the project and fully implemented.

Table 1: recommended design principles according to WRAP (2012), Nakajima (2014) and ABN AMRO (2014).

Resource efficient Design principles for the civil infrastructure systems

Design for deconstruction or design for assembly

This principle enables significant changes to be made to the civil engineering project during the course of its life.

Design for Reuse and Recycle

Choosing materials that can be reused and or recycled at the end of life cycle

Design for Adaptability or Flexibility

Enables significant changes to be made to the system during the course of its life.

Design for Durability

Design for durability means matching materials to the planned life of the project/structure with fewer life cycle replacements and reduced maintenance cycles. This can be achieved by using materials with a long technical life cycle and less maintenance.

According to WRAP (2012), the most opportunities to apply resource efficient principles occur during the design stage and in particular preliminary and detailed design. WRAP (2012) recommends the use of three-step process for applying resource efficient principles during the design stage. Below, once again the three steps [figure 15]:

Figure 15: Implementing of resource efficient design criteria (WRAP, 2012)

Step 1- Identify

As stated by WRAP " the purpose of Step 1 is to identify as many potential opportunities as possible to improve materials resource efficiency in theproject through the design, and then to Rationalise the list by prioritising thosewhich will provide the biggest benefits and be easiest (and most cost efficient) toimplement. This approach ensures that no opportunities are missed, and thenthat time and effort is not spent pursuing insignificant ones" (WRAP, 2012). By this stage thedesign will be sufficiently advanced for initial material selection and method ofconstruction to be discussed but still at a stage where options can be considered.At this stage, the potential for change still exceeds the cost and resistance to change (WRAP, 2012).

Step 2- Investigate

In Step 2 each of relevant ideas is investigated fully to ascertain its viability and potential benefits of opportunities to maximise value and minimise costs and risks (WRAP, 2012). A key aspect in this step is the quantification of the benefits and impact of each design opportunity. As stated by WRAP (2012) "it is important to quantify the benefits and impact of each design opportunity so that decisions about which solutions to pursue further are made objectively based on evidence". For this goal, it must be made use of metrics which help decision making easier, include cost savings and resource efficiency in the key metrics measured. In this research, use is made of AHP methodology in order to investigate the opportunities.

Step 3- Implement

''Once client approval to proceed with therecommended design opportunities hasbeen obtained, they should be fully workedup into design solutions and frozen into thedesign. Design decisions, quantification and details of the solutions should alsobe recorded in a document. Recording the quantified benefits alsoenables the designer to demonstrate thatthey have delivered cost and other savings tothe client/contractor, which can help themto win repeat business with future projects ''(WRAP, 2012).

Guidance Systems Engineering (*version 1*, 2007) indicates the same principle in order to come to the best design alternatives/solution, in this case a resource efficient design. Below the design and engineering process based on SE principle is indicated [figure 16]. More information about this process can be found at paragraph 2.2.2 of this report or at the report

"Guidline Systems Engineering for Public Works and Water Managemen, version 1"
introduced by Rijkswaterstaat, ProRail, ONRI, Bouwend Nederland (2007).
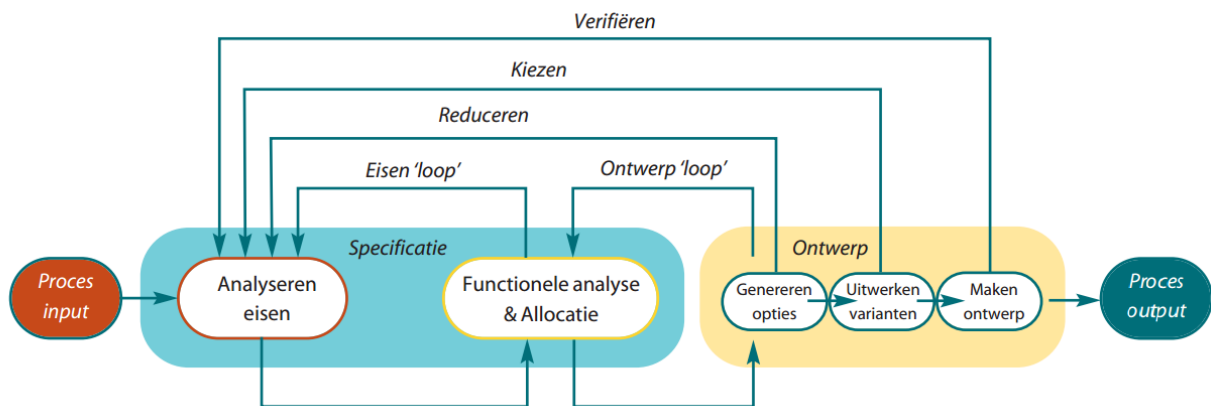
Figure 16: Design and engineering process of civil infrastructure systems, (Guideline SE, version 1, 2007)

An important aspect that both WRAP and SE (and also many other literature) emphasize, is use of 'Value Engineer or value management'. The term value refers to "the value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected ", (NASA, 2007). Value engineering is a process of searching for opportunities with the goal to reducing risk and cost and maximizing the performance (value) of the system. This is a continuing process that can be tracked (for example by value manager) in each life cycle stage of systems. As stated by WRAP (2012), " value Engineering is a style of management particularly dedicated to motivate people, develop skills and promote synergies and innovation with the aim of maximising the overallperformance of an organisation and or a project. It involvesproduction of a value management plan andopportunities register at the start of theproject, which are updated at each stage". According to Guidance Systems Engineering, version 3 (2013), " Value Engineering (VE) is a systematic, multidisciplinary approach that - with the aid of function analysisand creative techniques - the value of the system optimizes the entire lifecycle. The concept of valuereferring to the amount of functionality (with performance) compared to the life cycle cost. This value hasconcern what the customer considers important, such asdurability, money or limiting nuisance. VE wants this value for the customer to make as large as possible".

3.3 Conclusion

This chapter provides an answer to the research questions 1, 2 and 3. The answers have been concluded from the studied literature during the research which is described in chapter 2 and chapter 3 (paragraphs 3.1 and 3.2). Below the answers for the questions are as follow:

Question 1: *To what extent does the current engineering process of civil infrastructure systems, based on systems engineering and performance based contracting, differs from the principles of the circular economy?* Circular economy introduces a service and system-oriented development of products including 'a design'. In the circular economy, services should be purchased instead of products and systems should be developed instead of objects. In general, the engineering process based on performance based contracting is in line with the idea of purchasing services. Performance based contracts provide the opportunity for the infrastructure clients to express their needs as services that has to be designed. In addition, systems engineering as a management tool stimulates the engineering community towards a circular economic system. Systems engineering integrates more disciplines and specialty groups into a team effort to think in whole and to (re)act as whole in order to develop systems.

Question 2*: What is the potential impact of circular economy on the civil infrastructure systems?* Civil infrastructure systems are an important economic engine being one of the largest users of raw materials and energy. Moreover, civil infrastructure systems are highly dependent on fossil fuels and energy, and they produce large amount of CO_2 emission. By optimal use of resources the value that is created by the system should increase.

Question 3: *Which design criteria can be used in order to design infrastructure systems according to circular economy principles?* The most important goal of circular economy, which is namely missed in the current engineering process, is the optimal use of natural resources including energy and materials by using renewable energy and the 'design waste out' principle. The goal of this principle is to make optimal use of materials by creating a closed loop for the material flow in each system. According to this principle, waste does not exist when systems are designed in such a way that materials are reused or recycled effectively at the end of their life cycle. To design waste out, use should be made of resource efficient design criteria such as design for adaptability, design for deconstruction, design for

durability and design for reuse or recycle. Design for durability refers to the life time extension of the infrastructure systems by means of choosing for design alternatives and materials which have higher technical life time and require less maintenance. Design for adaptability express designing systems in such a way that they can be expanded or changed in the future. Design for deconstruction means designing systems in such a way that the integrated components and materials can be easily disassembled for reuse or recycle at the end of its service life. Design for reuse or recycle point out to choosing for materials and components which can be easily reused/recycled to a great extent at the end of its service life.

Question 4: *Which strategy can be used in order to integrate resource efficient design criteria into the engineering process?* Using the design waste out principle and involving the stakeholders through the value chain to the design process are the strategic approaches in order to design resource efficient civil infrastructure systems. The expertise and specialization of different experts through the value chain is needed in order to design a resource efficient civil infrastructure systems.

4.   Methodological Approach

This chapter describes and applies the methodological approach in order to involve more disciplines effectively, into the preliminary stage of the design process. This can done by using a multi criteria decision support system such as Analytical Hierarchy Process (AHP). In this paragraph AHP is applied to a case study. This chapter consists of 6 paragraphs. Paragraph 4.1 introduces the AHP method as a multi criteria decision support system. Paragraph 4.2 describes the working of AHP method in steps. Paragraph 4.3 represents the case study in which the AHP method is applied. Paragraph 4.4 discusses the results and the sub-conclusion that is drawn by some results. Paragraph 4.5 maps the identified relation between criteria based on results.

4.1 Introduction

As concluded so far, using the design waste out principle and involving the stakeholders through the value chain to the design process are the strategic approaches in order to design resource efficient civil infrastructure systems. By designing resource efficient systems, the value that is created by the system increases. However, resource efficient design criteria are not the only criteria that a system has to meet and or provide value. In addition to the resource efficient design criteria, the systems have to function properly according to RAMS criteria (see more about RAMS at paragraph 2.2.1). Reliability, availability, safety and maintainability are also criteria that offer value in term of functionality or costs for the systems. By integrating these criteria together, created value by the system increases. However, it is difficult to design a system which has to meet multiple criteria. For example, the client's satisfaction and the life cycle costs are two conflicting criteria when choosing a design alternative. In order to take into account multiple criteria during the design process, use can b made of multi criteria decision support system such as Analytical Hierarchy Process (AHP). In this research use is made of AHP:

-   to determine the relative important of the multiple criteria that a design has to meet,
-   to determine effectively the best design alternatives with respect to the criteria,
-   and to make efficient and effective use of expertises and experiences of other disciplines during the preliminary design process.

4.2 Analytical Hierarchy Process

AHP is a multi-criteria decision Analysis (MCDA) and a structured technique developed by Thomas Saaty in 1970 for organizing and analysing complex decisions, based

on mathematics and psychology (Saaty et al. , 2008). AHP is in particular used for group decision making (Saaty et al. , 2008) in a wide variety of decision situations around the world in fields such as government, business, construction industry and education (Saracoglu, 2013). Decision situations to which the AHP can be applied include (Forman et al. 2001):

- Choice – selection of one alternative from a set of alternatives.
- Prioritisation/evaluation – determining the relative merit of a set of alternatives.
- Resource allocation – finding best combination of alternatives subject to a variety of constraints.
- Benchmarking – of processes or systems with other, known processes or systems.
- Quality management.

The main factor that makes the AHP method strong compared to many other methods is reducing bias in decision-making. AHP helps capture both subjective and objective evaluation measures, providing a useful mechanism for checking the consistency of the evaluation measures and alternatives suggested by the team (NASA, 2007). According to NASA (2007) "AHP as a proven, effective means to deal with complex decision-making for the engineering of all kind of systems to assist with identifying and weighting selection criteria, analysing the data collected for the criteria, and expediting the decision making process" (NASA, 2007).

A stated by Saaty (2008) AHP generates priorities that are needed to decompose the decision into the following steps.

1. Define the problem and determine the kind of knowledge sought;
2. Structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives);
3. Construct a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it;
4. Use the priorities obtained from the comparisons to weigh the priorities in the level immediately below. Do this for every element. Then for each element in the level

below add its weighed values and obtain its overall or global priority. Continue this process of weighing and adding until the final priorities of the alternatives in the bottom most level are obtained.

4.3 Case study

For the case study, a lock gate is chosen since in this case, multiple experts and disciplines can be involved into the design process (e.g. as compared with a tunnel or path). In addition, lock gate is a hydraulic component in which functional performance criteria play an important role in this. In general, lock gates can be made from 4 types of materials. These include: steel, composite, concrete and wood. Based on AHP questionnaire, 20 experts were asked to prioritize these four alternatives with respect to the 9 criteria. Table 4 represent the distribution of project criteria and their definition. In addition they were asked to determine relative importance of the criteria regard the project goal. The project goal was indicated as follow: "Choosing the best gate for a lock with a functional lifecycle of minimal 100 years. The gate should consist of high resource efficiency; high reliability and safety; less maintenance during use phase; and low life cycle cost". Figure 17 shows the hierarchy structure between the objectives, criteria and alternatives. The pairwise comparison scale of Saaty is used to express the relative importance of criteria or alternatives according to experts opinion [Table 2].

Table 2: Fundamental Scale of Saaty (2008)

Scale	Intensity of Relevance	Description
1	Same relevance	Both tasks contribute equally to the purpose.
3	A little more relevant	Experience and judging favor one task in relation to another.
5	Considerably more relevant	Experience and judging strongly favor one task in relation to another.
7	A lot more relevant	A task is a lot more strongly favored in relation to another.
9	Extremely relevant	An evidence favors a task in relation to another with the highest level of reliability.

Participant Characteristics

The survey was conducted among 20 experts from different disciplines. The most experts were from the company Iv-infra. The appropriate experts for each discipline have been chosen by the involved division head. The most experts had a minimal work experience of 5 years governing their working area. These include; RAMS managers, hydraulic engineers, constructors, maintenance engineers, cost expert, project leaders and the involved department heads. Table 3 represent the involved participants in the survey.

Table 3: Involved participants in the AHP survey, created by author

Division	Number
RAMS and Contract Management	4
Hydraulic Engineers	3
Constructors	4
Maintenance Engineers	5
Project leaders	4
Total	**20**

Questionnaire design

The study was conducted by delivering the questionnaire survey in person to the participants, explain the study, and then collect the questionnaires at a set date after completion. The survey consisted of two parts. Part (I) provides necessary information to fill the questionnaire correctly. In this part examples are used to provide a clear instruction for the participants about how the questionnaires must be completed. Part (II) is the questionnaire itself. Both parts can be found in appendix II of this report.

Table 4: distribution of criteria and their definition, created by author

Criteria	Description
C1- Resource Efficiency	
C 1.1 Availability	The ability to make significant changes during the course of the life cycle of a system (for example by expansion).
C 1.2 Deconstruction	The ability to dismantle/dissemble components or materials at the end of life cycle or when it is needed on any reason (for example by replacing).
C 1.3 Technical life time	The period that a material, component or machine lasts until it is worn out, (until no longer meets the required quality).
C 1.4 Reuse/Recycle	The ability to reuse, remanufacture or recycle a material or component at the end of its life cycle.
C2- R(A^6)MS	
C2.1 Reliability	The probability that the required function is carried out under given conditions for a given time period.
C2.2 Maintainability	Maintainability refers to the possibility to maintain a system component. In this research maintenance means, the process of keeping something in good condition.
C2.3 Safety	The capacity of a system not to create damages to people or things.
C3- Life Cycle Costs	
C3.1 Design and Construction Costs	Costs necessary for design and realization of the system such as labor cost, material cost, transport cost and construction costs.
C3.2 Operation and Maintenance Cost	Cost necessary in order to keeping systems in good condition (such as: costs for corrective, preventive and predictive maintenance) and cost to keep the system functioning according to the agreed requirements during its whole life cycle (such as: cost of failures, cost of repairs, cost for spares and downtime costs).

As shown in Figure 12, the first level of hierarchy is the ultimate goal of the project; the second and third levels represent the main and sub-criteria that have to be evaluated. And finally, the fourth level presents the alternatives.

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[6] In this research the criterion 'availability' is not included in the criteria, because it is not logical to say which alternative is most available. The degree of availability of an alternative can be determined on degree of other criteria such as maintainability and reliability.
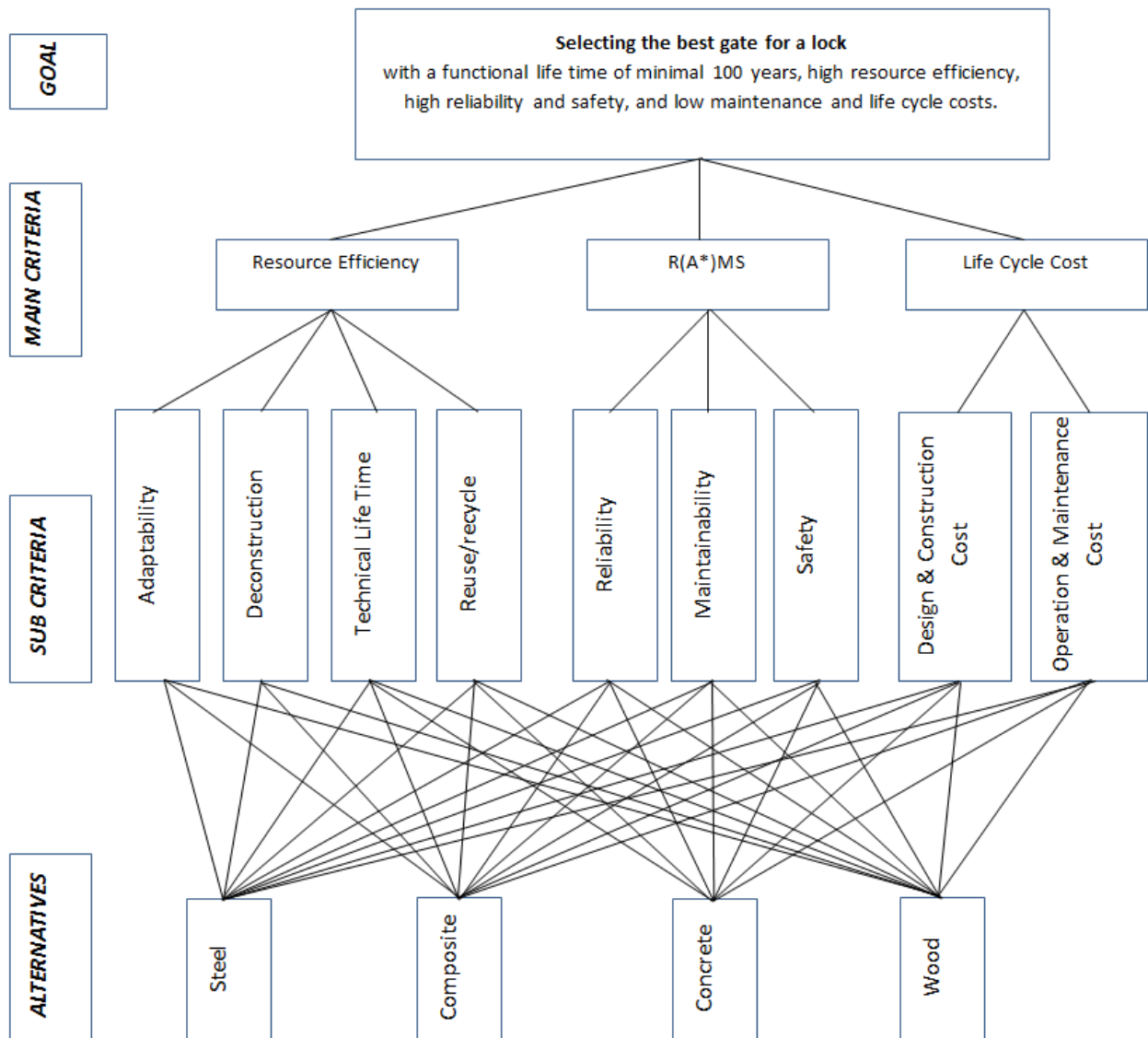
* In this research the criterion `availability` is not included in the criteria, because it is not logical to say which alternative is most available. The degree of availability of an alternative can be determined on the basis of other criteria such as maintainability and reliability.

Figure 17: Hierarchy structure for choosing best gate (created by author)

4.4 Results

For the respondent a consistency ratio of 0.15 (15%) was maintained. All 20 participants completed the questionnaire. In each section of the questionnaire, there were small numbers of inconsistent answers. The inconsistent answers have not been included in the results. Below the results and the conclusion that is drawn by results is indicated.

Relative importance of sub and main criteria

As indicated before, in this research Analytics Hierarchy Process (AHP) is used to determine the relative important of the criteria that is used for the case study. In this case, the importance of criteria is primarily determined by the experts of Iv-Ifra. The criteria are divided in to the three main criteria categories: RAMS, resource efficiency and life cycle costs [Figure 18].
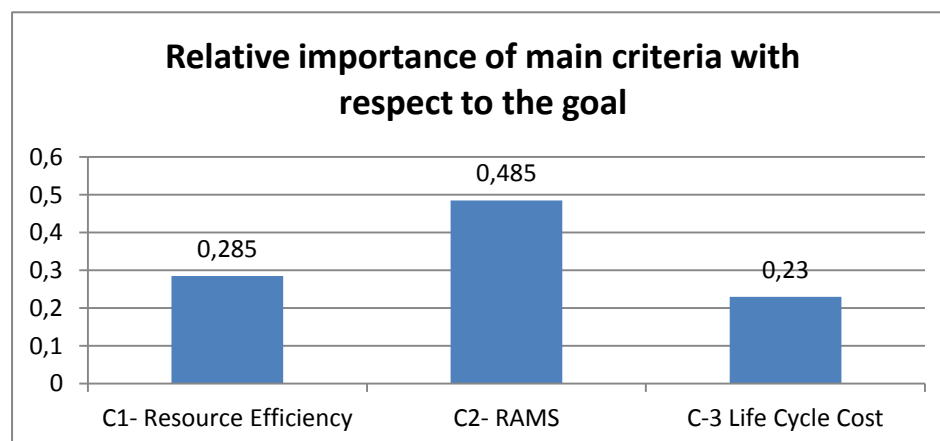
Figure 18: Relative importance of main criteria with respect to the goal

According to experts, the 'RAM' criteria is the most important main criterion by choosing a gate for a lock with a functional life time of 100 years. RAMS criteria refer to the functional performance of the system, therefore it is indicated as most importance main criteria. Within RAMS, the sub criteria safety and reliability have scored the highest [Figure 19]. The second important criteria is resource efficiency. The sub criteria technical life time and adaptability are the most important sub criteria [Figure 19]. Finally, the life cycle cost criteria is the third most important main criterion with respect to the goal. The 'operation and maintenance cost' sub criterion is the most important sub criterion relating life cycle cost criterion. Figure 20 maps the relative importance of all sub criteria with respect to the goal.
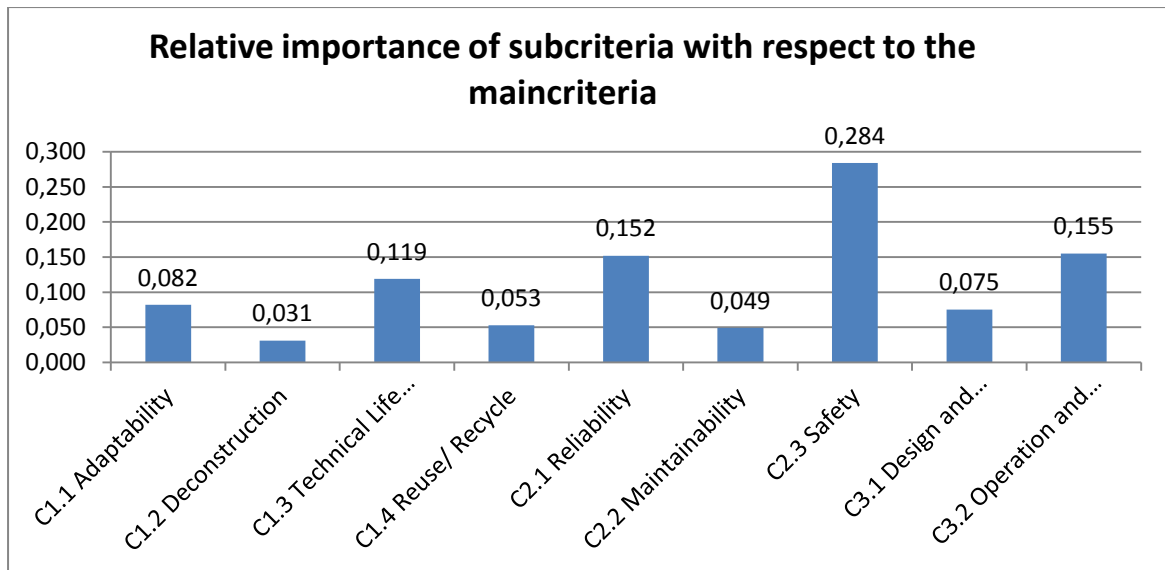
Figure 19: Relative importance of the sub criteria with respect to the goal
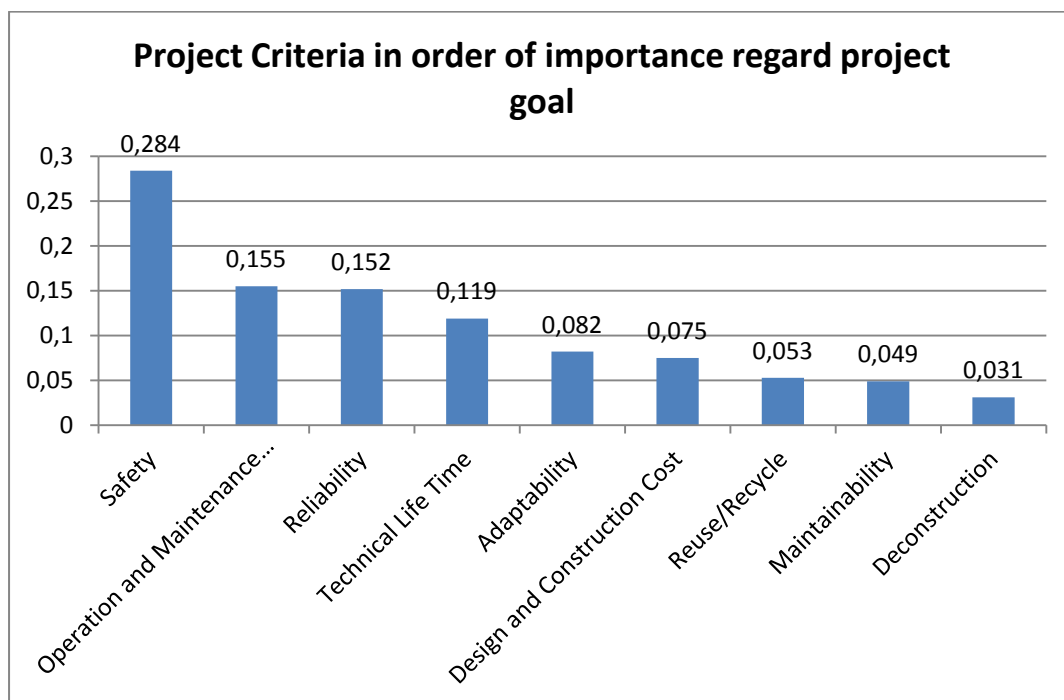
Figure 20: Relative importance of the criteria in order of importance with respect to the goal

Relative weight of alternatives regards to criteria

To determine which gate meet best the criteria, AHP survey is used. Also in this part, the AHP questionnaire is namely completed by the experts from the engineering company Iv-Infra. The relative weight of each alternatives concerning criteria is indicated below.

Relative weight of alternatives with respect to the 'Adaptability' criterion

Number of consistent answers: 19 of 20.

Figure 21: Relative weight of the alternatives with respect to the adaptability criterion

Figure 21 indicates the relative weight of alternatives with respect to the adaptability criterion. In case of a lock gate, for example the possibility to adapt a gate because of a higher water level and or increasing shipping traffic. Steel gate scores the highest in the adaptability criterion. According to experts, steel offers the possibility to weld or to saw components when necessary. This also applies to wood because it offers opportunities such as nailing or sawing. In case of concrete such possibilities are limited. The possibilities of composites regarding adaptability are not really known by (some) experts due to a lack in knowledge and experience. Nevertheless, in general most experts believe that composite scores low for this criterion.

Conclusion: it can be concluded that material properties determine to a large part the degree of adaptability of a material. The material properties of steel make this material weldable or the properties of wood which makes nailing possible for example. Also, the possibilities such as sawing or cutting by both steel and wood make these materials adaptable. On the other hand, the properties of concrete such as fragility make it less suitable for such operations. Concrete is very sensitive to these operations because the reinforcing structure of concrete can thereby be jeopardized. However, the new types of concrete such as fiber concrete or reinforcing free concrete would make concrete more adaptable.

Relative weight of alternatives with respect to the 'Deconstruction' criterion
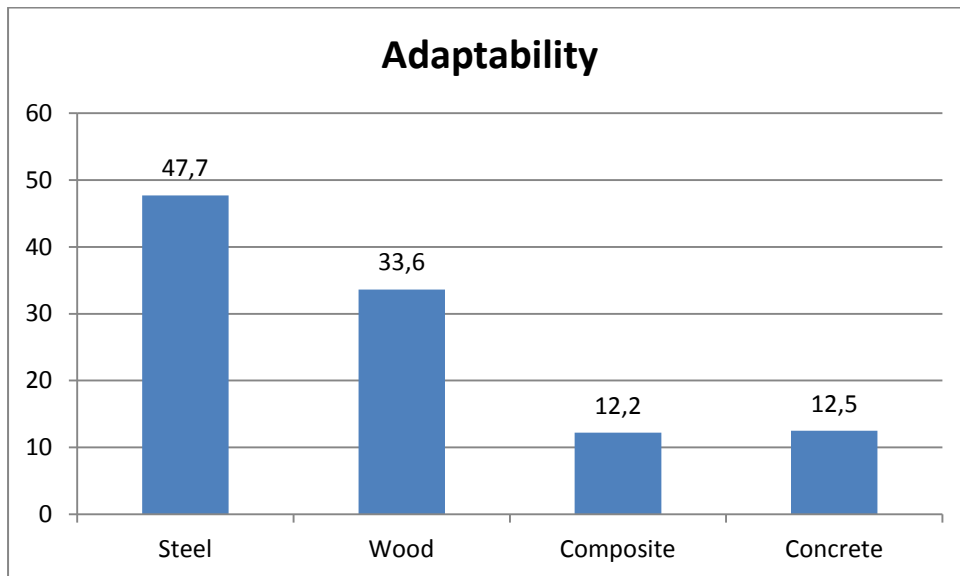
Number of consistent answers: 18 of 20.

Figure 22: Relative weight of the alternatives with respect to the deconstruction criterion

Figure 22 indicates the relative weight of alternatives with respect to the deconstruction criterion. In case of deconstruction, the ease which components and or the integrated materials in a component can be dissembled is primarily taken into account. According to experts, wood provides much design freedom and therefore it scores the highest, relatively with a large difference, compared to other options. After wood, steel followed by composite are the best options. Steel may also provide these capabilities but in a lesser extent as compared to wood. However experts are not sure about the possibilities of composite hence they 'expect' that this material scores better than concrete.

Conclusion: from above results can be concluded that ease of disassembly is namely depending on the design freedom that a material provides to the designers. Also, it can be concluded that the design freedom is determined by versatility of a material in terms of dimensions, sizes and ease of (dis)connectivity. For example, wood is available in different sizes which are standardized to a great extent. Due to this, a wooden gate can consists of several small components that together function as a whole. Also, the components and materials can easily be '(dis)connected to the wood. This is mainly due to the material property of wood which make screwing, nailing, anchoring and gluing easier. Contrary, materials such as concrete which do not have this property (or have it less) are produced as a whole large component. This makes concrete awkward. This may also be the reason that

materials incorporated into concrete such as the metal reinforcements cannot easily be dissembled.

Relative weight of alternatives with respect to the 'Technical Life Tim' criterion
Number of consistent answers: 17 of 20.

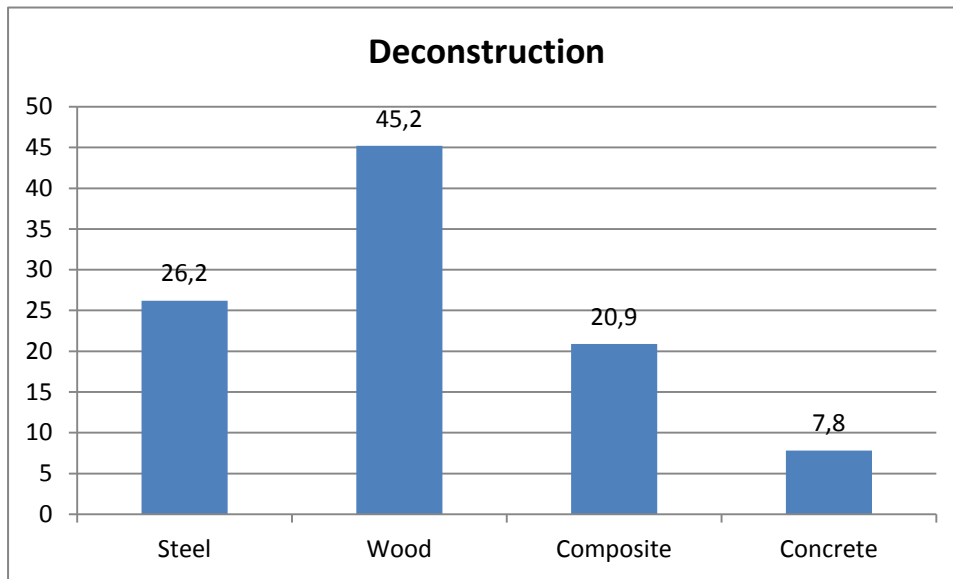**Longer technical life time**
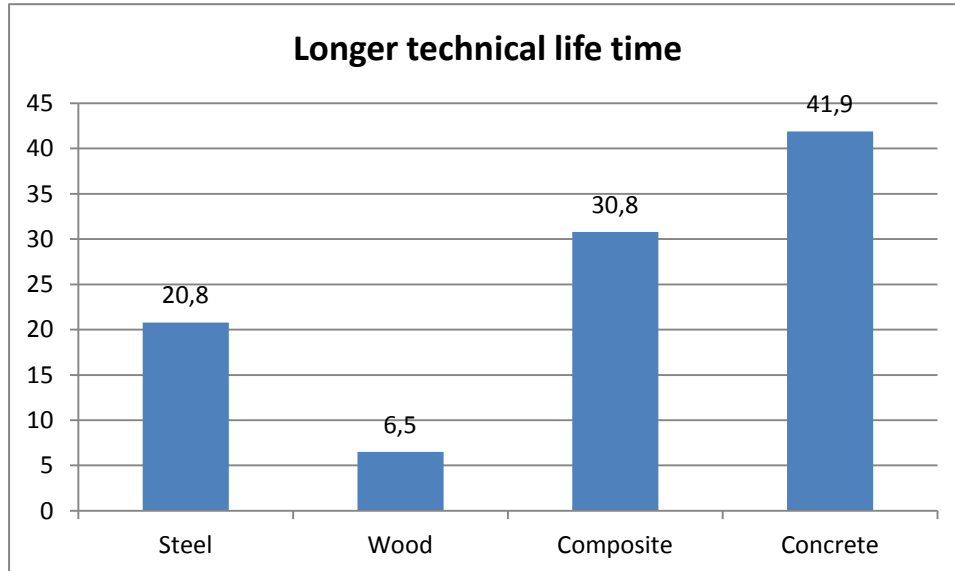
Figure 23: Relative weight of the alternatives with respect to the technical life time criterion

Figure 23 indicates the relative weight of alternatives concerning the technical life time criterion. Concrete following by composite score the highest with respect to this criterion. According to experts, both of these materials can have a longer technical life time of 100 years, provided they are properly constructed and maintained. In addition, it is 'expecte' that composite may still have a longer life time than concrete.

Conclusion: by investigating why materials such as concrete and composite have a longer life span in comparison to wood or steel we end up on material properties which ensure that a material keeps or loses its quality during years. For example, steel and wood are sensitive to sunlight, temperature, moisture and climate. As result, the microstructure of these materials is constantly changing. Therefore the quality and strength decrease during years. In contrast, the particles in the concrete such as cement and sand are less sensitive for these factors. Probably less chemical reaction occur in the concrete and composite which results in less changing and moving structure and consequently longer technical life time.

Relative weight of alternatives with respect to the 'Recyclability/Reusability' criterion
Number of consistent answers: 18 of 20.
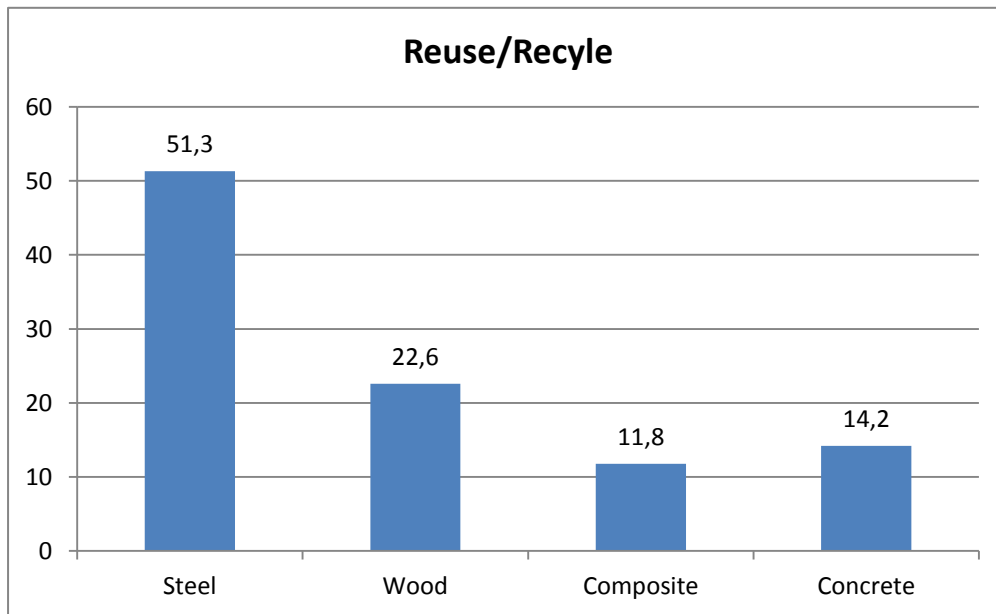
Reuse/Recyle

Figure 24: Relative weight of the alternatives with respect to the reuse/recycle criterion

Figure 24 indicates the relative weight of alternatives concerning the deconstruction criterion. Basically, all four materials can be recycled or reused. According to experts, steel gates can be upcycled (recycled and reused for the same goal) since steel is dissolvable. Steel is also multi-usable. Therefore, steel scores higher than other materials regarding recyclability or reusability. For wood and concrete opportunities for upcycling are limited. Both can be cascaded and used for other purposes. However, wood scores higherthen concrete because it is easier to recycle and reuse wood than concrete. In addition wood is multi-usable while concrete can be recycled and re-used as concrete granulate in for example foundations. Furthermore, wood provides design freedom in comparison to concrete. little information is known by experts with respect to reuse/recycling of composite.

Conclusion: it can be concluded that recyclability /reusability has to do with the material properties and the potential of a material for reuse or recycle. The manner in which a material is integrated in a design is an additional factor. For example steel has the potential to be recycled and reused for the same purposes repetitively. But this may be limited when steel is integrated in concrete.

Number of consistent answers: 19 of 20.
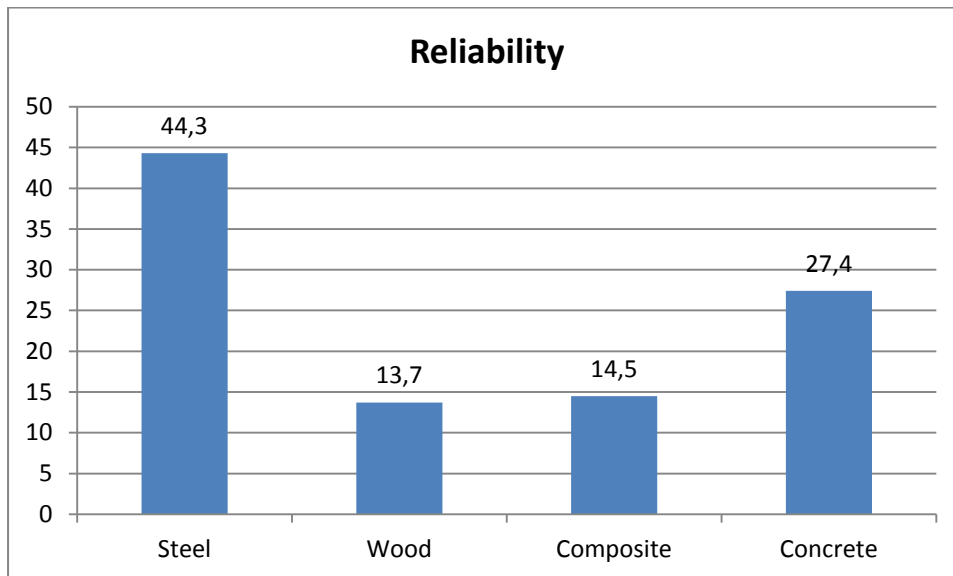
Reliability

Figure 25: Relative weight of the alternatives with respect to the criterion reliability

Figure 25 indicates the relative weight of alternatives regarding the reliability criterion. Reliability means the probability that the required function is carried out under given conditions for a given time interval.The main functions of a lock gate are primarily: blocking or turning water, maintaining the water level and locking ships. In order to increase the probability of functioning of a gate functioning as intended the factors that may hinder its operation must be mapped and reduced. In other words, reducing risk and reducing the probability of failure. In general, the operation of a port can be hindered by internal and external factors. Internal factors relate primarily to material properties such as fatigue and degradation. External factors relate to the external events such as human failures, vandalism and or collision. According to experts, steel scores high on reliability because it does not break under external events such as collision. Furthermore, steel is often used as a lock gate and therefore its bottlenecks are well known. The probability of failure by steel can be reduced because of this. However, steel is very sensitive to some internal factors such as degradation. Therefore, steel scores very low on the criterion maintainability. With respect to wood, the most experts indicate that natural materials such as wood have a low reliability in comparison to man-made materials. For example in wood, two exactly the same wood types may have different quality depends on their origin. In case of concrete, there are little experiences with concrete as a lock gate. Concrete is a well-known material however in other construction applications. As expected, concrete scores high on internal factors and less on

external factors. As indicated before, the information and experience of expert with composite is limited. This is may be why composite scores low with respect to reliability.

Conclusion: after analysing results and discussing with experts one may conclude that the degree of reliability depends on reliable information about a particular material or component and the sensitivity of the materials (properties) on external and internal factors. It can be concluded that the more experience and reliable data available about a given material, the greater the certainty and thus the higher the reliability in terms of information. Steel scores the highest with respect to this factor. In this case, a low score for composite and concrete does not mean that these materials are poor with respect to reliability, but it may be because of limited experience and knowledge which has been built up so far. The presence of techniques which make it possible to observe the degradation and failures is a form of information which influences the degree of reliability of materials as well. These techniques make it possible to make explicit calculations, rather than implicit. On the basis of these techniques, the degradation of materials can be detected earlier. As a result, the reliability increases.

With respect to the external and internal factors, it can be concluded that the material properties determine the sensitivity of the material on internal and external factors. Steel scores high on external factors such as collision for example because of its plasticity and toughness while concrete scores less because concrete may break down in such a situation. This does not always have to be the case however. Concrete scores high on the other hand in internal factors such as fatigue and degradation because material properties of concrete are less sensitive for these factors. In general it may be concluded that materials with a longer technical life time such as concrete and composite should have a higher reliability regarding internal factors in comparison to the materials with a shorter life time such as steel and wood.

Relative weight of alternatives with respect to the "maintainability" criterion

*Number of consistent answers: 20 of 20.*

Less maintenance

Figure 26: Relative weight of the alternatives with respect to the maintenance criterion.

Figure 26 indicates the relative weight of alternatives concerning the criterion maintainability When it comes to the maintenance, composite following by concrete scores the highest. While most experts believe that there are many possibilities to reduce maintenance in wood and steel gates, still both materials should be maintained regularly in order to retain their quality. In contrast, experts believe that composite and concrete requires no to low maintenance during their whole technical life time.

Conclusion: with respect to the maintenance, the same conclusion can be drawn as technical life time. Mainly material properties determine the level of maintenance in a given material. For example, steel and wood are sensitive to sunlight, temperature, moisture and climate and such factors. As result, the microstructure of these materials is constantly changing. Therefore the quality and strength may decrease during year. In contrast, the particles in composite and concrete are less sensitive for these factors and therefore the microstructure of these materials is relatively constant. This is a possible reason why concrete and composite requires less maintenance. In addition the maintainability can be affected by the material knowledge of designers, executers, producer or supplier. For example, a lack of knowledge of designers about the expansion coefficients of materials cans results to fail or earlier degradation of material during operation stage. Other example, if concrete is not mixed properly by executer or producer, the risk of cracking during operation stage increases. This can also be occurring by using wrong sand type in concrete. So, it can be concluded that a

close collaboration between hydraulic engineers, maintenance experts, (sub) contractors, suppliers is crucial to reduce the probability on degradations and both planned and unplanned maintenance.

Relative weight of alternatives with respect to the 'Safety' criterion
Number of consistent answers: 20 of 20.
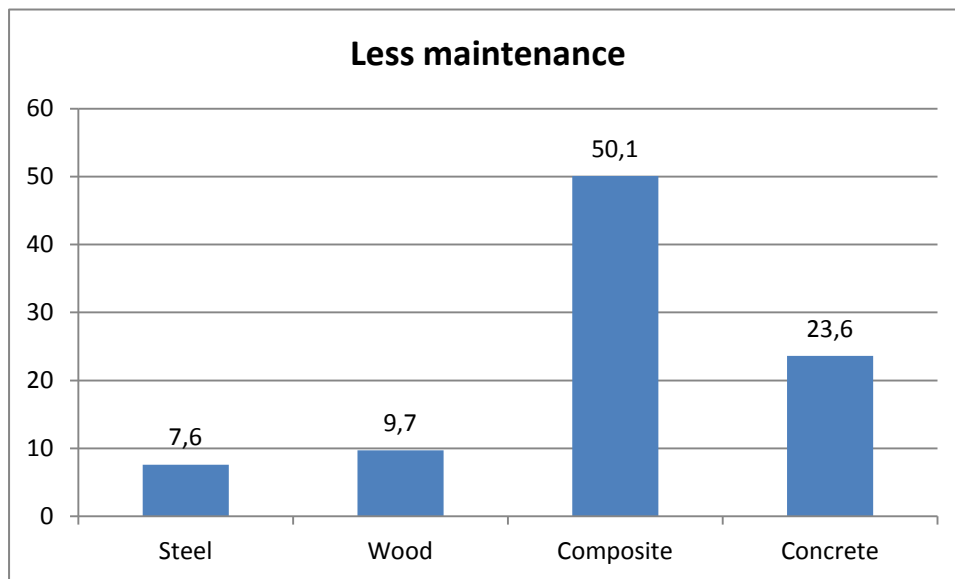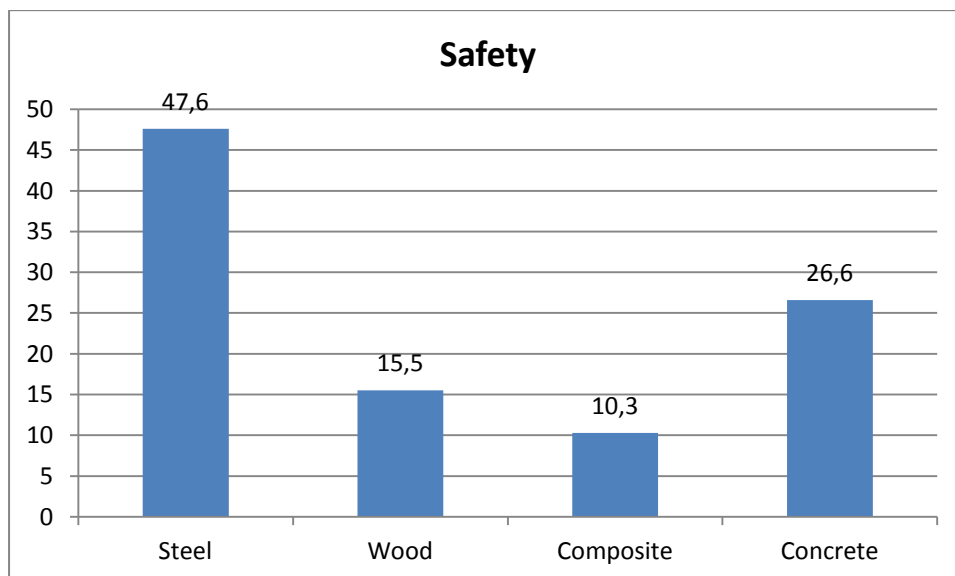

Figure 27: Relative weight of the alternatives with respect to the safety criterion

Figure 27 indicates the relative weight of alternatives with respect to the safety criterion. In this case safety expresses the resistance of a gate by the influencing factors such as fire or collision of ships and or huge water pressure. The priorities of expert concerning the safety criterion are approximately the same as the reliability criterion. Some experts have given exactly the same score to the alternatives with respect to safety as reliability. According to expert steel scores highest for safety because it is more resistance to a collision. However steel is less resistance to fire, the probability on damage from collision is higher than fire. Concrete scores high regarding fire but not in case of collision because it can break. Wood can both burn and break. Since composite is a new material it scored lowest for the criterion safety.

Cconclusion: by analysing the results and discussions with experts it appears that in some cases, there is a close relationship between safety and reliability. This relationship mainly applies to the function of the material or components. This is especially true when the materials or components have a structural function, e.g. in the case where due to choice of material a gate can break easily in a collision. In this case, reliability has an impact on safety.

Relative weight of alternatives with respect to the 'Design and Construction Cost' criterion
Number of consistent answers: 20 of 20.

Less design and construction cost

Steel: 17,8
Wood: 40,9
Composite: 16,1
Concrete: 25,2
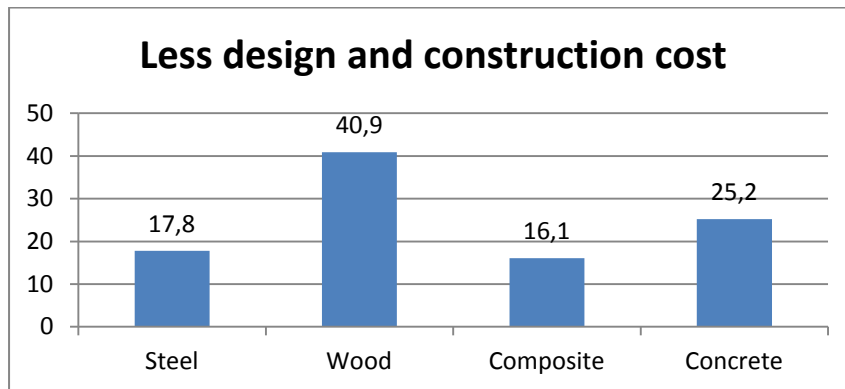
Figure 28: Relative weight of the alternatives with respect to the design and construction cost criterion

Figure 28 indicates the relative weight of alternatives with respect to the criterion design and construction cost. The construction cost is the focus of this criterion. Most experts found it difficult to make an (reliable) estimation of the construction cost of a material since. The range of opinions about design and construction costs with respect to the alternatives (expect for wood) are not much different from each other in comparison with other criteria.

Relative weight of alternatives with respect to the 'Maintenance and Operation Cost' criterion. Number of consistent answers: 20 of 20.

Less operation and maintenace cost

Steel: 11
Wood: 11,9
Composite: 43,7
Concrete: 33,4
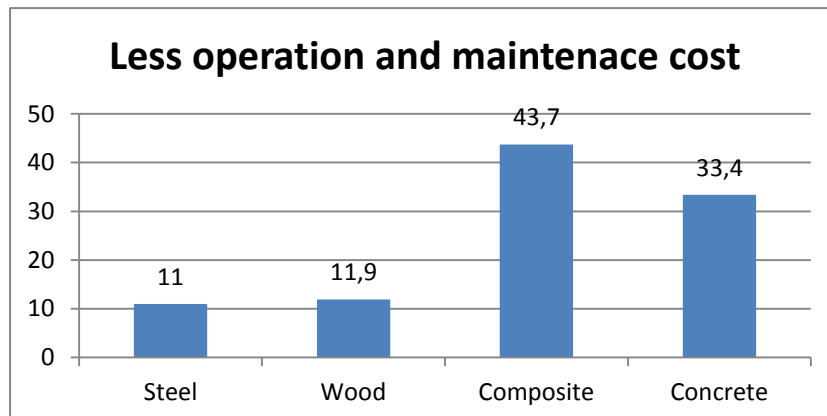
Figure 29: Relative weight of the alternatives with respect to the operation and maintenance cost criterion

Figure 29 indicates the relative weight of alternatives concerning the operation and maintenance cost criterion. In contrast to the design and construction costs, experts had a stronger priority for operation and maintenance costs. Composite followed by concrete have scored the highest with respect to the "less operation and maintenance cost" criterion. This is mostly because most experts agreed that concrete and composite gates do not have to be

replaced during the whole life cycle of a system. In addition, according to experts both alternatives require less maintenance compared to steel and wooden gates.

Beset alternatives with respect to the goal

As seen in figure 30, steel is the best design alternatives with respect to the project criteria and project goal, bearing in mind that the possibilities of composite were not really known to the experts. The results may also have been different if more stakeholders through the value chain (such as: contractors, subcontractors, suppliers and or manufacturer) were involved in this process.
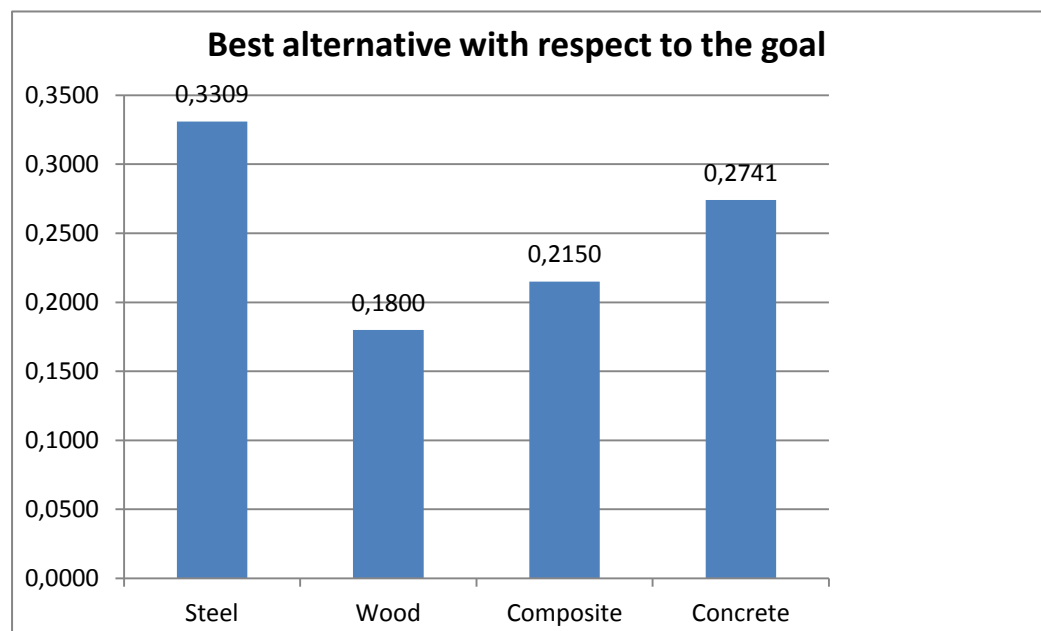
Figure 30: Best alternatives with respect to the goal.

4.5 Identified relations between criteria based on results

It is remarkably that steel and wood scored high for the 'adaptability', 'deconstruction' and 'reuse/recycle' and they score low for 'technical life time', 'maintainability' and 'operation and maintenance cost'. The opposite occurs in composite and concrete. Composite and concrete score high for the criteria 'technical life time', 'maintenance' and 'operation and maintenance cost' and low for the criteria 'adaptability', 'deconstruction' and 'reuse/recycle'. Generally, it can be concluded that materials with a long technical lifetime and less maintenance, such as concrete and composite, are less adaptable, demountable and reusable. Also a relationship between the criteria safety and reliability is noticeable. According to experts however, there is not always a relationship between these two criteria,

but it depends on the function of materials or components. In this case study a gate has structural function. Breaking gate takes the safety of people at risk, therefore it should be reliable. Generally speaking one can conclude that materials such as concrete or composite that score well against internal factors can provide the most value for a lock gate. It is strange that we use steel and wood as lock gates while we know that these materials require maintenance and are sensitive to internal factors such as water (moisture), sunlight and temperature. That these internal factors will occur is a fact (when not maintained), but external factors do not necessarily occur. Of course the consequence of external factors could be high, as compared to the internal factors, but these could be prevented by a smart and integral design.

5. Conclusion, recommendation and discussion

5.1 Conclusion

Circular economy introduces a new way of developing and designing products and systems. In the circular economy, services should be purchased instead of products and systems should be developed instead of objects. In general, developing infrastructure projects, based on performance based contracting is in line with the idea of purchasing services. Performance based contracts provide the opportunity for the infrastructure clients to express their needs as services that has to be designed. In addition, systems engineering, as a management tool, moves the engineering community towards a circular economic system. Systems engineering integrates more disciplines and specialty groups into a team effort to think in whole and to (re)act as whole in order to develop and design systems. The most important goal of circular economy, which is namely missed in the current engineering process, is the optimal use of natural resources including energy and materials.

One of the main challenges for civil infrastructure designers is extending the lifespan of infrastructure systems. This can be achieved by use of materials with a long service life, and or by increasing the life cycle of materials. Another challenge is designing systems so that after reaching end of life, the materials and components end up in material flows with high-quality. In other words, waste does not exist when systems are designed in such a way that materials are reused or recycled effectively at the end of their life cycle. To design waste out, use should be made of resource efficient design criteria such as design for adaptability, design for deconstruction, design for durability and design for reuse or recycle.

Since the civil infrastructure systems are large users of natural resources, by optimal use of materials the service quality and the total created value by the system increase. This requires knowledge and information about materials, material properties and the factors that positively or negatively affect the service life of materials. In fact, the needed information is distributed among the different construction stakeholders through the value chain including contractors, subcontractors, suppliers, material experts, maintenance specialists, demolition contractors and other specialist works. To design waste out optimally, design should be done

collaborative with stakeholders through the value chain. The stakeholders should be involved in preliminary stage of design process. Together, there should be sought to the design solutions that create most value . Transparency, innovation and creativity are essential keys in order to achieve the best design alternatives.

5.2 Recommendation and further research

Based on conclusion, following are recommended to the engineering company Iv-Infra.

Involve stakeholders through the value chain
Involve different stakeholders through the value chain including contractors, subcontractors, suppliers, material experts, maintenance specialists, demolition contractors and other specialist works. Make evident that the cooperation cannot always lead to a job.

Apply resource efficient design principles
Apply resource efficient design principles and or 'cradle to cradle' principle such as design for adaptability, design for deconstruction, design for durability and design for reuse or recycle. Develop knowledge about these principles in the construction sector by cooperating with universities and in particular industrial designers.

Use own expertise optimally
Make optimal use of own expertise within the company. Involve them actively in the preliminary design process and search together for solutions. Encourage staffs to following the innovation and developments in their field of expertise. Help them to do this by organizing workshops, following congress and or courses.

Create a new department for managing information
Create a new department for managing data and information, in particular information about materials. This department should ensures the collection, structuring and analysing information for designers and engineers in an efficient and effective manner.

Measure de circularity of design alternatives
Create a decision support model in order to measure the resource efficiency or material circularity of design alternatives.

Recommended ideal workflow

In addition to above recommends, an ideal workflow is recommended [Figure 31]. Use the workflow in order to achieve the best design solution with respect to the functional performance, resource efficiency and life cycle costs. This ideal workflow has been developed based on the literature study, research methodology and the conclusion that has been drawn in this research. The ideal workflow is a complement to the workflow introduced in the report "Guideline systems engineering within the civil engineering sector ", version 1 (Rijkswaterstaat, et al., 2007). Below the workflow in steps:

1- Analyse system requirements

Analyse the de desired need and requirements of the client. Ascertain to which problem a a solution might find. Determine the system boundaries such as conditions, regulations and restrictions. Translate the system requirements and system function in measurable system requirements and system functions. If necessary, translate functions and requirements into more detailed level, derived from the design choices that have been established. The requirements should be structures in upper and lower requirements either main requirements and sub/derived requirements.

2- Analyse and allocate system functions

Transform the functions of the system that has to be designed into subsystems (also known as "function enablers") on the basis of the contracting authority and/or stakeholders' needs. Prepare a specification that documents the requirements that system and subsystems expected to meet. Follow below steps to analyze and allocate systems functions:

- Specify in detail all of the system's functions,
- derive the subsystems (function enablers) from these functions,
- create structure and coherence among these subsystems,
- link the resource efficient requirement and other requirements from the requirements analysis to these subsystems.

3- Translate requirements into the performance criteria

Translate the system requirement into the performance criteria. These requirements refer to the functional requirement and resource efficiency as determined for each object in the functional analysis. The criteria can be further refined and structured into the sub criteria including: reliability, maintainability, safety, adaptability, deconstruction, durability and

reuse or recycle.

4- Determine the relative importance of criteria with respect to the goal

Ensure that the system contains the most essential functions and needs of clients by ascertaining the relative importance of criteria with respect to the goal. Determining the relative importance of criteria can be tricky since some criteria are difficult to weight against each other. Use a multi criteria analysis method such as Analytical Hierarchy Process(AHP) to determine the relative importance in an efficient and effective way. This method helps to make the necessary trade-off decisions by making the importance of the criteria explicit. Discuss the results of analysis with the client to ensure whether the order of criteria corresponding to the needs of the client.

5- Identify as much as possible alternatives

Involve as much as possible partners or stakeholders through the value chain to the design process. Accomplish brainstorming sessions to identify all possible solution directions for the system. Explain exactly for which problem (or function) a solution is sought. Encourage the stakeholders to search for the most innovative and creative solutions of their expertise. Perform the initial survey of options without any consideration of value to stimulate 'out of box thinking', in order to produce a comprehensive list that does not 'overlook' any potentially acceptable solutions. Reduce the generated options subsequently to a limited number of feasible solutions by way of an elimination process based on one or more requirements and preconditions. Put only those options that are inherently capable of meeting all of the requirements. Document the entire process.

6- Investigate which alternative best meets to the performance criteria and provides most value.

Investigate together with multiple experts, partners or project stakeholders which design alternative best meets all systems requirements and system performance or criteria including: reliability, safety, maintainability, deconstruction, adaptability, durability, reuse/recycle and life cycle costs. Comparing the design alternative against criteria by using a multi criteria decision support system, such as AHP, in order to make the necessary trade-off decisions in an efficient and effective way. For best results, the AHP should be completed jointly so that discussion can arise between different partners or experts on their products or systems. Parties must be able to indicate the possibilities of their materials, products with respect to the

criteria. By jointly completing AHP, parties receive comments from counterparties or other stakeholders. So they have to defend their product why their product scores high for a certain criterion. As result, the real best alternative can be achieved instead of the commercial best alternative .This process applies also to the international suppliers. They should also be present during such session to indicate the possibilities of their products with respect to the project criteria. After selecting the best variant(s) as the solution for the system, investigate whether the client proceed with the recommended design opportunities. If is not the case, make sure you understand the problem and if necessary, begin with one of the preceding steps. Otherwise, develop the best alternative in order to bring the option judged as being feasible to a level of detail that allows the variants to be mutually compared on the basis of the specified requirements and criteria.

7- Implement the best alternative

Implement the selected design alternative and develop the solution in further design. Use RAMS analysis, life cycle analysis and material circularity analysis in order to measure the quality of design or system. Together with partners and or project stakeholders search for possibilities to create more value with respect to availability, life cycle costs, material use and CO_2 emission by increasing the reliability, safety, deconstruction, adaptability, technical life time, reusability/recyclability and reducing the maintenance. As example, below it is indicated what should be south for the criteria.

*Reliability & safety :*Develop and use database that indicates the sensitivity of materials and components on external factors (such as influence of human fails or vandalism) and internal factors (influence of weather or materials on material properties). By knowing this, failures and degradation can reduced. This database could be a complement to the current material database for example NEN2767. The database can also be extended by applying much promise and unproven materials such as composite in small pilot projects. The input of stakeholders such as maintenance engineers and suppliers can help to gather a lot of data in a short time. Jointly with stakeholders, search to reduce material derogations and or to measure the degradation explicit based on measuring techniques and devices. In addition, be up to date with new safety regulation regards the system that should be designed.

Adaptability, deconstruction, reuse & recycle: Involve stakeholders and accomplish brainstorming sessions to identify opportunities to increase the up-cycling of materials by increasing the adaptability and deconstruction. Be innovative and creative. Search actively to

design strategies such as modular design in particularly for materials which are less adaptable such as concrete.

Technical life time and maintenance (Durability): Extend the technical life time of materials by investigating whether why material degrade. Find the cause of material degradation from the root. Prevention is better than treat. Search together with material experts, maintenance engineers and suppliers to the solution in order to prevent the degradation. Collect and put this information in to the material database. Life time extending and prevention can also be done by using measuring techniques and devises which make possible to observe the material degradation from an early stadium.
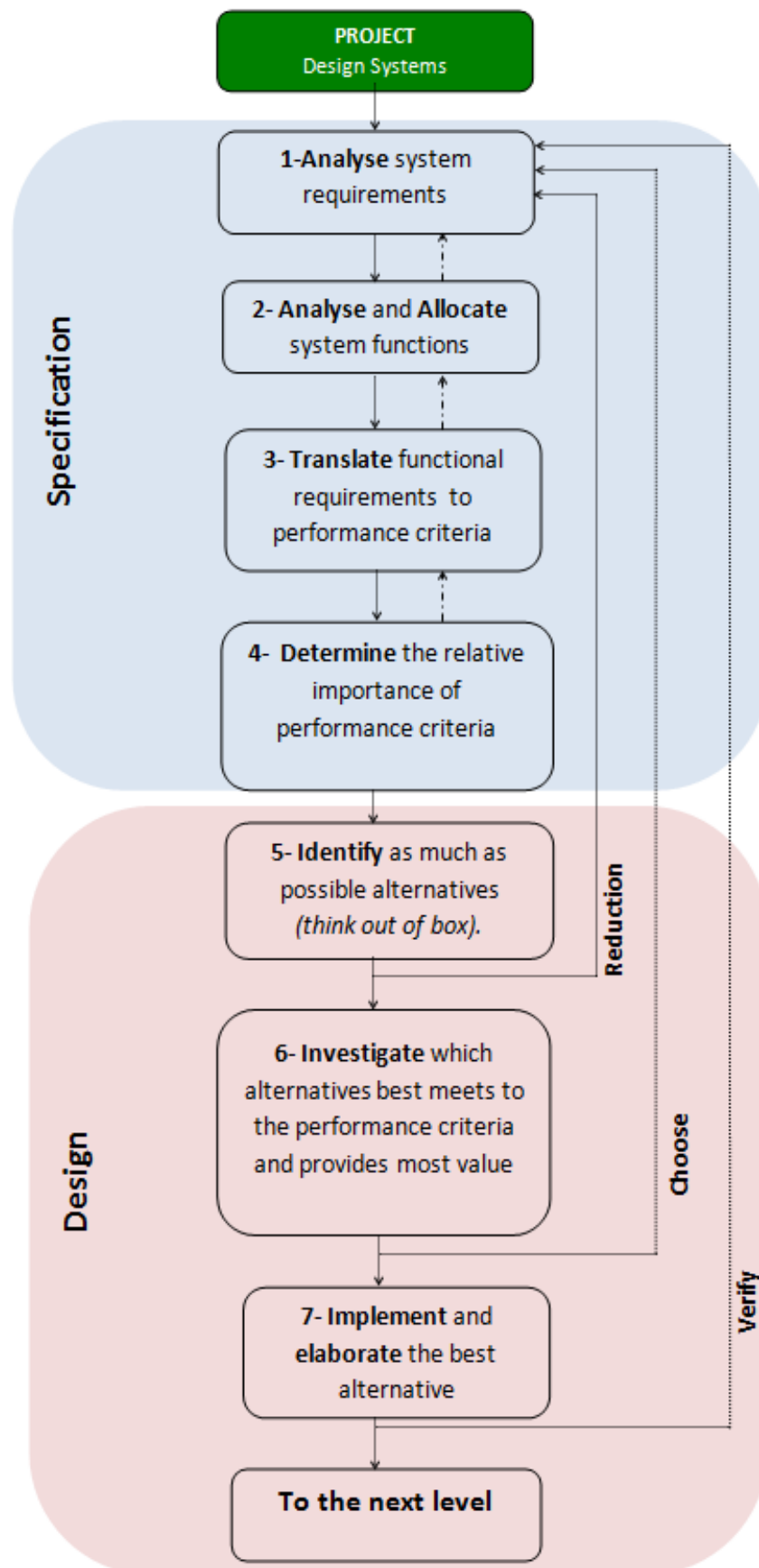
Figure 31: Ideal workflow, created by the author

To the next level

Depends on the system complexity, repeat the workflow for each design level one or more times, from the highest level down to the lowest level, until a production-ready design for the system to be constructed is reached (Rijkswaterstaat et al., 2007). However, it is not possible to say in advance how many design iterations are required to come up with a production-ready design (Rijkswaterstaat et al., 2007). This may vary by system component or materials. The decision to develop the design down to one more level of detail is based on an assessment of whether the design is feasible, maintainable and manageable in terms of time, money, quality and risk (Rijkswaterstaat et al., 2007). Figure 32 depicts the link between the iterative engineering processes based on the ideal workflow at various levels of detail. Figure 33 shows how the ideal workflow is further elaborated into the next level.
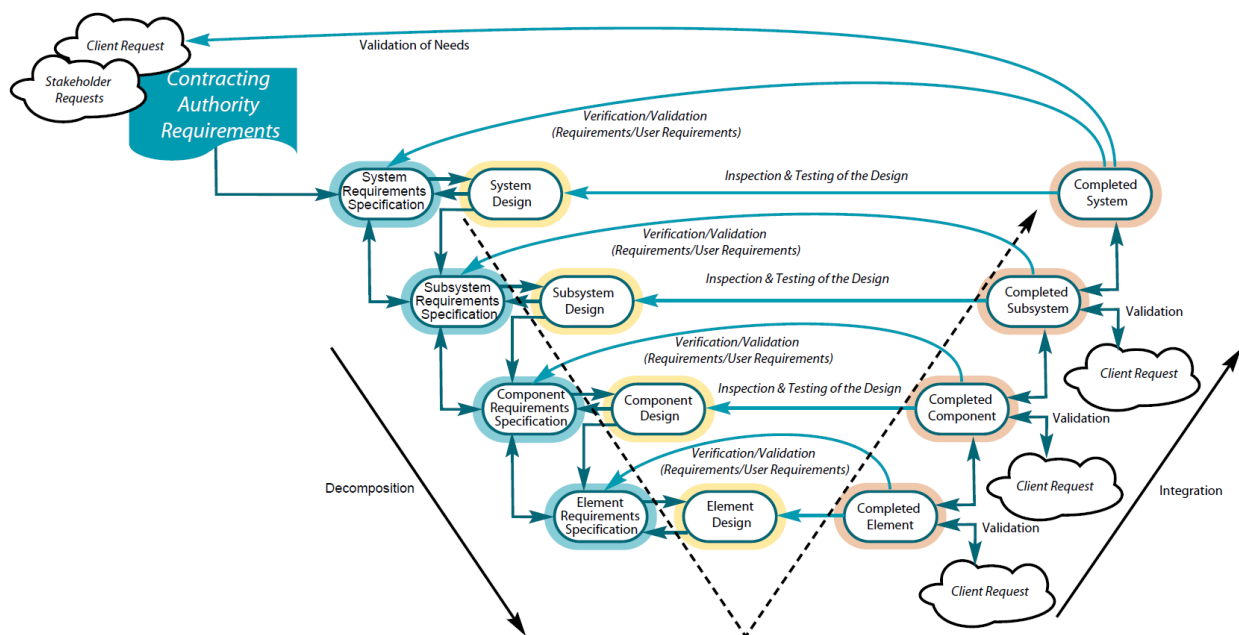
Figure 32: Integrated V-model of systems engineering process, (Rijkswaterstaat, et al., 2007).
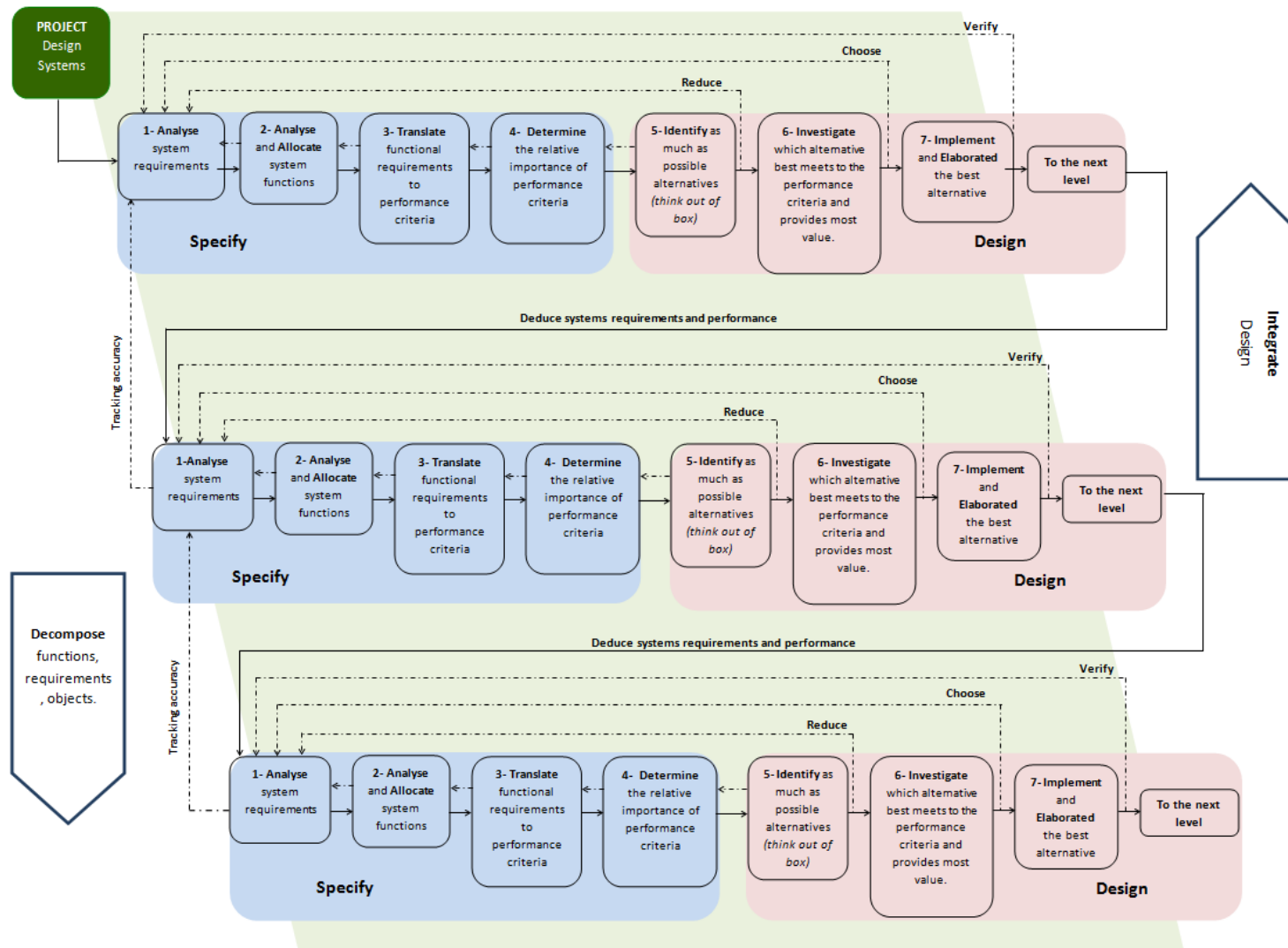
Figure 33: the iterative engineering processes based on the ideal workflow at various levels of design, modified by the author

5.3 Discussion

This research was conducted to obtain an understanding how the principles of circular economy can be integrated in the design process of civil infrastructure systems. Following the most important discussion point.

Theoretical framework

In this study there was no attention paid to measuring of resource efficiency based on Material Circularity Indicators (MCI). Further research is needed to create a decision support model in order to measure the material circularity of systems.

AHP method

This survey was conducted to involve more disciplines into the preliminary design process in an effective and efficient way by using AHP decision support system in order to achieve a best design solution that meet the project criteria. However, it is important to take into account of possible pitfalls by using AHP. Below, some key issues are indicated.

First, in this research the AHP method is used by experts within the company Iv-Infra. However, to achieve the most valuable design alternative the AHP survey should be completed by all stakeholders throughout the chain such as clients, contractor, sub-contractor, suppliers, manufacturer, civil-engineering works and control and operating systems.

Second, each criterion means something different for each specific system, subsystem or component. Therefore the project goal and performance that has to be achieved should be very clear to all stakeholders. Use can be made of a designated person/role within the company who is especially assigned to gives workshops and to inform and motivate stakeholders about the project goal and project performance to achieve this.

Third, it is important that the questionnaire is completed by experts. For this, there should be taking into account with the relative information of an expert and degree of reliability of the estimates of the expert. However, AHP offers the possibility to reduce the risk of the wrong

estimates of the expert by consistency check. Nevertheless the experts should be familiar with aspects such as system thinking and life cycle based design.

Fourth, there will always be criteria that are related to each other. In this case, it could be better to use Analytical Hierarchy process (ANP) rather than AHP. AHP structures a decision problem into a hierarchy with a goal, decision criteria, and alternatives, while the ANP structures it as a network. Both then use a system of pairwise comparisons to measure the weights of the components of the structure, and finally to rank the alternatives in the decision. In the AHP, each element in the hierarchy is considered to be independent of all the others—the decision criteria are considered to be independent of one another and the alternatives are considered to be independent of the decision criteria and of each other. In real cases, usually there is interdependence among the criteria and the alternatives. ANP does not require independence among elements, so it can be used as an effective tool in these cases.

Fifth, it is important to realize that AHP model, and all other decision support models, try to describe the reality in a simplified mathematical and statistical way and in no way is a representation of the reality.

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List of Acronyms

Acronym	Meaning
AHP:	Analytical Hierarchy Process
C&D:	Construction and Demolition
CE:	Circular Economy
CSF:	Critical Success Factors
EMF:	Ellen MacArthur Foundation
EPA:	Environmental Protection Agency
FFA:	Functional Analysis and Allocation
LCA:	Life Cycle Analysis, Life Cycle Assessment
LCC:	Life Cycle Costs
LE:	Linear Economy
MCI :	Material Circularity Indicators
NASA:	National Aeronautics and Space Administration
PBC:	Performance Based Contracts
3R:	Reduce, Reuse, Recycle
RAMS:	Reliability, Availability, Maintainability, Safety
RE:	Resource Efficiency
SE:	Systems Engineering
SEP:	The Systems Engineering Process
SERI:	The Sustainable Europe Research Institute
TEEB:	The Economics of Ecosystems and Biodiversity
UNEP:	the United Nations Environment Program
USI:	Utrecht Sustainability Institute
WLC:	Whole Life Cost
WMM:	World Market Monitor

Appendix

Appendix 1: Recycling rate of Construction and demolition waste in Europe

Source	UBA 2009			ETC/RWM 2009		
Country	Year	Arising (million tonnes)	% re-used or recycled	Year	Arising (million tonnes)	% re-used or recycled
Austria	2004	6,6	76%	2006	6,7	60%
Belgium		12,3	86%	2004	11	68%
Belgium - Brussels	2000	1,2	59%	-	-	-
Belgium - Flanders	2006	9	92%	-	-	-
Belgium - Wallonia	1995	2,1	74%	-	-	-
Bulgaria	-	-	-	2004	3	-
Cyprus	-	-	-	2004	0,4	1%
Czech Republic	2006	8,4	30%	2006	11,8	23%
Denmark	2003	3,8	93%	2004	21,7	94%
Estonia	2006	2,4	73%	2006	0,7	92%
Finland	2004	1,6	54%	2004	20,8	26%
France	2004	47,9	25%	2004	342,6	62%
Germany	2002	73	91%	2006	192,3	86%
Greece	1999	2	5%	2004	4,1	-
Hungary	-	-	-	2006	5,4	16%
Ireland	2005	2,3	43%	2006	16,6	80%
Italy	2004	46,5	-	2004	46,3	-
Latvia	-	-	-	2006	0,1	46%
Lithuania	2006	0,6	-	2006	0,6	60%
Luxembourg	2005	7,8	46%	2004	2,7	-
Malta	-	-	-	2004	0,8	-
Netherlands	2005	25,8	95%	2005	25,8	98%
Poland	2000	2,2	75%	2006	16,8	28%
Portugal	1999	3	5%	2004	11,4	-
Romania	-	-	-	2005	0,4	-
Slovak Republic	-	-	-	2004	1,4	-
Slovenia	2005	1,1	53%	-	-	-
Spain	2005	35	-	2006	38,5	14%
Sweden	2006	11	-	2004	10,2	
UK		100,4	82%	2006	114,2	65%
UK - England	2005	89,6	80%	-	-	-
UK - Scotland	2003	10,8	96%	-	-	-
Average for x countries with available data			86%			66%
Total amount of C&D waste on which the estimation is based			252,7			820,2

Recycling rate of Construction and demolition waste in Europe, (UAB, 2008 & ETV/RWM 2009)

Part I

Introduction

Questionnaire survey regarding graduation research

Name Graduator:	Javad Alizadeh
Master Program:	3TU master program 'Construction Management and Engineering'
University:	Eindhoven University of Technology
Name Company:	Iv- Infra, Department RAMS and Contract Management

Date: 12 September 2015

Dear Participant,

Currently I am undertaking a graduation research by Iv-Infra, department RAMS and Contract Management. The research subject is " Circular Economy and Civil Infrastructure Systems". The goal of the research is to identify whether circular principles can be integrated into the engineering and design process of civil infrastructure systems that have to be developed according to performance based contracts. As part of the research, I am conducting a multi criteria analysis in order to elicit expert opinions for evaluating the design alternatives and the project criteria for the development of a lock (Dutch: sluis).

During this trade off, the principles of circular economy or in other words ''*Resource efficient design criteria''* play a significant role alongside RAMS criteria and life cycle cost. The exact meaning of these criteria is explained in the following pages. Through this questionnaire survey, I would like to obtain your opinion as an expert in which you are requested to prioritise the alternatives with respect to the criteria and to prioritise the criteria with respect to the project goal. The information you provide will be of great value for this research, and accordingly, your participation is anticipated and very much appreciated.

Thank you in advance.
Javad Alizadeh
E: J.Alizadeh@iv-infra.nl
M: 06 52 613 113

Dear Participant,

You are being asked to participate in a questionnaire survey. Investigator, Javad Alizadeh, is conducting this research under the supervision of:

Prof.dr.ir. Bauke de Vries:	1st supervisor, TU Eindhoven,
Dr. Qi Han	2nd supervisor, TU Eindhoven,
Prof.dr.ir. Pieter van Gelder	3rd supervisor, TU Delft),
Ir. Arno Willems	1st company supervisor, Iv-Infra
Drs. Antal Hartman	2nd company supervisor, Iv-Infra
Dr. ir. Sten de Wit	External supervisor, TNO.

The survey consists of two parts: **PART(I)** is the preparation for the questionnaire.
In part (I) you will find the necessary information to fill the questionnaire correctly.
Please I want to ask you to read the information in PART (1) '' <u>Carefully</u>''. **PART(II)** is the questionnaire itself. You should ask researcher (Javad Alizadeh) to explain any sections that are unclear to you and to answer any questions that you may have. If, after deciding to participate in this study, you find you have more questions, you should contact the investigator at the number given at the previous page.

Conducting Survey

The survey will take about 30 minutes and it will be conducted by:
- Delivering the questionnaire in person to the participants, explain the study, and then collect the questionnaires at a date after completion.
- Mailing questionnaires directly to participants and to mail the survey back when completed.

Confidentiality

The information provided by participants will not be disclosed. Participant's name, address and other personal data are not asked, however, if provided, they will be removed from the questionnaire and not known to others. The answers will be only used for research purposes and for writing a report.

Availability of Results

A summary of the results is expected to be available by November 2015. Participants wanting a copy should forward their request directly to the investigator.

Preparing For The Questionnaire

Introduction

One of the most important forms of sustainable development is the concept of ' *'Circular Economy*''. Circular economy is a new economic system in which industries have to deal differently with *Resources* (materials). The other name for circular economy is ''*Resource Efficiency*'', hence this concept focuses on the resources. According to the literature *resource efficiency* can provide financial benefits and it can help to reduce CO_2 emission in a large extent. Resource efficiency is specially supported and stimulated by national and international governments and the world industrial market leaders. The power of circular economy lies in ''design'' and ''design stage''. For the engineering design team of infrastructure systems it means using *resource efficient design criteria*. These criteria are :

1- Design for deconstruction (design for disassembly),

2- Design for adaptability (design for the future or design for flexibility),

3- Design for reuse, recycle and recovery (using materials with high recyclability and reusability),

4- Design for durability (choosing materials with a long technical life time and less maintenance).

As you know, Resource-Efficient Criteria are not the only criteria to take into account when designing systems. There are also other important criteria such as functional requirements (RAMS criteria) and the life cycle costs that a design has to meet. In order to take into account all of these criteria Analytical Hierarchy Process (AHP) can be used. AHP is a multi-criteria analysis method and it is designed to help in prioritizing very complex decision alternatives involving multiple stakeholders and multiple goals. Pair-wise comparisons are the fundamental buildings block of AHP. By using the questionnaire, the participants compare the relative importance of the decision alternatives with respect to criteria and the project goal (Figure 1). Each participant is requested to enter his/her judgements and makes a distinct, identifiable contribution to the project goal. The procedure of the AHP results in not only the identification of the most important alternative but also the preference of all alternatives for each respondent. As shown in Figure 1, the first level of hierarchy is the ultimate goal of the project; the second and third level represent the main and sub-criteria that have to be evaluated. And finally, the fourth level presents the alternatives.
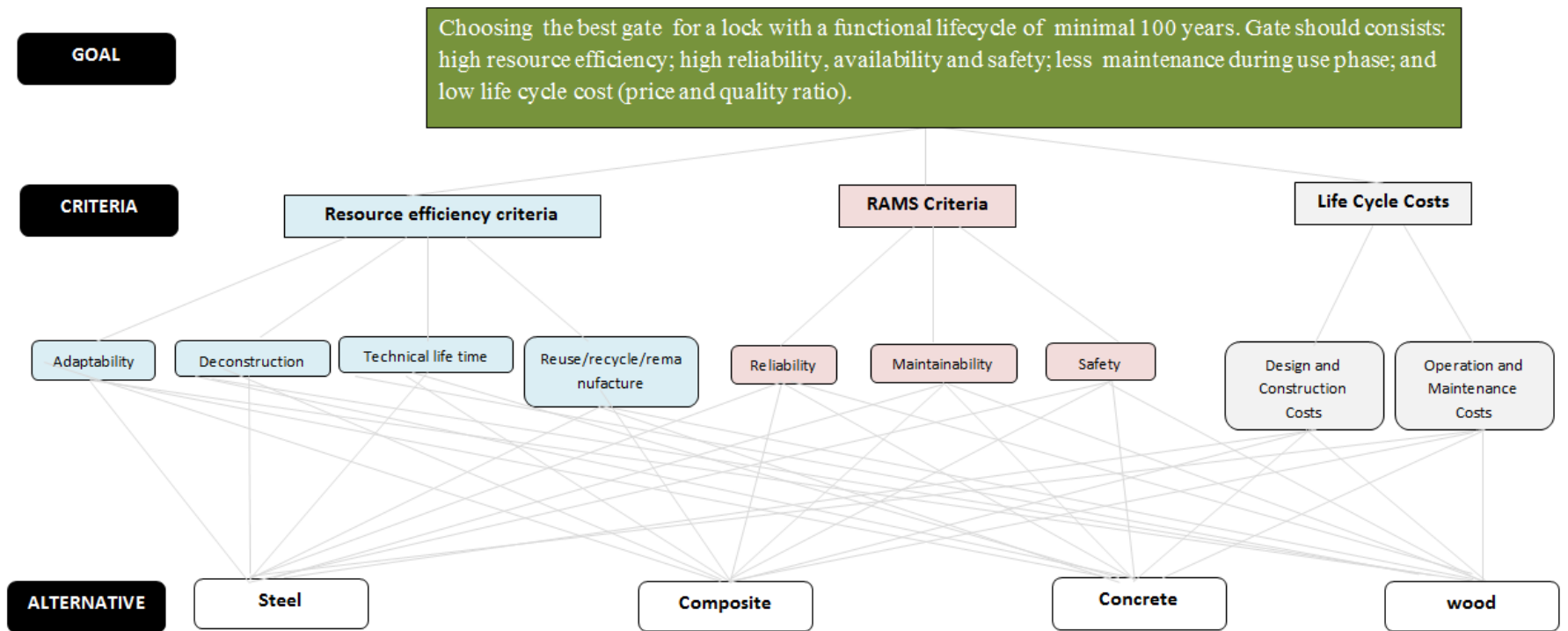
Figure 1: Hierarchy structure of Goal, Criteria and Alternatives.

Case Study: Lock gate

Suppose we are in the preliminary design phase of a lock with the following data:

Lock type: Free to choose (Mitre gates, Rolling gates)

Lock parts: lock Gate

Functional service life: Minimal 100 years

Design stage: Preliminary design

CEMT Class: VIb, gate width approximately 23 meters

Goal: Choosing the best gate for a lock with a functional lifecycle of minimal 100 years.
Gate should consists with high resource efficiency; high reliability, availability and safety; less
maintenance during use phase; and low life cycle cost (price and quality ratio).

Alternative lock gates : Steel, Composite, Concrete, Wood

Main Criteria and Sub criteria

Resource Efficient Design Criteria	R(A*)MS Criteria	Life Cycle Costs
- Adaptability - Deconstruction - Technical life time - Reuse/ Recycle/ remanufacture	- Reliability - Maintainability - Safety	- Design and Construction Costs - Operation and maintenance Costs

Availability*: availability is an important part of RAMS criteria. Degree of Availability can be determined by the degree of the criteria Reliability, Maintainability and safety (to a large extent). Hence this criterion is not used in this questionnaire. (High reliability and lower maintenance result in higher availability).

 In the next page the main and sub criteria are defined.

Resource Efficient design Criteria

Resource Efficient Design Criteria refer to the circular economy principles for improving resource efficiency in the civil infrastructure systems occur during the design stage. Implementing these principles can provide significant reduction in cost, waste and carbon.
Below these criteria are indicated and defined.

Adaptability:
''The ability to make significant changes during the course of the life cycle of a system'' (for example by expansion).

Deconstruction:
'The ability to dismantle/dissemble components or materials at the end of life cycle or when it is needed any reason''(for example by replacing).

Technical Life Time:
''The period that a material, component or machine lasts until it is worn'', (until no longer meets the required quality).

Reuse, recycle, remanufacture:
''The ability to reuse, remanufacture or recycle a material or component at the end of its life cycle''.

R(A)MS criteria

RAMS is an acronym for Reliability, Availability, Maintainability and Safety. RAMS criteria are related to the functionality objectives of a system during its whole life cycle. RAMS criteria make it possible to ensure the successful accomplishment for the operational or functional objectives of a system. These criteria are defined as follow:

Reliability:

'' the probability that the required function is carried out under given conditions for a given time interval''.

Maintainability:

In this survey maintainability refers to maintenance, *the process of keeping something in good condition*. This can be quantified in hours per year [number of times maintenance per year x duration of each time in hours]. It means *how often* an item must be maintained and *how long* does it takes each time.

Safety:

''Safety is defined as ''the capacity of a system not to create damages to people or things''.

Life Cycle Cost

Life cycle cost include all costs associated with the system life cycle. The focus of this research is on ''design and construction cost'' and operation and maintenance cost''.

Design and Construction Costs

''Costs necessary for design and realization of the system such as labour cost, material cost, transport cost and construction costs''.

Operation and Maintenance Costs

''Cost necessary in order to keeping systems in good condition (such as costs for corrective, preventive and predictive maintenance) and cost to keep the system functioning according to the agreed requirements during its whole life cycle (such as: cost of failures, cost of repairs, cost for spares and downtime costs)''

What we have to do:

- Determining the best alternative that fits the criteria.

- Determining the importance of each criterion with respect to the project goal.

In general, there are two questions that have to be answered during this survey.

1- Which alternative is better with respect to a *criterion* and to which degree?

2- Which *criterion* is important with respect to *the goal* and how important is it?

To answer the questionnaire correctly, it is very important to understand the project goal and the definition of the criteria (*Please read these ''carefully''*). In addition following sheet is used to elicit your opinion in order to select among the alternatives. The pairwise comparison scale is used to express the importance or the degree of your priority on one option over another (Table 1). See examples in the next page to get a clear understanding how the questionnaire works.

Table 1: Pairwise Comparison**,** Thomas Saaty

Explanation	Numeric Value
If you think option A and option B are equal: mark →	1
If you think option A is moderately more stronger than option B : mark →	3
If you think option A is strongly more stronger than option B: mark →	5
If you think option A is very strongly more stronger than option B: mark →	7
If you think option A is extremely more stronger than option B: mark →	9

Examples

Question 1: Which alternative is better with respect to the *criterion* and to which degree?

The question is: ''which alternative requires <u>less maintenance</u> and in which degree?''

If you think a <u>Composite lock</u> in column (B) is <u>strongly better than a Steel lock</u> in column (A)

regarding <u>less maintenance</u> then you mark 5(x) on the right hand side.

Which alternative requires <u>less maintenance</u> and to which degree?									
A	*extremely*	*Very strong*	*Strongly*	*Moderately*	*Equally*	*Moderately*	*Strongly*	*Very strongly*	*Extremely*	**B**
Steel	9	7	5	3	1	3	5	7	9	**Composite**

Question 2: Which *criterion* is important ''with respect to the goal'' and how important is it?

The question is: ''which criterion is important (stronger) with respect to the goal and how important is it''? If *you think the sub criterion <u>Safety</u> in column A is <u>very strongly more important</u> <u>than</u> the sub criterion <u>Maintainability</u> in column B ''<u>with respect to the goal</u>'', then you mark 7(x) on the left hand side.*

Which criterion is important with respect to the RAMS criteria and how important is it?									
A	*extremely*	*Very strong*	*Strongly*	*Moderately*	*Equally*	*Moderately*	*Strongly*	*Very strongly*	*Extremely*	**B**
Safety	9	7	5	3	1	3	5	7	9	**Maintainability**

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Part II

The

Questionnaire

Question 1:

Which *alternative* is better " with respect to the criterion" and to which degree?

Which alternative is **more Adaptable** by changes and to which degree?										
A	extremely	Very strong	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	B
Steel	9	7	5	3	1	3	5	7	9	Composite
Steel	9	7	5	3	1	3	5	7	9	Concrete
Steel	9	7	5	3	1	3	5	7	9	Wood
Wood	9	7	5	3	1	3	5	7	9	Composite
Wood	9	7	5	3	1	3	5	7	9	Concrete
Composite	9	7	5	3	1	3	5	7	9	Concrete

Which alternative is **easier to Dissemble/ Dismantle** after end of life and to which degree?)										
A	extremely	Very strong	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	B
Steel	9	7	5	3	1	3	5	7	9	Composite
Steel	9	7	5	3	1	3	5	7	9	Concrete
Steel	9	7	5	3	1	3	5	7	9	Wood
Wood	9	7	5	3	1	3	5	7	9	Composite
Wood	9	7	5	3	1	3	5	7	9	Concrete
Composite	9	7	5	3	1	3	5	7	9	Concrete

Which alternative has a longer Technical Life Time and to which degree?									
A	extremely	Very strong	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	B
Steel	9	7	5	3	1	3	5	7	9	Composite
Steel	9	7	5	3	1	3	5	7	9	Concrete
Steel	9	7	5	3	1	3	5	7	9	Wood
Wood	9	7	5	3	1	3	5	7	9	Composite
Wood	9	7	5	3	1	3	5	7	9	Concrete
Composite	9	7	5	3	1	3	5	7	9	Concrete

Which alternative has a higher Recyclability /Reusability after end of life and to which degree?									
A	extremely	Very strong	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	B
Steel	9	7	5	3	1	3	5	7	9	Composite
Steel	9	7	5	3	1	3	5	7	9	Concrete
Steel	9	7	5	3	1	3	5	7	9	Wood
Wood	9	7	5	3	1	3	5	7	9	Composite
Wood	9	7	5	3	1	3	5	7	9	Concrete
Composite	9	7	5	3	1	3	5	7	9	Concrete

Which alternative has a higher Reliability and to which degree?
In other words, which alternative has less failure?

A	extremely	Very strong	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	B
Steel	9	7	5	3	1	3	5	7	9	Composite
Steel	9	7	5	3	1	3	5	7	9	Concrete
Steel	9	7	5	3	1	3	5	7	9	Wood
Wood	9	7	5	3	1	3	5	7	9	Composite
Wood	9	7	5	3	1	3	5	7	9	Concrete
Composite	9	7	5	3	1	3	5	7	9	Concrete

Which alternative requires less Maintenance and to which degree?

A	extremely	Very strong	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	B
Steel	9	7	5	3	1	3	5	7	9	Composite
Steel	9	7	5	3	1	3	5	7	9	Concrete
Steel	9	7	5	3	1	3	5	7	9	Wood
Wood	9	7	5	3	1	3	5	7	9	Composite
Wood	9	7	5	3	1	3	5	7	9	Concrete
Composite	9	7	5	3	1	3	5	7	9	Concrete

Which alternative provides A _higher Safety_ and to which degree? (For example, against a crash)

A	extremely	Very strong	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	B
Steel	9	7	5	3	1	3	5	7	9	Composite
Steel	9	7	5	3	1	3	5	7	9	Concrete
Steel	9	7	5	3	1	3	5	7	9	Wood
Wood	9	7	5	3	1	3	5	7	9	Composite
Wood	9	7	5	3	1	3	5	7	9	Concrete
Composite	9	7	5	3	1	3	5	7	9	Concrete

Which alternative requires _less Design and Construction Cost_ and to which degree?

A	extremely	Very strong	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	B
Steel	9	7	5	3	1	3	5	7	9	Composite
Steel	9	7	5	3	1	3	5	7	9	Concrete
Steel	9	7	5	3	1	3	5	7	9	Wood
Wood	9	7	5	3	1	3	5	7	9	Composite
Wood	9	7	5	3	1	3	5	7	9	Concrete
Composite	9	7	5	3	1	3	5	7	9	Concrete

Which alternative requires <u>less Maintenance and Operation Cost</u> and to which degree?									
A	extremely	Very strong	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	B
Steel	9	7	5	3	1	3	5	7	9	Composite
Steel	9	7	5	3	1	3	5	7	9	Concrete
Steel	9	7	5	3	1	3	5	7	9	Wood
Wood	9	7	5	3	1	3	5	7	9	Composite
Wood	9	7	5	3	1	3	5	7	9	Concrete
Composite	9	7	5	3	1	3	5	7	9	Concrete

Question 2:

Which *criterion* is important " with respect to the goal" and how important is it?

Which main criterion is important with respect to the main criteria and how important is it?									
A	extremely	Very strong	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	**B**
Resource Efficient Design Criteria	9	7	5	3	1	3	5	7	9	RAMS Criteria
Resource Efficient Design Criteria	9	7	5	3	1	3	5	7	9	Life Cycle Costs
RAMS Criteria	9	7	5	3	1	3	5	7	9	Life cycle Costs

Which criterion is important with respect to the life cycle cost and how important is it?									
A	extremely	Very strong	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	**B**
Design and Construction Costs	9	7	5	3	1	3	5	7	9	Operation and Maintenance Costs

Which criterion is important(stronger) with respect to the RAMS criteria and how important is it?									
A	extremely	Very strong	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	**B**
Reliability	9	7	5	3	1	3	5	7	9	Maintainability
Reliability	9	7	5	3	1	3	5	7	9	Safety
Maintainability	9	7	5	3	1	3	5	7	9	Safety

Which criterion is important with respect to the resource efficiency and how important is it?									
A	extremely	Very strong	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely	**B**
Adaptability	9	7	5	3	1	3	5	7	9	Deconstruction
Adaptability	9	7	5	3	1	3	5	7	9	Technical life time
Adaptability	9	7	5	3	1	3	5	7	9	Reusability, Recyclability
Reusability, Recyclability	9	7	5	3	1	3	5	7	9	Deconstruction
Reusability, Recyclability	9	7	5	3	1	3	5	7	9	Technical life time
Deconstruction	9	7	5	3	1	3	5	7	9	Technical life time

End of Questionnaire.

Thanks for your participating.

English Summary

Circular Economy and Civil Infrastructure Systems

Applying the principles of circular economy into the design and engineering process of civil infrastructure systems.

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Graduation Program:

Construction Management and Engineering 2015-2016

Graduation committee:

- Prof. dr. ir. B. de Vries (TU/e)

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Date of graduation:

27-01-2016

Abstract

The economic growth of industrial countries is increasingly hindered due to the huge demand for natural resources such as energy, raw materials and minerals. While resource demand in the world increases the current economic model, the 'linear economy', entails significant limits and resource losses. Circular economy is an alternative economic system for the linear economy in which the economic growth is decoupled from the resource use. The construction sector, including civil infrastructure, is an important economic engine with one of the largest users of raw materials and energy. Therefore the potential impact of circular economy in this sector is enormous. In this research, the concept of circular economy including the principles and circular economy loops is described. In addition the barriers and strategies for the integrating of the circular economy principles into the design and engineering process is analysed. Making use of resource efficient design principles and involving stakeholders in the early design stage are the main steps in order to integrate the principles of circular economy into the engineering process of civil infrastructure systems.

Keywords: Circular Economy, Systems Engineering, Design Process, Multi Criteria Group Decision Making Systems, Analytical Hierarchy Process.

Introduction

Linear economy is the current economic system of industrial countries in which companies extract and transport resources from different countries; add energy labour and information to manufacture a product; and sell it to an end consumer, who then discards it when it no longer serves its purpose. In recent decennia, the world demand for natural resources is increased. While the resource demand in the world increases, the linear economy entails significant limits and resource losses such as: resource loss as waste in production chain, resource loss as end-of-life waste and resource loss as energy. Circular Economy (CE) is an alternative economic system for the linear economy in which the economic growth is decoupled from the resource use. Resources decoupling means "using less resources per unit of economic output for more people and reducing the environmental impact of any resources that are used or economic activities that are undertaken" (UNEP, 2011) [Figure 1].
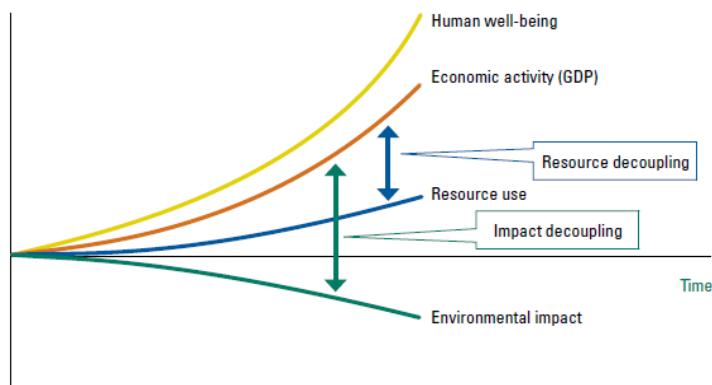

Figure 1: Decoupling natural resource use and environmental impacts from economic growth, (UNEP, 2011).

As stated by WRAP (2012), in the circular economy the resources are used as long as possible until the maximum value from them are extracted whiles in use and then the products and materials are recovered and regenerated at the end of their life cycle (WRAP, 2012). To achieve this goal, circular economy strategy and circular economy principles are introduced.

Problem definition

Circular economy introduces a new way of thinking and designing products or systems in order to maximize the value of all kind of resources. The construction sector is an important economic engine with one of the largest users of raw materials and energy. Circular economy can create value in different ways for the construction industry and specially for the construction customers. Therefore, infrastructure clients will stimulate the transition towards a circular economy by using Performance Based Contracting (PBC) to express their needs and Systems Engineering (SE) to minimize the failures and mishaps. The goal of this research is to investigate whether the circular economy principles can be integrated into the design and engineering process of the civil infrastructure systems. In particular the study is aimed to:

- Providing information about the circular economy concept, circular economy strategies and principles.
- Identifying the potential impact of circular economy in the construction sector.
- Identifying the barriers and the strategies for applying the circular economy principles in the design process of construction systems, in particular civil infrastructure systems.
- Identifying the ideal workflow to apply circular economy principles in to the design and engineering process of civil infrastructure systems.

Subsequently, the research objectives are expressed in the following main and sub questions:

Research question: How can the principles of circular economy be integrated into the engineering and design process of civil infrastructure systems?

Question 1: To what extent does the current engineering process of civil infrastructure systems differs from the principles of the circular economy?

Question 2: What is the potential impact of circular economy in the civil infrastructure sector?

Question 3: Which circular economy criteria can be used in order to design resource efficient infrastructure systems?

Question 4: Which strategy can be used in order to integrate these criteria into the design

process?

Question 5: What is the ideal workflow to apply circular economy in the engineering and design process of civil infrastructure systems?

Circular Economy Concept

Circular economy introduces a development strategy that optimizes natural and social capitals by creating an effective closed system for materials flow, energy flow, labour flow and information flow. For this purpose circular economy principles are introduced.

Circular economy principles

The fundamental principles of circular economy are: " Design out waste, build resilience through diversity, rely on energy from renewable sources, think in systems and waste is food" (EMF et al., 2012). 'Design out waste' stimulates a design strategy in which products should be designed by intention to fit within a material loop (EMF et al., 2012). 'Build resilience trough diversity' ensures the flexibility of systems for the future changes and needs by using the design principles such as modularity, versatility and adaptively. ' Shift to renewable energy sources' aims to use renewable energy such as solar energy, energy from soil and or wind power for producing materials or systems through the supply chain. 'System thinking' is a process of understanding and it refers to the system theory and in particular self-regulating systems or systems self-correcting through (Biel et al., 200). According to EMF and others (2012), "Systems thinking usually refers to the overwhelming majority of real-world systems which are non-linear, feedback-rich, and interdependent". 'Waste is food' refers to the Cradle to Cradle principle and it expresses the circular philosophy and design out waste principle (EMF et al., 2012). This principle divided the materials into the biological nutrient in which biological products and materials go back into the biosphere and the technical nutrients in which technical materials can be up cycled, recycled and reused for the same or other products or systems (EMF et al., 2012).

Circular economy strategy
'Cradle to cradle' and 'industrial symbiosis' are the fundamental pillars of the circular economy

strategy. The cradle to cradle principle refers to the product design for durability, disassembly and refurbishment. It expresses that businesses should apply the principles of eco-design to all their products, i.e. use as little non-renewable resources, eliminate as many toxic elements and hazardous materials as possible, use renewable resources (at or below their rates of regeneration), increase the life and reuse potential of products, and facilitate the sorting and final recovery of products (EU, 2014). Furthermore, it changes the model of consumption from buyer to user (EU, 2014). Industrial symbiosis expresses a cross-sector approach and cooperation between actors unaccustomed to cooperate (e.g. between product designers and recyclers), along the whole supply chain of a product, in order to optimise its life-cycle (EU, 2014).

Creating value by circular economy loops
As indicate by EMF (2014) the circular economy can create value through the circular economy loops in four ways including: the power of inner cycle, the power of circling longer, the power of cascading use and the power of pure input (EMF et al., 2014). The power of the inner circle minimises the comparative materials use vis-à-vis the linear production system (EMF et al, 2014). According to EMF (2014) "the tighter the circle, i.e. the less a product has to be changed in reuse, refurbishment and remanufacturing and the faster it returns to use, the higher the potential savings on the shares of material, labour, energy and capital still embedded in the product, and the associated externalities". The power of circling longer maximize the number of consecutive cycles (be it repair, reuse, or full remanufacturing) and/or the time in each cycle (EMF et al., 2014). 'The power of cascading use' diversify the reuse across the value chain (EMF et al., 2014). The power of pure inputs refers to the increasing of uncontaminated material streams by efficient collection and redistribution of materials (EMF et al., 2014).

Circular Economy in the civil infrastructure sector

The construction sector is an important economic engine with one of the largest users of raw materials and energy. Therefore, construction sector (buildings and infra) is a priority sector for the transition to the circular economy (EU, 2014). By applying the principles of circular economy, different types of value can be created. However, there are barriers that make the transition towards the resource efficient construction sector difficult. One of the main barriers is

lack of applying resource efficient design principles during the design stage (Nakajima et al., 2014). The current design methodology is focused on construction and not deconstruction of systems (Nakajima et al., 2014). The designers have to create design solutions that minimise waste and use resources efficiently (WRAP, 2012) by using resource efficient design principles such as 'design for deconstruction' and 'design for reusability/recyclability'. ABN AMRO and Circle Economy emphasize using resource efficient design principles as one of the most important factors to enable reuse and recycle in the construction sector (ABN AMRO et al., 2014). Table 1 indicates the recommended design principles according to WRAP (2012), Nakajima (2014), ABN AMRO and Circle Economy (2014).

Table 1: recommended design principles according to WRAP (2012), CIB (2014), ABN AMRO and Circle Economy (2014).

Resource efficient design principles for the civil infrastructure systems
Design for deconstruction or design for assembly enables significant changes to be made to the civil engineering project during the course of its life.
Design for reuse and recycle means choosing materials that can be reused and or recycled at the end of life cycle.
Design for adaptability or flexibility enables significant changes to be made to the system during the course of its life.
Design for durability expresses matching materials to the planned life of the project/structure with fewer life cycle replacements and reduced maintenance cycles. This can be achieved by using materials with a long technical life cycle and less maintenance.

Less involving of stakeholders through the value chain during the design process is the other main barrier in the construction sector (Nakajima et al., 2014). Designers have to involve project stakeholders to the design process in order to create an integrated design. They should ensure that perspectives of the stakeholders are included before final design is determined. It ensures that the most resource efficient opportunities are take into account in the design.

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Research methodology

As concluded so far, using resource efficient design principles and involving stakeholders through the value chain to the design process are the strategic approaches in order to design resource efficient civil infrastructure systems. However, in addition to these principles, system has to function properly according to RAMS (Reliability, Availability, Safety and Maintainability) criteria and life cycle costs. By integrating of all these principles and criteria the design process become complex. This especially when different stakeholders are involved into the design process. In order to take account into multiple criteria and at the same time to involve stakeholders into the design process, use can be made of 'multi-criteria group decision support systems' such as Analytical Hierarchy Process (AHP). AHP is a multi-criteria decision Analysis (MCDA) and a structured technique developed by Thomas Saaty in 1970 for organizing and analysing complex decisions (Saaty et al. , 2008). AHP is in particular used for group decision making (Saaty et al. , 2008) in a wide variety of decision situations around the world in fields such as government, business, construction industry and education (Saracoglu, 2013). In this research, AHP is used to structure and determine the relative importance among the criteria. In addition, AHP is used to involve multiple experts into the design process and in particular to determination best design alternative that best meets all the criteria.

Case study

For the case study, a lock gate is chosen since in this case multiple experts and disciplines can be involved into the design process (e.g. as compared with a tunnel or path). In addition, lock gate is a hydraulic component in which RAMS criteria are applicable. In general, lock gates can be made from 4 types of materials. These include: steel, composite, concrete and wood. Based on AHP questionnaire, 20 experts were asked to prioritize these four alternatives with respect to the 9 criteria. Table 4 represents the distribution of project criteria and their definition. In addition the experts were asked to determine relative importance of the criteria regard the project goal. The project goal was indicated as follow: "Choosing the best gate for a lock with a functional lifecycle of minimal 100 years. The gate should consist of high resource efficiency; high reliability and safety; less maintenance during use phase; and low life cycle cost". Figure 2 shows the hierarchy structure between the objectives, criteria and alternatives. The pairwise

comparison scale of Saaty is used to express the relative importance of criteria or alternatives according to experts opinion [Table 2].

Table 2: Fundamental Scale of Saaty (2008)

Scale	Intensity of Relevance	Description
1	Same relevance	Both tasks contribute equally to the purpose.
3	A little more relevant	Experience and judging favor one task in relation to another.
5	Considerably more relevant	Experience and judging strongly favor one task in relation to another.
7	A lot more relevant	A task is a lot more strongly favored in relation to another.
9	Extremely relevant	An evidence favors a task in relation to another with the highest level of reliability.

Participants Characteristics

The survey was conducted among 20 experts from different disciplines. The most experts were from the company Iv-Infra. The appropriate experts for each discipline have been chosen by the involved division head. The most experts had a minimal work experience of 5 years governing their working area. These include; RAMS managers, hydraulic engineers, constructors, maintenance engineers, cost expert, project leaders and the involved department heads. Table 3 represents the involved participants in the survey.

Table 3: Involved participants in the AHP survey, created by author

Division	Number
RAMS and Contract Management	4
Hydraulic Engineers	3
Constructors	4
Maintenance Engineers	5
Project leaders	4
Total	20

Questionnaire design

The study was conducted by delivering the questionnaire survey in person to the participants, explain the study, and then collect the questionnaires at a set date after completion. The survey was consisted of two parts. Part (I) provided necessary information to fill the questionnaire correctly. In this part examples were used to provide a clear instruction for the participants about how the questionnaires must be completed. Part (II) was the questionnaire itself.

Table 4: distribution of criteria and their definition, created by author

Criteria	Description
C1- Resource Efficiency	
C 1.1 Availability	The ability to make significant changes during the course of the life cycle of a system (for example by expansion).
C 1.2 Deconstruction	The ability to dismantle/dissemble components or materials at the end of life cycle or when it is needed on any reason (for example by replacing).
C 1.3 Technical life time	The period that a material, component or machine lasts until it is worn out, (until no longer meets the required quality).
C 1.4 Reuse/Recycle	The ability to reuse, remanufacture or recycle a material or component at the end of its life cycle.
C2- R(A^7)MS	
C2.1 Reliability	The probability that the required function is carried out under given conditions for a given time period.
C2.2 Maintainability	Maintainability refers to the possibility to maintain a system component. In this research maintenance means, the process of keeping something in good condition.
C2.3 Safety	The capacity of a system not to create damages to people or things.
C3- Life Cycle Costs	

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[7] In this research the criterion 'availability' is not included in the criteria, because it is not logical to say which alternative is most available. The degree of availability of an alternative can be determined on degree of other criteria such as maintainability and reliability.

C3.1 Design and Construction Costs	Costs necessary for design and realization of the system such as labor cost, material cost, transport cost and construction costs.
C3.2 Operation and Maintenance Cost	Cost necessary in order to keeping systems in good condition (such as: costs for corrective, preventive and predictive maintenance) and cost to keep the system functioning according to the agreed requirements during its whole life cycle (such as: cost of failures, cost of repairs, cost for spares and downtime costs).

As shown in Figure 2, the first level of hierarchy is the ultimate goal of the project; the second and third levels represent the main and sub-criteria that have to be evaluated. And finally, the fourth level presents the alternatives.
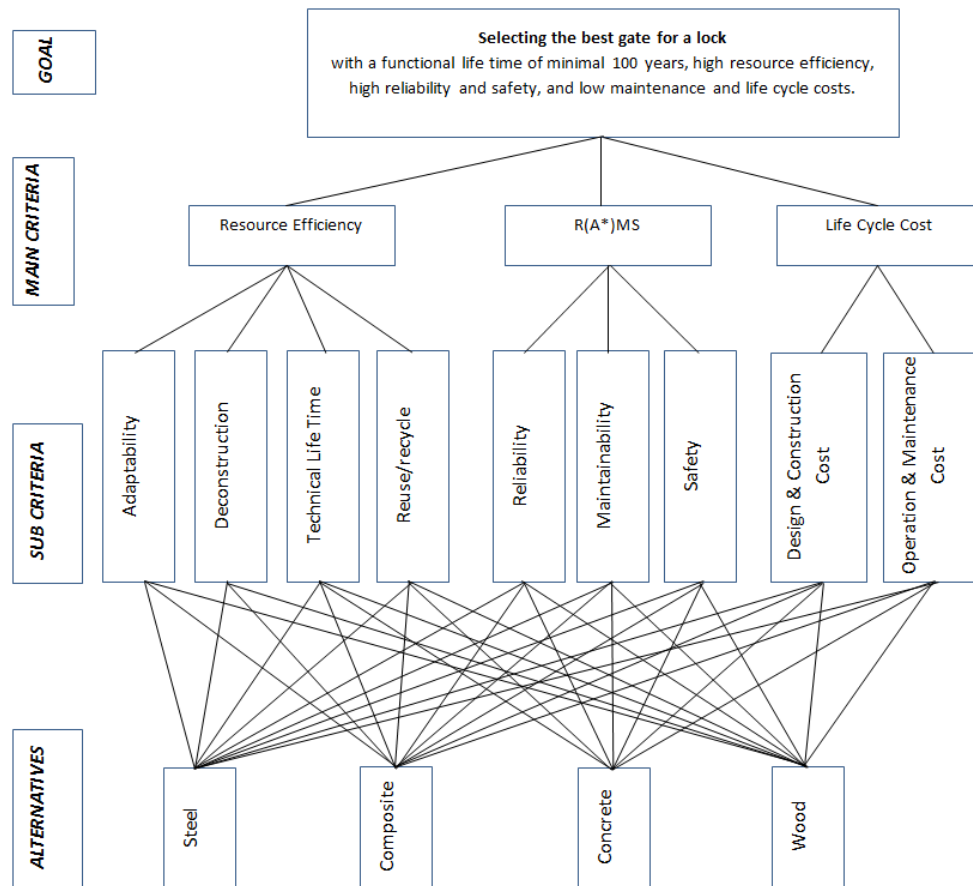
* In this research the criterion `availability` is not included in the criteria, because it is not logical to say which alternative is most available. The degree of availability of an alternative can be determined on the basis of other criteria such as maintainability and reliability.

Figure 2: Hierarchy structure for choosing best gate, created by author

Results

For the respondent a consistency ratio of 0.15 (15%) was maintained. All 20 participants completed the questionnaire. In each section of the questionnaire, there were small numbers of inconsistent answers. The inconsistent answers have not been included in the results. Below the results is indicated.

Relative importance of sub and main criteria

The criteria are divided in to the three main criteria namely: RAMS, resource efficiency and life cycle costs. According to experts, the RAMS criteria following by resource efficiency and LCC are the most important main criteria [Figure 3].
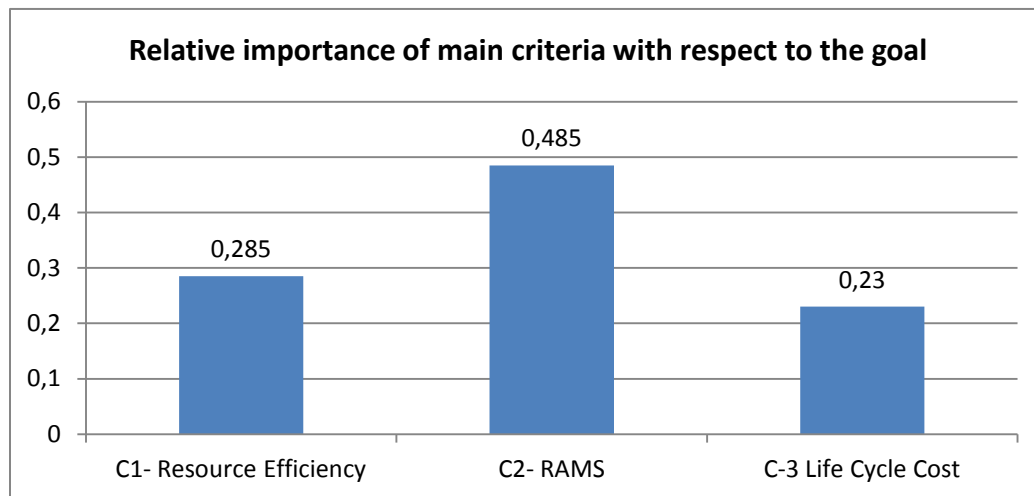
Figure 3: Relative importance of main criteria with respect to the goal

Within RAMS, the safety and reliability sub criteria have scored the highest [Figure 4]. Regards resource efficiency, the technical life time criterion and adaptability criterion are the most important sub criteria , according to experts[Figure 4]. When it comes to LCC the 'operation and maintenance costs' is the most important sub criterion relating life cycle cost criterion. Figure 20 maps the relative importance of all sub criteria with respect to the goal.
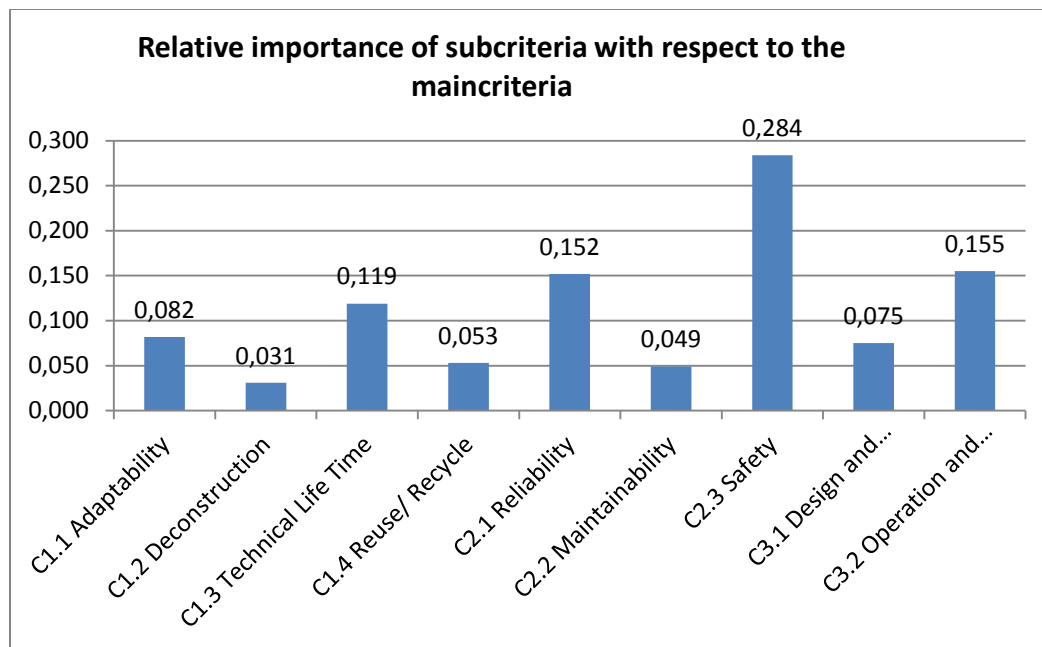
Figure 4: Relative importance of the sub criteria with respect to the goal

Relative weight of alternatives regards to the criteria

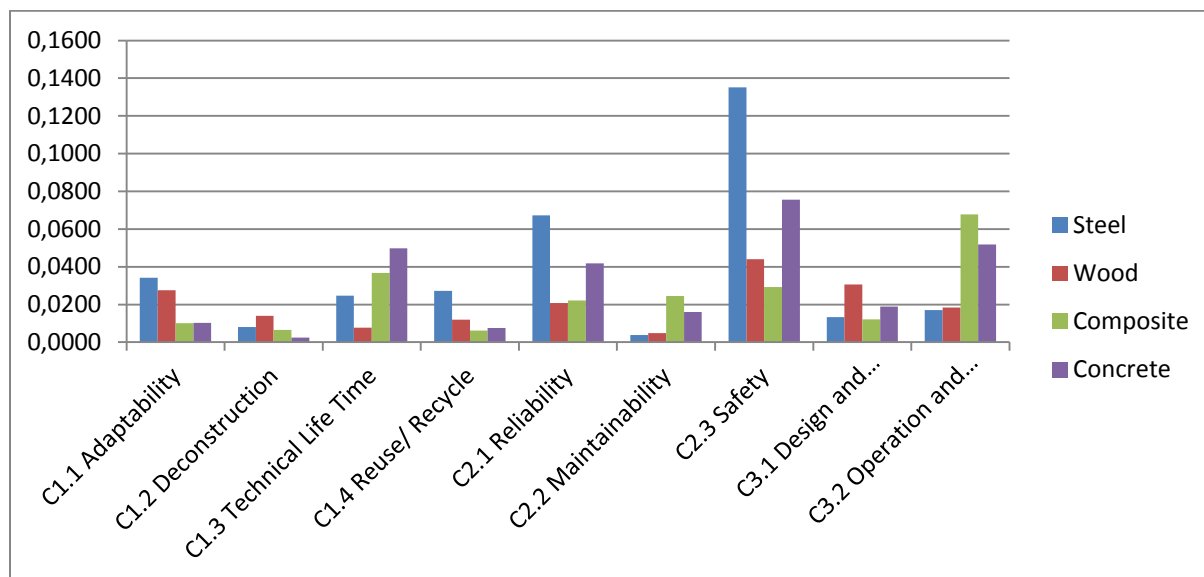The relative weight of each alternatives concerning criteria is indicated in figure 5.

Figure 5: Relative weights of the alternatives with respect to the criteria.

Beset alternative with respect to the goal

As seen in figure 6, steel is the best design alternatives with respect to the project criteria and

project goal, bearing in mind that the possibilities of composite were not really known to the experts. The results may also have been different if more stakeholders through the value chain (such as: contractors, subcontractors, suppliers and or manufacturer) were involved in this process.
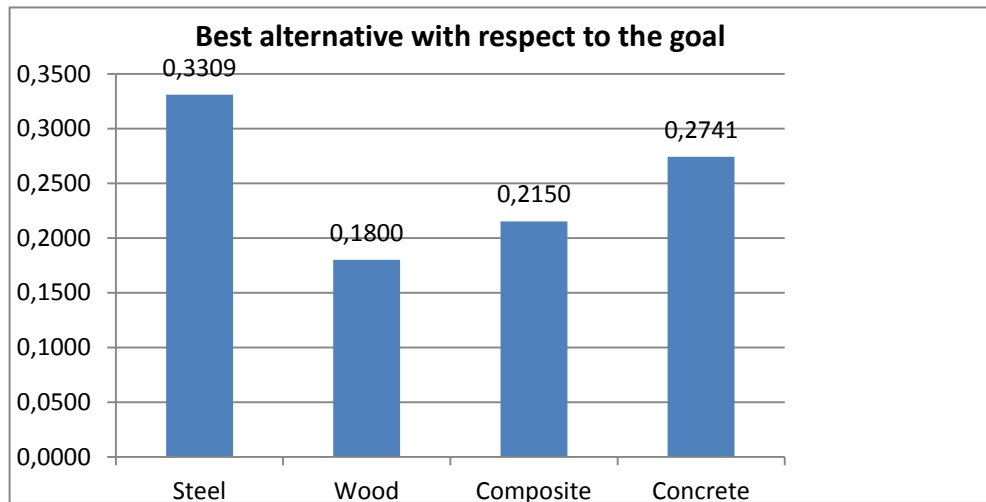

Figure 6: Best alternatives with respect to the goal.

Identified relations between criteria based on results

It is remarkable that both steel and wood have scored high for 'flexibility', 'deconstruction' and 'reuse / recycle' criteria. On the other hand, both materials have scored low on 'technical life', 'maintainability' and 'operation and maintenance costs' criteria. The opposite happened with composite and concrete. Composite and concrete both have scored high on 'technical life', 'maintenance' and 'operation and maintenance costs' criteria and scored low for the 'flexibility', 'deconstruction' and 'reuse / recycle' criteria. In general, there can be concluded that materials which have a long service life require less maintenance and are less flexible, removable and reusable. Inc comparison to concrete and composite, steel and wood are very sensitive to factors such as water, sunlight and temperature (internal factors). Therefore, these materials often require more maintenance than materials such as concrete and composite, which are less sensitive to these factors. Knowing this, it is strange that in practice steel and wood are usually used as lock gate and not concrete or composite. One reason for this choice is that concrete and

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composite are less resistant (because less elastic and plastic properties of these materials) to external factors such as collision, although the existence of such consequences can be reduced by innovative and creative designing.

Conclusion and further research

Circular economy introduces a new way of developing and designing products and systems. One of the main challenges for civil infrastructure designers is extending the lifespan of infrastructure systems. This can be achieved by the use of materials with a long service life, and or by increasing the life cycle of materials. This requires knowledge and information about materials, material properties and the factors that positively or negatively affect the service life of materials. Another challenge is designing systems so that after reaching end of life the materials and components end up in material flows with high-quality. To do this, resource efficient design principles can be used. It would also need a close corporation between designers and the parties in the value of materials. For the further investigation, it is proposed to develop a decision support model in order to determine the efficiency or resource circularity of design alternatives.

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About the author

My name is Javad Alizadeh, born in 1988 in Herat. I began my engineering studies in 2006 at the Hogeschool Rotterdam, graduating as Bachelor of Built Environment in 2011. After earning my bachelor's degree, I decided to expand my knowledge in the field of construction industry and to work on my personal development, entrepreneurship and management aspect. Therefore I chose for the Master Construction Management and Engineering at the Eindhoven University Of Technology. I'm glad that I finish the master`s program with this challenging graduation research. I would like to thank everyone who helped me in this research.

Educations

2013 – 2016   Master Construction Management and Engineering

2012– 2013   Pre-master's program 'Construction Management and Engineering'

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2003 – 2006   Senior General Secondary Education

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Dutch Summary

Circulaire Economie en Civiele Infrastructuur Systemen

Het toepassen van de principes van circulaire economie in het ontwerp- en engineeringproces van civiele infrastructuur systemen.

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Afstudeer Programma:

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Afstudeerdatum:

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Abstract

Economische groei van industriële landen wordt in toenemende mate belemmerd als gevolg van grote vraag naar natuurlijke hulpbronnen zoals energie, grondstoffen en mineralen. Terwijl de vraag naar grondstoffen in de wereld toeneemt, het huidige economische model, de 'lineaire economie', veroorzaakt aanzienlijke beperkingen en grondstofverliezen. Circulaire economie is een alternatief economisch systeem voor de lineaire economie waarin de economische groei wordt losgekoppeld van het gebruik van hulpbronnen. De civiele infrastructuur sector is een belangrijke economische motor van een land en tegelijkertijd een van de grootste gebruikers van grondstoffen en energie. Daarom is de potentiële impact van circulaire economie in deze sector enorm. In dit onderzoek is het concept en de principes van circulaire economie bestudeerd. Bovendien, er is aangegeven welke barrières en strategieën nodig zijn om de principes van circulaire economie te integreren in het ontwerp en engineeringproces van civiele infrastructuursystemen. Het toepassen van resource efficiënte ontwerpprincipes en het betrekken

van belanghebbenden in de vroege stadia van ontwerpfase zijn de belangrijkste stappen om circulair te kunnen ontwerpen.

Trefwoorden: circulaire economie, systems engineering, multi- criteria groep besluitvorming systemen, analytisch hiërarchisch proces.

Lineaire economie is het huidige economische systeem van industriële landen. In de lineaire economie de grondstoffen worden uit verschillende landen geëxtraheerd en getransporteerd. Vervolgens worden informatie, energie en arbeid aan toegevoegd om een materiaal of product van te maken. Het product wordt aan een klant verkocht die het product weggooit of voor een lage prijs doorverkoopt wanneer het niet meer aan zijn eisen en wensen voldoet. In de afgelopen decennia, de vraag naar allerlei grondstoffen in de wereld is toegenomen. Terwijl de vraag naar grondstoffen toeneemt, lineaire economie brengt aanzienlijke beperkingen en zorgt voor het verlies van grondstoffen in de vorm van afval zoals: afval in productieketen, afval aan het einde van de levensduur en afval in de vorm van energie. Als alternatief voor lineaire economie, het concept van circulaire economie (CE) is geïntroduceerd waarbij de economische groei wordt ontkoppeld van brandstofverbruik. In deze context, 'ontkoppelen' betekent het gebruik van minder resources per economische productie-eenheid voor meer mensen en het verminderen van de milieu-impact van grondstoffen die worden gebruikt of economische activiteiten die worden ondernomen (UNEP, 2011), [figuur 1].
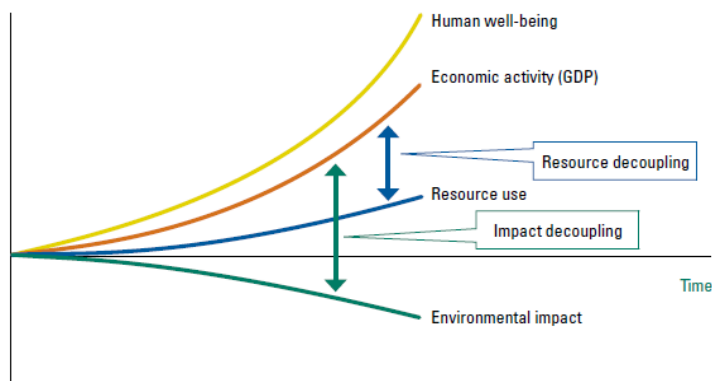
Figuur 1: Ontkoppeling van grondstofgebruik en milieueffecten van de economische groei, (UNEP, 2011).

Zoals door WRAP (2012) wordt aangegeven, in de circulaire economie de grondstoffen worden zo lang mogelijk gebruikt totdat hun maximale waarde wordt benut (WRAP, 2012). Vervolgens producten en materialen worden teruggewonnen en hergebruikt aan het einde van hun levenscyclus (WRAP, 2012). Om dit doel te bereiken de principes van circulaire economie zijn geïntroduceerd.

Probleemomschrijving

Circulaire economie introduceert een nieuwe manier van denken en ontwerpen van producten of systemen met het doel om de waarde van alle soorten resources te maximaliseren. De civiele infrastructuur sector is een van de belangrijkste economische motors van landen en tegelijkertijd een van de grootste gebruikers van grondstoffen en energie. Door het toepassen van de principes van circulaire economie in deze sector, er kan veel waarde gecreëerd worden. Het doel van dit onderzoek is om te analyseren of de principes van circulaire economie in het ontwerp- en engineeringproces van de civiele infrastructuur systemen geïntegreerd kunnen worden. Het onderzoek is voornamelijk gericht op:

- Het verstrekken van informatie over het concept van circulaire economie, circulaire economie strategieën en principes.
- Het identificeren van de potentiële impact van circulaire economie in de bouwsector.
- Het identificeren van de belemmeringen en de strategieën voor de toepassing van de principes van de circulaire economie in het ontwerpproces.
- Het identificeren van een workflow om de principes van circulaire economie toe te passen in het ontwerp- en engineering proces van civiele infrastructuur systemen.

Deze doelstellingen zijn verder uitgedrukt in de volgende hoofd- en deelvragen:

Onderzoek vraag: Hoe kunnen de principes van de circulaire economie worden geïntegreerd in het engineering- en ontwerpproces van civiele infrastructuur systemen?

Vraag 1: In hoeverre is er verschil tussen het huidige ontwerpproces van de civiele infrastructuur systemen en de principes van circulaire economie?

Vraag 2: Wat is de mogelijke impact van circulaire economie op de civiele infrastructuur sector?

Vraag 3: Welke circulaire economie criteria kunnen worden gebruikt om resource efficiënte infrastructuur systemen te kunnen ontwerpen?

Vraag 4: Welke strategie kan worden gebruikt om de principe van circulaire economie te kunnen integreren in het ontwerpproces?

Vraag 5: Wat is de ideale workflow om de principes van circulaire economie te kunnen toepassen in het engineering- en ontwerpproces van civiele infrastructuur systemen?

Het concept van circulaire economie

Circulaire economie introduceert een ontwikkelingsstrategie die de waarde van natuurlijke en sociale kapitalen optimaliseert door het creëren van een effectief gesloten systeem voor materiaalstromen, energiestromen, arbeidstromen en informatiestromen. Hiervoor wordt gebruik gemaakt van de principes van circulaire economie.

The principes van circulaire economie
De fundamentele principes van circulaire economie zijn onder andere: afvalvrij ontwerpen, veerkracht bouwen door middel van diversiteit, gebruiken van energie uit hernieuwbare bronnen, denken in systemen en door het toepassen van het principe 'afval is voedsel'. 'Afvalvrij ontwerpen' stimuleert een ontwerpstrategie waarin producten worden ontworpen met de intentie dat ze na het einde van hun levensduur weer kunnen terugstromen binnen een materiaalstroom (EMF et al., 2012). 'Veerkracht bouwen door middel van diversiteit' zorgt voor de flexibiliteit van systemen voor de toekomstige veranderingen en door het gebruiken van ontwerpprincipes zoals modulair, veelzijdig en adaptief ontwerpen. 'Verschuiving naar hernieuwbare energiebronnen' stimuleert het gebruik van hernieuwbare energie bronnen zoals zonne-energie, energie uit de bodem en of windenergie voor de productie van materialen of systemen. 'Systeem denken is een proces dat verwijst naar de systeemtheorie en in het bijzonder zelfregulerende systemen of zelfherstellende systemen (Biel et al., 200). Volgens EMF en anderen (2012), " systeemdenken verwijst meestal naar het overgrote deel van real-world systemen. Deze systemen zijn meestal niet-lineaire, terugkoppelingrijke en onderling afhankelijk systemen".

'Afval is voedsel' verwijst naar het 'Cradle to Cradle' principe en het benadrukt de circulaire filosofie en 'afvalvrij ontwerpen' principe (EMF et al., 2012). Dit principe verdeelt de materialen in twee categorieën namelijk: biologische voedingsstoffen waarin biologische producten en materialen teruggaan in de biosfeer en de technische voedingsstoffen waarin technische materialen worden upcycled, hergebruikt of gerecycled voor diezelfde of andere producten of systemen (EMF et al., 2012).

Circulaire economie strategie
'Cradle to cradle' en industrial symbiosis' zijn de fundamentele pijlers van de circulaire economie strategie. Het 'cradle to cradle' principe verwijst naar een ontwerpmethodologie voor duurzaamheid, demontage en renovatie. Bovendien dit principe verandert het consumptiemodel van koper naar gebruiker (EU, 2014). 'Industrial symbiosis' benadrukt een sectoroverschrijdende een samenwerkende aanpak tussen actoren, die meestal niet gewend zijn om samen te werken (bijvoorbeeld tussen productontwerpers en recyclingbedrijven), langs de gehele levensketen van een product, met de bedoeling om de levenscyclus van producten te optimaliseren (EU, 2014).

Het creëren van waarde aan de hand van circulaire economie loops
Zoals aangeven door EMF (2014), circulaire economie kan op vier manieren waarde creëren. Deze zijn te verdelen in: de kracht van de binnenste cyclus, de kracht van langer cirkelen, de kracht van cascadegebruik en de kracht van pure input (EMF et al., 2014). De kracht van de binnenste cirkel minimaliseert het gebruik van vergelijkbare materialen ten opzichte van het lineaire productiesysteem (EMF et al, 2014). Volgens EMF (2014) " hoe strakker de binnenste cirkel, hoe minder een product hoeft worden veranderd bij hergebruik, renovatie en remanufacturing. Des te sneller het materiaal terug gebruik kan worden, des te groter de besparing is op de aandelen van materiaal, arbeid, energie en kapitaal." De kracht van langer cirkelen maximaliseert de aantal opeenvolgende cycli en of de tijd in elke cyclus (EMF, 2014). De kracht van cascadegebruik zorgt ervoor dat een materiaal op diverse manieren wordt hergebruik in de waardeketen (EMF et al., 2014). De kracht van zuivere input verwijst naar de toenemende van onbesmette materiaalstromen door efficiënt verzamelen en herverdeling van materialen (EMF et al., 2014).

Circulaire economie in de civiele infrastructuur sector

Bouwsector is een belangrijke economische motor van een land en tegelijkertijd een van de grootste gebruikers van grondstoffen en energie. Hierdoor is de bouwsector (gebouwen en infra) een van de sectoren die in de transitie naar een circulaire economie prioriteit gaat krijgen (EU, 2014).

Circulaire economie kan diverse waarde creëren voor de bouwobjecten waaronder civiele infrastructuur systemen. Om als voorbeeld te noemen: reductie in CO_2-uitstoot, reductie van life cycle costs, vermindering van het energieverbruik, vermindering van afval en het creëren van een robuust systeem. Momenteel zijn twee belangrijke beperkingen die de transitie naar een circulaire bouwsector belemmeren, namelijk: het ontbreken van de resource efficiënte ontwerpprincipes tijdens de ontwerpfase en niet betrokkenheid van de project belanghebbenden tijdens het ontwerpproces (Nakajima et al., 2014). De huidige ontwerpmethodologie van bouwobjecten is gericht op monteren (bouwen) van systemen en niet op demonteren daarvan (Nakajima et al., 2014). Daarnaast de ontwerpers zouden de systemen als een geheel moeten beschouwen in plaats van zich te richten op individuele componenten of producten (RSA, 2012). Om deze belemmering weg te werken, men kan gebruik maken van resource efficiënte ontwerpprincipes zoals 'ontwerp voor deconstructie' en 'ontwerp voor hergebruik of recycle'. ABN AMRO en Circle Economie benadrukken dat het toepassen van resource efficiënte ontwerp principes tijdens de ontwerpfase is een van de belangrijkste strategieën om hergebruik en recycle van resources in de bouwsector mogelijk te maken (ABN AMRO et al., 2014). Tabel 1 weergeeft de resource efficiënte ontwerpprincipes die door WRAP (2012), CIB (2014), ABN AMRO en Circle Economie (2014) zijn aanbevolen.

Tabel 1: aanbevolen ontwerpprincipes volgens WRAP (2012), Nakajima (2014), ABN AMRO and Circle Economy (2014).

Resource efficient design principles for the civil infrastructure systems
Design for deconstruction or design for assembly: it enables significant changes to be made to the civil engineering project during the course of its life.
Design for reuse and recycle: it means choosing materials that can be reused and or recycled at the end of life cycle.
Design for adaptability or flexibility: it enables significant changes to be made to the system during the course of its life.
Design for durability: it express matching materials to the planned life of the project/structure with fewer life cycle replacements and reduced maintenance cycles. This can be achieved by using materials with a long technical life cycle and less maintenance.

Naast het toepassen van resource efficiënte ontwerpprincipes, verschillende belanghebbenden van een materiaal- of productketen moeten betrokken worden bij een zeer vroeg stadium van het ontwerpproces. Om tot de meest resource efficiënte ontwerpalternatieven te komen is het belangrijk dat de perspectieven van de betrokken partijen meegenomen worden voordat het definitief ontwerp wordt vastgesteld.

Onderzoeksmethode

Zoals tot zover is geconcludeerd, gebruiken van resource efficiënte ontwerpprincipes en betrekken van de belanghebbenden van een materiaalketen tijdens de ontwerpfase zijn de belangrijkste strategieën om resource efficiënte infrastructuursystemen te kunnen ontwerpen. Naar resource efficiëntie criteria, zijn ook criteria zoals RAMS criteria en life cycle die een infrastructuur systemen aan moeten voldoen. De combinatie van al deze criteria maakt het ontwerpproces erg complex, vooral wanneer meerdere belanghebbenden worden betrokken bij het ontwerpproces. Hiervoor, er kan gebruik worden gemaakt van 'multi- criteria groep besluitvorming systemen' . In dit onderzoek Analytische Hiërarchie Proces(AHP) is gebruikt.

AHP is een multi- criteria besluitvorming analyse methode en een gestructureerde techniek die door Thomas Saaty in 1970 ontwikkeld is voor het organiseren en analyseren van complexe beslissingen (Saaty et al., 2008). In dit onderzoek, AHP is gebruikt voor het structureren en bepalen van het relatieve belang tussen de criteria. Daarnaast is deze methode gebruikt om meerdere expertises te betrekken bij het ontwerpproces en in het bijzonder bij het bepalen van de ontwerpalternatief die het beste voldoet aan alle criteria.

Case studie

Een sluisdeur is als casestudie gebuikt omdat in dit geval meerdere deskundigen en disciplines betrokken kunnen worden. Daarnaast, sluisdeur bevat hydraulische componenten waardoor functionele prestatiecriteria (RAMS criteria) kunnen worden toegepast. In het algemeen een sluisdeur wordt gemaakt van 4 materiaalsoorten waaronder: staal, composiet, beton en hout. In de case studie, 20 deskundigen werden gevraagd om hun prioriteiten aan te geven ten opzichte van projectdoel, ontwerpcriteria en alternatieven. Tabel 4 representeert de verdeling van project criteria en de definities daarvan. Daarnaast werden deskundigen gevraagd om hun relatieve belang aan te geven ten opzichten van criteria en het project doel. Het doel van het project was aangeduid als volgt: " Het kiezen van de beste sluisdeur met een functionele levensduur van minimaal 100 jaar. De poort moet voldoen aan de volgende eisen: hoge resource efficiency, hoge betrouwbaarheid en veiligheid, weinig onderhoud tijdens de gebruiksfase en lage life cycle kosten." Figuur 2 toont de hiërarchische structuur tussen de doelstellingen, criteria en alternatieven. De paarsgewijze vergelijking schaal van Saaty werd gebruikt voor het bepalen van het relatieve belang van de criteria of alternatieven [Tabel 2].

Tabel 2: Fundamentele Schaal van Saaty (2008)

Scale	Intensity of Relevance	Description
1	Same relevance	Both tasks contribute equally to the purpose.
3	A little more relevant	Experience and judging favor one task in relation to another.
5	Considerably more relevant	Experience and judging strongly favor one task in relation to another.
7	A lot more relevant	A task is a lot more strongly favored in relation to another.
9	Extremely relevant	An evidence favors a task in relation to another with the highest level of reliability.

Deelnemers Kenmerken

Het onderzoek werd uitgevoerd onder 20 experts uit verschillende disciplines. De meeste deskundigen waren afkomstig van het bedrijf Iv- Infra. Per discipline, de experts zijn bepaald door de betrokken afdelingshoofd. De meeste deskundigen hadden een minimale werkervaring van 5 jaar in hun vakgebied. De verschillende disciplines waren onder andere: RAMS managers, hydraulische ingenieurs, constructeurs, onderhoudsdeskundigen, kostendeskundige, projectleiders en de betrokken afdelingshoofden. Tabel 3 toont aantal deskundigen per discipline.

Table 3: Involved participants in the AHP survey, created by author

| Division	Number
RAMS and Contract Management	4
Hydraulic Engineers	3
Constructors	4
Maintenance Engineers	5
Project leaders	4
Total	20

De vragenlijst

De studie werd uitgevoerd door het persoonlijk leveren van de enquête aan de deelnemers, het geven van uitleg over het doel van het onderzoek en het verzamelen van de vragenlijsten na voltooiing. Het onderzoek bestond uit twee delen. Deel (I) gaf de benodigde informatie om de vragenlijst correct te kunnen invullen. Deel (II) was de vragenlijst zelf. Zoals te zien in figuur 2, het eerste niveau van de hiërarchie weergeeft het uiteindelijke doel van het project; het tweede en derde niveau verwijzen naar de hoofd- en sub- criteria van het project. Tenslotte, het vierde niveau representeert de alternatieven.

Table 4: distribution of criteria and their definition, created by author

Criteria	Description
C1- Resource Efficiency	
C 1.1 Availability	The ability to make significant changes during the course of the life cycle of a system (for example by expansion).
C 1.2 Deconstruction	The ability to dismantle/dissemble components or materials at the end of life cycle or when it is needed on any reason (for example by replacing).
C 1.3 Technical life time	The period that a material, component or machine lasts until it is worn out, (until no longer meets the required quality).
C 1.4 Reuse/Recycle	The ability to reuse, remanufacture or recycle a material or component at the end of its life cycle.
C2- R(A^{8})MS	
C2.1 Reliability	The probability that the required function is carried out under given conditions for a given time period.
C2.2 Maintainability	Maintainability refers to the possibility to maintain a system component. In this research maintenance means, the process of keeping something in good condition.
C2.3 Safety	The capacity of a system not to create damages to people or things.
C3- Life Cycle Costs	
C3.1 Design and Construction Costs	Costs necessary for design and realization of the system such as labor cost, material cost, transport cost and construction costs.
C3.2 Operation and Maintenance Cost	Cost necessary in order to keeping systems in good condition (such as: costs for corrective, preventive and predictive maintenance) and cost to keep the system functioning according to the agreed requirements during its whole life cycle (such as: cost of failures, cost of repairs, cost for spares and downtime costs).

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[8] In dit onderzoek het criterium 'beschikbaarheid' is niet opgenomen in de criteria. De mate van beschikbaarheid kan worden bepaald door criteria betrouwbaarheid en onderhoudbaarheid.
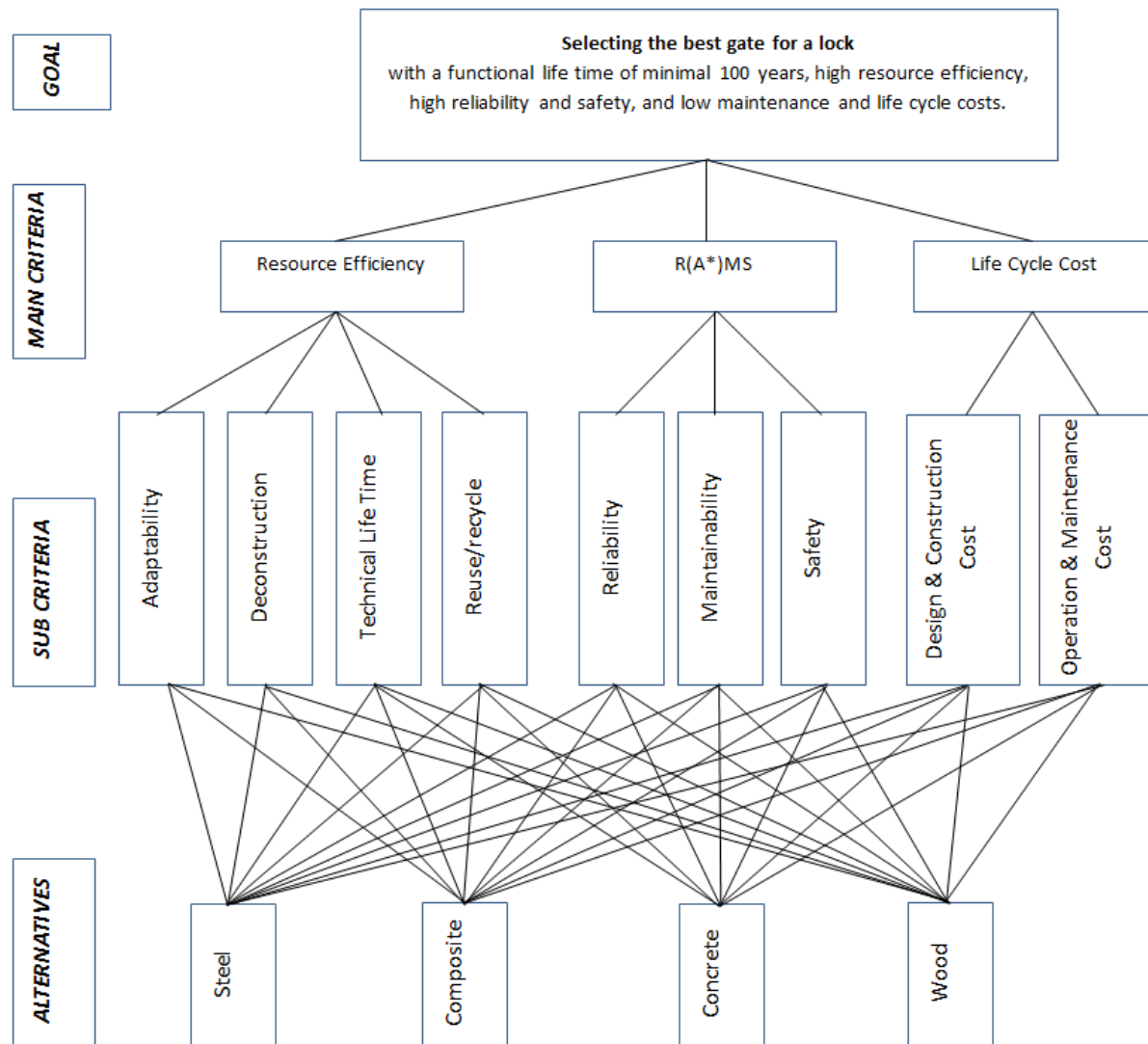
Figure 2: Hierarchy structure for choosing best gate, created by author

Resultaten

Voor de respondenten werd een consistentie ratio van 0,15 (15%) gehandhaafd. Alle 20 deelnemers hebben de vragenlijst ingevuld. In elk deel van de vragenlijst, waren aantal inconsistente antwoorden. De inconsistente antwoorden zijn niet opgenomen in de resultaten. Hieronder zijn de resultaten aangegeven.

Relatieve belang van sub en hoofdcriteria

De criteria waren onderverdeeld in drie hoofd criteria namelijk: RAMS, resource efficiëntie en LCC. Volgens deskundigen, de RAMS criteria gevolgd door resource efficiëntie en LCC zijn in chronologische volgorde de belangrijkste criteria [Figuur 3].
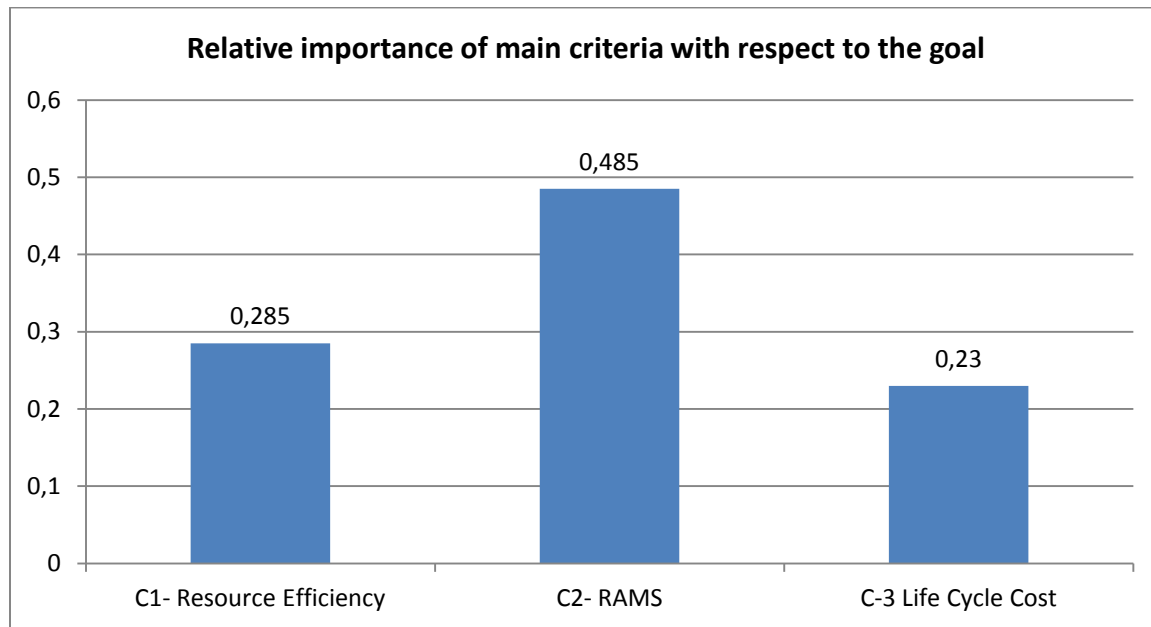

Figure 3: Relative importance of main criteria with respect to the goal

Binnen RAMS, hebben de sub criteria veiligheid en betrouwbaarheid de hoogste gescoord [Figuur 4]. Volgens deskundigen, het technische levensduurcriterium en het aanpassingsvermogencriterium zijn de belangrijkste sub criteria betreffende resource efficiëntie [Figuur 4]. Beheer- en onderhoudskosten zijn de belangrijkste sub criterium als het gaat om life cycle kosten. Figuur 20 weergeeft het relatieve belang van subcriteria ten opzichte van projectdoel.
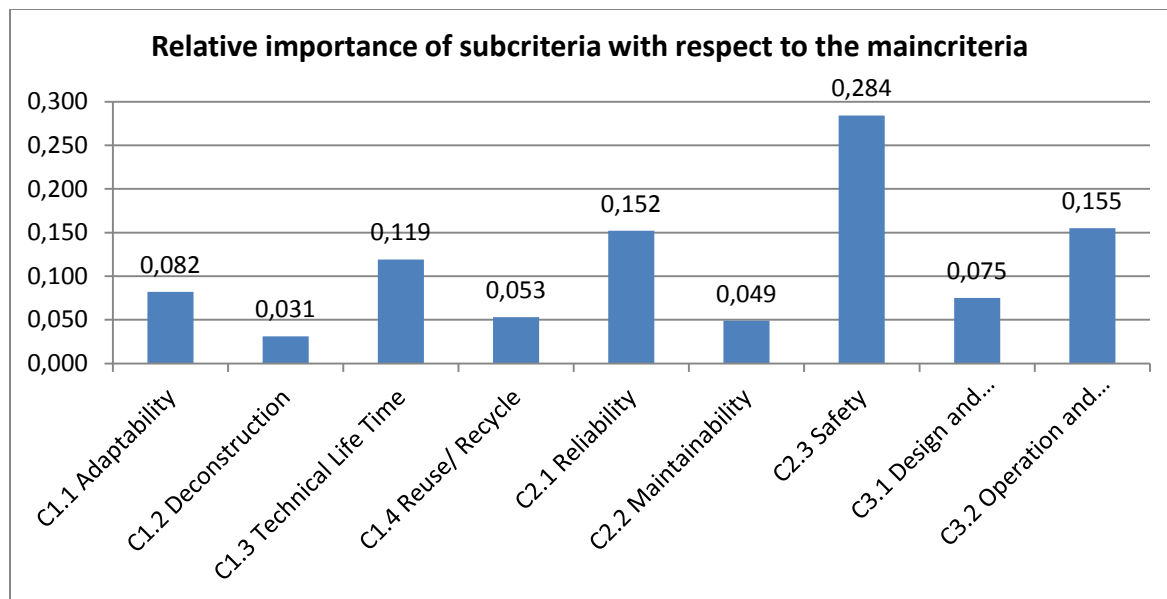
Figure 4: Relative importance of the sub criteria with respect to the goal

Wegingsfactor alternatieven met betrekking to criteria

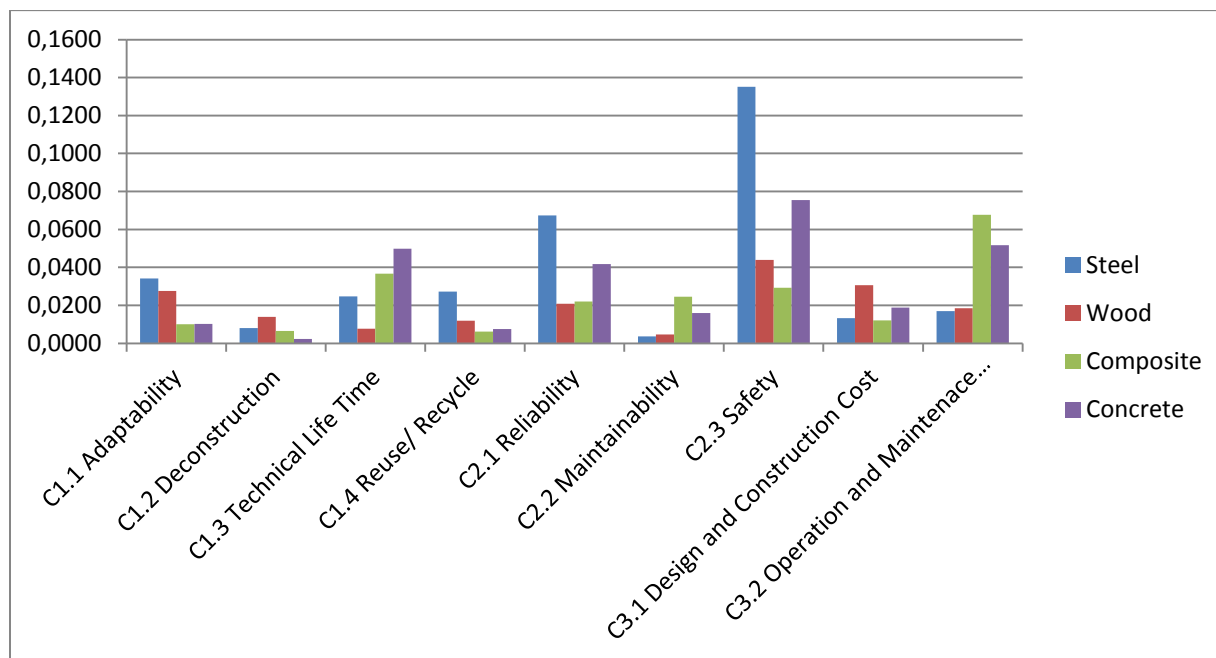Figuur 5 weergeeft het relatieve belang van elk alternatief ten opzichte van projectcriteria.

Figure 5: Relative weights of the alternatives with respect to the criteria.

Beste alternatief met betrekking tot het projectdoel

Volgens het resultaat va het onderzoek, staal scoort het beste met betrekking tot criteria en projectdoel [figuur 6]. Hou in de gedachten dat de mogelijkheden van het materiaal 'composiet' waren niet echt bekend bij de experts. Et is ook belangrijk om in gedachte te houden dat de resultaten konden anders zijn indien er meer belanghebbenden (zoals: aannemers, onderaannemers, leveranciers en of de fabrikant) betrokken waren bij het onderzoek. Tevens de resultaten konden anders zijn als de questionnaire in een gezamenlijke sessie werd ingevuld.
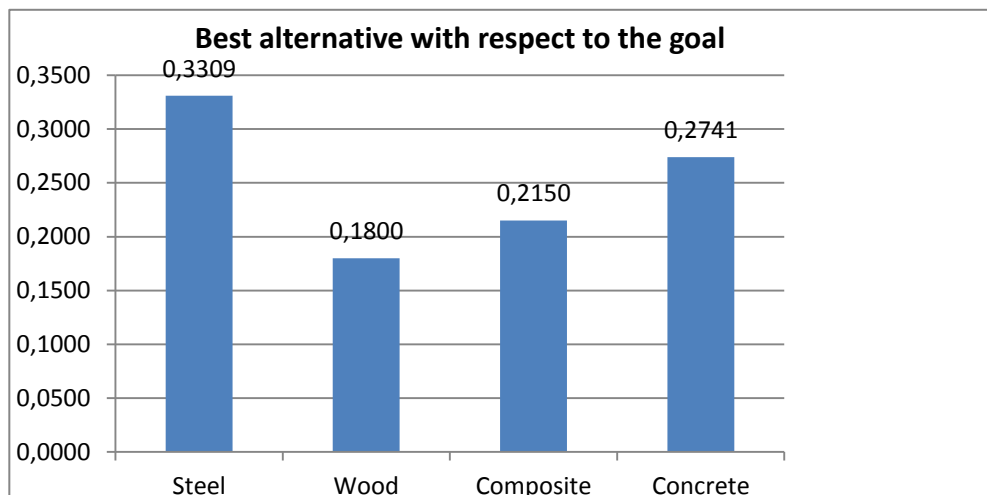

Figure 6: Best alternatives with respect to the goal.

Geïdentificeerd relaties tussen criteria op basis van de resultaten

Het is opmerkelijk dat staal en hout beide hoog gescoord hebben voor 'flexibiliteit', 'deconstructie' en 'hergebruik / recyclen' criteria. Aan de andere kant beide materialen hebben laag gescoord op 'technische levensduur', 'onderhoudbaarheid' en 'exploitatie en onderhoud kosten' criteria. Het tegenovergestelde is gebeurd met composiet en beton. Composiet en beton hebben beiden hoog gescoord voor 'technische levensduur', 'onderhoud' en 'exploitatie en onderhoud kosten' criteria en laag voor de 'flexibiliteit', 'deconstructie' en 'hergebruik / recyclen' criteria. In het algemeen, er kan worden geconcludeerd dat materialen met een lange technische levensduur minder onderhoud vergen en minder flexibel, demontabel en herbruikbaar zijn. Daarnaast het kan geconcludeerd worden dat staal en hout erg gevoelig zijn voor factoren

zoals water, zonlicht en temperatuur (interne factoren). Daarom vergen deze materialen vaak meer onderhoud dan materialen zoals beton en composiet die minder gevoelig zijn voor deze factoren. Dit wetende, het is vreemd dal alsnog in de praktijk stalen en houten sluisdeuren toegepast worden en niet beton of composiet. Een reden die voor deze keuze gebruik wordt is dat beton en composiet minder bestendig zijn (vanwege minder elastische en plastische eigenschappen van deze materialen) voor externe factoren zoals een aanvaring, hoewel dergelijke gevolgen kunnen voorkomen worden door innovatief en creatief ontwerpen.

Conclusie en verdere onderzoek

Circulaire economie introduceert een nieuwe manier van ontwikkelen en ontwerpen van producten en systemen. Een van de belangrijkste uitdagingen voor civiele infrastructuur ontwerpers is het verlengen van levensduur van infrastructuur systemen. Dit kan bereikt worden door het toepassen van materialen met een lange levensduur en of door het verlengen van levensduur van materlianen. Dit vergt kennis en informatie over materialen, materiaaleigenschappen en de factoren die de levensduur van materialen positief of negatief beïnvloeden. Een andere uitdaging is zodanig ontwerpen van systemen zodat de materialen en componenten na het bereiken van einde levensduur, met hoge kwaliteit, in materiaalstromen terecht komen. Hiervoor kunnen resource efficiënte ontwerpprincipes gebruik worden. Ook zou er nauw samengewerkt moeten worden tussen ontwerpers en de partijen in de waardeketen van materialen. Voor het verder onderzoek, er wordt voorgesteld om een besluit support model te ontwikkelen om de resource efficiëntie of circulariteit van ontwerpalternatieven te bepalen.

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Mijn naam is Javad Alizadeh, geboren in 1988 te Herat. Ik begon mijn technische studie in 2006 aan de Hogeschool Rotterdam, afgestudeerd als 'Bachelor of Built Environment' in 2010. Na het behalen van mijn bachelor, besloot ik om mijn kennis op het gebied van de bouwwereld verder te vergroten en daarnaast werken aan mijn persoonlijke ontwikkeling, managementschap en ondernemerschap. Daarom koos ik voor de brede masteropleiding 'construction management and engineering' aan de Technische Universiteit Eindhoven. Ik ben blij dat ik mijn masteropleiding met dit uitdagende onderzoek beëindigd heb. Ik wil graag iedereen bedanken die mij bij dit onderzoek heeft geholpen en ondersteund.

Opleidingen

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