TOWARDS A CLOSED MATERIAL CYCLE IN THE INFRASTRUCTURE

A Reverse Logistic network model for processing demolition waste
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A Reverse Logistic network model for processing demolition waste

H. K. Moonen

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Student number: 4080734
Master program: Construction Management & Engineering

Thesis committee:
- Prof. dr. A.R.M. Wolfert
- Dr. D.F.J. Schraen
- Dr. P.L. van den Berg
- Ir. J. Flapper

 TU Delft

 Supervisor, Erasmus University

 Daily supervisor, Antea Group

 TU Delft

 antea group
Sustainability has always been my field of interest. Therefore, I enjoyed to do my research about circular economy in the construction sector, which I think is a very current issue. The construction sector has still a long way to go when it comes to sustainability and hopefully I can contribute a little in this in my future career. In these final months of my study, I have learned a lot. Among others, I have learned how to conduct a research, writing a thesis and how to use the linear programming technique.

Writing this thesis has been a journey with ups and downs. Without the help of some persons this research would not have been conducted (or at least, it would have taken longer and it would have been harder). Therefore, I would like to thank the following people:

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Hanna Moonen
Delft, November 2017
The construction industry is a large generator of waste. The interest in improving the resource efficiency is growing. A move towards a Circular Economy (CE) has been assigned as the solution for a more efficient use of resources in the construction industry. The aim of a circular economy is to create a system in which waste and energy leakage is minimised and resource input is avoided by closing the material and energy loops. Despite the advantages of CE, the construction industry has not yet made a significant step towards the CE. The main obstacle that keeps the industry from the transition is the financial uncertainty. The theory of Reverse Logistics (RL) could be the solution to overcome this obstacle. RL in the construction sector is defined as the management of collecting, sorting, processing and reusing construction waste. In the field of RL, quantitative models have proven to be a successful tool to combine environmental goals with financial constraints. However, such models are missing in the field of construction industry. In this context, this research proposed a general applicable RL-model that supports decision-makers in implementing circular principles in the return flow of their assets while minimising the costs. Because the construction sector is a large sector, the focus in this research is on the infrastructure.

Literature review has been conducted to obtain a theoretical framework for the model design. The first part of the literature study has provided a framework to prioritise different waste management strategies based on their level of circularity. The second part of the literature study has been conducted to get an insight in the characteristics of the reverse logistics in the infrastructure and how the principles of circular economy can be included in the RL-process. The fundamental characteristics of the reverse logistics in the construction industry are the high level of fluctuation of the reverse material flow, the immobility of assets and the large volumes of material flow. The consequence is that it is not possible to design a fixed network which is applicable for every project. Moreover, the high level of fluctuation of the reverse material flow results in the mismatch between demand and supply of materials. The most suitable modelling approach for the proposed problem has been found to be linear programming.

The proposed RL-model has been designed as a transshipment model and is based on mixed integer linear programming (MILP). A transshipment model enables to match the demand and supply of the reverse flow by setting flow constraints. The proposed model design simulates the reverse flow of one asset moving from a deconstruction project, through the processing facilities to the final redistribution. The proposed model has been complemented by a guideline that supports the application of the model for specific cases. This guideline includes, among other, the inventory of the specific process and assigning levels of circularity.

To test the applicability of the model and the proposed guideline, the model has been applied on two different types of assets in the infrastructure: concrete and street lights. The steps proposed in the guideline have been followed to obtain the right structure of the RL-model that fits the asset. The model for both cases have been run for multiple scenarios, based on the developments in the industry. Both cases were found to fit the proposed structure of the model. However, some adjustments on the mathematical formulation had to be made for the street lights case. The results of the model provides two types of information. Firstly, it provides a trade-off between the level of circularity and the costs. Secondly, it gives the corresponding network-design for the different outcomes. It was found that technical innovations in combination with an efficient network design will help to create return flow in the infrastructure, according to the principles of circular economy, which is financially feasible.

Overall the model has been proven to be general applicable and it supports decision-makers in making decisions about the reverse flow. The outcome gives information about the financial impact on implementing circular principles. The corresponding RL-network provides an insight in which aspects in the RL-process have a large influence on the outcome.
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Material consumption is a big concern in the construction industry. More than 50% of the resources in the Netherlands are used in the construction sector. This high consumption rate has several negative environmental consequences. The extraction of primary resources to produce these construction materials puts a pressure on the environment (Rijkswaterstaat, 2015). The earth has a finite amount of resources available which means that extracting raw materials cannot continue forever (MacArthur, 2013). Harvesting and processing of the materials in the construction industry requires a lot of energy. The construction industry is responsible for 4.5% of the energy used in the Netherlands (CE100, 2016). Moreover, the high consumption level results in the fact that the construction industry is a large generator of waste: in 2014 was the construction industry is responsible for about 40% of the waste generated in the Netherlands (Rijkswaterstaat, 2013).

The interest in improving the resource efficiency is growing in the European Union. The European Commission started an initiative to promote a more efficient use of resources in the construction industry. In their mission statement, they propose a set of alternatives to reach the goal of reducing energy consumption and the use of resources. This initiative is part of the ambition of the European Commission to move towards a circular economy (European commission, 2017). The principle of the circular economy (CE) is based on the eco-system. In the eco-system, there is no landfill: one specie’s waste is another specie’s food. Circular economy aims for rebuilding capital, which can be financial, manufactured, social or natural (ING, 2015).

Today’s economy is a linear economy. The limits of the linear approach of resource consumption, which is based on “take-make-dispose” becomes more visible (MacArthur, 2013). In a linear system, the resources are extracted from the earth and placed in the economic system. At the end of its lifetime it will be detached from the economic system as waste. This linear way of living results in serious problems which the world is facing currently. The climate change, ozone layer depletion and the exhausting of resources are all linked with this linear way of thinking (MacArthur, 2013). Figure 1.1a and 1.1b show the differences between a linear and circular economy.
The need to move towards a CE in the construction industry to reduce the construction waste has also been adopted by private and public institution on national level. Different “Green Deals” have been signed between the government and companies since 2011 to support circular innovations (Green Deals, 2017). These deals are with all kinds of sectors and all different approaches to reduce energy and material consumption. There are different approaches for applying the principles of CE to reduce the material consumption in the construction industry. The lifespan of an asset can be extended, designing assets and organising waste management according the circular principles. Waste management according the circular principles involves reusing materials after demolition so that the material cycle will be closed which results in an elimination of waste. Applying the principles of CE in waste management of construction materials could lead to large gains. The benefits of designing according to the circular principles will be visible on the long term while while waste management pays off on the short term (Rijkswaterstaat, 2015).

1.1. Problem context

Despite the fact that the urgency of reducing material consumption have been gaining interest by the governance and businesses world, the construction industry has not yet made a significant step towards the CE. Different researches have been executed to address the challenges the construction industry faces in closing the material cycle and therefore becoming circular. The construction industry consists of expensive assets and moves therefore slowly when it comes to innovation (Doepel, 2015). The construction sector exists of long-lived assets and the circularity potential of these long-lived assets has gone untapped (MacArthur, 2013). Kok et al. (2013) has classified the obstacles of moving towards a circular economy in institutional, economic, technological, infrastructural and societal aspects. The main obstacle is a combination of the different aspects. Implementing circular principles in the construction waste management requires investment. Recycled materials have often a higher price than virgin materials due to the costs of collection and the low quality of the recycled materials. Deconstruction may cost more than demolition due of the higher labour costs and the more time that is required (Calkins, 2009). Materials from a de-constructed structure need to be stored until they can be reused in new structures. Storing materials off-site involves costs for transport and storage. These investments for transport and storage have a large risk due to the unknown residual value of used products. Without demand of used products, the value of the of the products will be zero. The problem of the construction sector there is not yet a scarcity which helps to increase the demand of used products (Rijkswaterstaat, 2015). The low demand of used products is also a result of the lack of confidence in the quality of used products and therefore is primary materials often more favourable (Ecorys, 2016). According to Kok et al. (2013), the reason for the undeveloped market for second-hand products is because a reverse collecting system which is cost-efficiency, user friendly and of a high quality is missing. Such a reverse collecting system can accelerate the development of a market for secondary resources.

1.2. Problem statement

The principles of CE have not yet been implemented on a large scale because it does not fit in the current systems of the construction waste management. The financial risk is too high due to the undeveloped take-back system. The following problem statement can be defined:

“Closing the material cycle in the construction industry is financially not feasible due to the lack of a fully developed reverse collecting system

According to (Doepel, 2015), the transition towards a circular construction sector will start at the logistics of demolition, storage and supply of used products. Therefore, the potential solution for the proposed problem can be found by using the theory of reverse logistics (RL) in the construction industry. Implementing RL in the construction industry could accelerate the transition towards a circular construction sector (CE100, 2016). RL in the construction sector is defined as the management of collecting, sorting, processing and reusing construction waste Sobotka and Czaja (2015). It can be applied to increase the high-value reuse and recycling in the construction industry. RL enables the implementation of CE in the construction industry by supporting reuse, repair, re-manufacturing and recycling. Reverse logistics has been emerged in different industries as a successful measure to address environmental concerns and also results in cost savings for the organisation Hosseini et al. (2015). It provides possibilities for new jobs and specialists. Therefore, RL can be defined as an economic opportunity. Cost savings can be found in the reduction of transportation of virgin
1. Introduction

materials to building sites, because second-hand materials can be found in a shorter distance. It will also reduce the cost associated with the landfill of construction waste. (Hosseini et al., 2015). Another economic benefit of closing the material cycle is that companies become less sensitive to price volatility of resources. It will result in a more stable market (Kok et al., 2013).

1.3. Research gap

Although RL has gained high attention in other sectors, there is a lack of studies that propose an application of RL in the construction industry. Due to the unique nature of the construction industry, there is not one RL-system which fits all projects Sobotka and Czaja (2015). There is a lack of studies to throw some light on financial aspects surrounding the RL in the construction industry Hosseini et al. (2014). (Sobotka and Czaja, 2015) conclude that there is a need of spreading the knowledge about the application of RL in the construction industry. Different researchers pointing out there is a need of developing a decision support system/tool for the reverse flow of goods (Ripanti et al., 2015) (Sobotka and Czaja, 2015). A general applicable RL-model that supports decision making in construction projects of a unique nature should be developed (Cardoso et al., 2013) (Sobotka and Czaja, 2015). There are many researches which focus on developing RL-models. However hardly any of these models are designed for the construction industry. Applying RL to accelerate reuse and to assist reduction of demolition waste is an overlooked area in the construction industry (Hosseini et al., 2015). Studies on RL in the construction industry do not focus on the development of a RL model. The most studies try to identify the challenges and potential benefits of adopting RL in the construction industry (Hosseini et al., 2014) (Schultmann and Sunke, 2007). Aidonis et al. (2008) is one of the few that has developed RL-model for the construction industry. The aim of the proposed model is to support decision making on what quantity of demolition waste will be recycled and what quantity will be send to landfill. It does not include the different types of recovery, which is essential for circular economy. The model does also not take into account the uncertainties involved in a reverse flow. Hence the recommendation of the researcher is to further develop the model and thereby considering fluctuations of the market (e.g. demand & supply) and adding meaningful environmental constraints (Aidonis et al., 2008).

1.4. Research objective

According to (Wang and Hsu, 2010), the improvement of both economic and environmental performances are one of the key aspects in a closed material cycle. The general objective of this research, following from the literature review, is to explore how the RL in the construction industry can be organised according to the principles of CE while taking into consideration the financial feasibility. The aim of the research is to develop a general model which supports decision-making in the infrastructure. The model should support stakeholders in reaching their circular goals while minimising the cost. The practitioners should benefit on different levels of the implementation of the circular economy, which will create the incentive for change. This tool will help practitioners in finding the best approach to create an economically feasible closed material loop, while dealing with the uncertainties of the market and the environmental constraints. In order to achieve this, firstly, a general applicable model should be designed. Secondly, the study should identify how the obtained model can be implemented in the practise of the construction industry. Therefore, guideline should be provided that will support decision-makers in applying the model in practise.

The research will focus on the whole process from demolition to the new application of the construction material. For all the decisions that can be made during the process, the potential of implementing the circular principles should be taken into consideration. This means that the circular principles are integrated in the whole process and has an effect on every level.

In order to make a model, it is important to study the key factors of CE and RL in the construction industry. This study should explore the relation between these two aspects and investigate how RL can accelerate the transition towards a circular construction industry. The research will focus on the whole process from demolition to the new application of the construction material. For all the decisions that can be made during the process, the potential of implementing the circular principles should be taken into consideration. This means that the circular principles are integrated in the whole process and has an effect on every level.
1.5. Research questions

The research objective and goal, lead to a research question. The goal can be summarised as the development of a tool that is applicable in the construction industry and will support decision makers by making the right circular choices in the process of waste management by using the principles of RL. To reach the goal of this research, the following research question needs to be answered:

*How to create a return flow of assets in infrastructure, according to the principles of circular economy, which is financially feasible?* How to create a return flow of assets in infrastructure, according to the principles of circular economy, which is financially feasible?

To find the answer to this question, more knowledge needs to be obtained about circular economy, reverse logistics and on the current practise of waste management in the infrastructure. Therefore, the sub-question have been defined. The following sub-questions will guide this research to the final answer of the research question:

1. What does circularity means in the infrastructure?
2. What are the characteristics of RL in the infrastructure?
3. What is the current practise of the waste management and were lie the opportunities and obstacles to change this practise?
4. How can RL contribute in overcoming the obstacles of implementing CE in the infrastructure?
5. What are the critical components to create an financially feasible reverse supply chain?
6. How can the proposed solution be general applicable for all kinds of assets in the infrastructure?

The first two questions are meant to provide knowledge on the two theories which this research is based on and to understand the obstacle and opportunities of introducing these theories in the infrastructure sector. The third and fourth question will contribute in setting a framework for the proposed model. Combining the two theories and placing it in the practise of waste management will provide a solution space. The fifth question helps to identify the success factor of a system. The last question is drafted to ensure that the proposed solution applies for infrastructure projects in general.

1.6. Scope

The construction industry is very large and includes all types of industry. It has been stated that the construction industry is known for its unique nature of each project. The focus on this research, as stated in the research question, is on the infrastructure. The aim is therefore to find a solution which is applicable for infrastructural projects in general, but is not by definitions applicable for other projects of the construction industry, like building projects. Besides, the geographical scope is the Netherlands. Therefore the Dutch practise and regulations of infrastructural projects will be taken into consideration. The goal of this research is to provide a model which supports practitioners in implementing the principles of CE in demolition projects. Different actors are involved who have all different interests and have to make different kinds of decision. Therefore, the choice has been made to have the owner of the asset which needs to be demolished as the central actor, for who the model will be applicable.
1.7. Research design

The research strategy and design should fit the research objective and research questions. It should be the most efficient way to find the intended answer (Oost and Markenhof, 2014). The strategy describes the approach on how to conduct this research and the design in the result of this strategy.

1.7.1. Research strategy

The result of this research should be general and widely applicable. This research will not be conducted to find an answer for one specific case, but aims to find a solution for a general problem. Therefore, this research can be defined as a quantitative research. In a quantitative research, the variables are related to answer the research question (Creswell, 2014). The strategy used in this quantitative research is divided in three parts.

Primarily, a desk research will be executed. The main characteristic of this approach is that existing material is used in combination with reflection. There will be no direct contact with the research object (Verschuren and Doorewaard, 2010). The aim of this strategy is to develop a theoretical framework. The essence of this method is to compare and reflect on existing theories and materials. This strategy will be applied for addressing research questions about the current situation and the desired state. This strategy involves studying literature of other logistic models which serve the same simulation goals and comparing them. Also, studying theories about the optimisation of the material flow in the infrastructure. The desk research will also be executed to select the modelling approach that fits best the objectives of this research. The desk research obtains theoretical knowledge which will be applied in the second part of the research, it provides a framework from where the model can be designed.

The aim of the second part of the research is to make a general design. A general design will be made for a model which simulates the logistic flows. The desk research will provide the input for the applied method and the aspects that should be included in the design. Besides the model design, a guideline will be developed for the application of the model. The result of the second part is a model that should be help to overcome the proposed problem and a guideline that will help to apply the model in practise.

The strategy for the third part of the research will be the execution of an experiment. This approach is suitable to acquire experience with newly created situations. An experiment will provide information about whether a specific treatment influences an outcome (Creswell, 2014) or not. The experiment approach has several variants and in this research one of the variants will be applied. This variant involves the simulation of the reality, in this case by doing a computer simulation. The advantage of a simulation is that it is easy to make variants in the model and that the effects can be measured in a limited time span. The disadvantage of a computer simulation is that it is not a complete reflection of the reality, as it only considers what is programmed (Verschuren and Doorewaard, 2010). The outcomes of the first parts of the research will be the input for the experiment. A simulation is useful to discover the most suitable solutions for optimising the system. The obtained model and guideline will be tested. The aim is to validate the model and the proposed guideline. To be able to draw a general conclusion, the model and the guideline will be tested on two varying assets in the infrastructure. The proposed guideline will be followed to obtain input for the model. This will be done by consulting experts in the field of the two assets.

The outcome of the experiments will be evaluate. Conclusions will be drawn by reflecting the outcomes on the research objectives and the theory.

1.7.2. Research outline

The structure of the thesis follows the structure of the research strategy. Figure 1.2 links the research strategy to the thesis outline. The second chapter is the theoretical framework. The third chapter described the development of the model design. In the fourth chapter the the proposed model will be tested. This will be done on basis of two test cases. The fifth chapter discusses the outcome of the test cases. The final chapter provides the conclusions, based on the findings, and recommendations for further research.
Figure 1.2: Research design
2 THEORETICAL FRAMEWORK
The introduction provided an outline of the current problem and proposed a research question that needs to be answered. In this chapter the key concepts of this research will be explained and theory that will be used to solve the proposed problem will be discussed. The goal of this research is to create a model that could support the optimisation of circularity of processing assets in their EoL phase while minimising the costs. The theoretical framework forms the base for the model design. The chapter starts with the explanation of the principle of circular economy in the EoL phase of assets in the infrastructure. The relation to the current waste management and what circularity means for assets at the EoL phase is also discussed. The chapter continues with an elaboration on the theory of reverse logistics. The key principles of reverse logistics in the construction sector will be identified. Moreover, it will be explained how reverse logistics can be the enabler of circular economy. The part ends with the key aspects of RL in the sector that should be taken into consideration in the model. The third part of the chapter will discuss the right modelling approach to solve the problem. The principles of CE, the characteristics of RL and the modelling techniques will form together the framework for the model design.

2.1. Circular Economy

Geissdoerfer et al. (2016) defined the following definition of CE based on literature review:

“Regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, re-manufacturing, refurbishing and recycling.”

The concept of circular economy has been introduced already in the 1970’s, where different researchers emerged the limits of resources and the need to create an economic system which is based on cycles. The researchers came to the insight that when the consumption of the world population continues to increase, this would lead to major problems. CE became widely known when it was introduced by the Ellen McArthur Foundation in 2010 (MacArthur, 2014). The aim of CE is to decouple economic growth and development from the consumption of finite resources. The goal is to create a system in which waste and energy leakage is minimised and resource input is avoided by closing the material and energy loops. In a circular world, there is...
no waste because all the residual streams are seen as resources and no primary resources are needed (Geissdoerfer et al., 2016). When closing the circularity by using waste as resources, value lost should be avoided as much as possible. This circular world requires a new way of thinking, designing, producing and consumption. The concept of CE can be best explained by the figure of the Ellen McArthur Foundation, figure 2.1. In a circular system, a distinguish is made between the nutrient cycle, which can be returned to the biosphere, and the technical cycle, which are based on finite resources.

![Figure 2.1: The principle of CE (adapted from MacArthur (2014))](image)

The figure shows on the right side how the materials cycle through the economic system. Different cycles have different characteristics on how materials re-enter the system. The inner circle is favourable over the outer circle because the smaller the circle the less cost, effort and energy is used (MacArthur, 2014). Creating a system with only closed material cycles requires a different economic system and a redesigning of current business cases. The current system is based on the linear principles and a transition requires a new approach (MacArthur, 2013).

### 2.1.1. Circular Economy at the End-of-Life phase in infrastructure

As has been stated in the introduction, the construction industry is a large generator of waste, \( CO_2 \) emission and uses a large amount of primary resources. Therefore the benefits of creating a circular construction industry would be very high. The aim of the the circular economy is obtaining a closed material cycle.

The construction sector is a large generator of waste and it uses a large amount of primary resources, which means that there is a large amount of resources that does not stay in the system. Therefore a transition towards a circular construction industry means a reduction in the throughput of resources. Reducing the throughput implies the decrease of primary resources input and waste output in the life cycle of an asset (Van Ewijk and Stegemann, 2016). This is shown in figure 2.2.
From the figure it is clear that throughput reduction can be obtained in different phases of the life cycle of an asset. The figure also shows the relation between the input and the output. Output reduction can be a consequence of input reduction, because waste output arises from the input of primary resources. On the other side, the reduction of primary resources input can be the consequence of the output stream (Van Ewijk and Stegemann, 2016). Good management of the output stream can create the possibility to use secondary resources in the design and construction phase.

The input of primary resources will take place in the design and construction phase of the life cycle, while the output is at the End-of-Life (EoL) phase. This means that demolition waste should be processed in such extent that it can re-enter the system.

Planbureau voor de leefomgeving (2016) emphasize the distinction that should be made between the existing stock and new products. For new products it is important to include the circularity in the design & construction phase (input), which can positively influence the EoL phase of the product. There are many opportunities to include circularity in new products. The current stock is often not designed and constructed while taken into account the principles of the CE. For the current stock the window of opportunities for CE is much smaller than that of new products. The possibilities of implementing CE in the current stock lies in the EoL phase of the product. A solution should be to find how to manage the end-of-life phase of the current stock to the extent that it positively influences the design and deconstruction phase of future projects. The current stock is a mine of valuable resources and the waste is a loss of value (Planbureau voor de leefomgeving, 2016). The aim is to leverage this great opportunity. As stated in the introduction, the construction industry is responsible for about 40% of the waste stream in the Netherlands, which means that there is an enormousness loss of value. Maximising the use of the demolition materials and components supports the circulation and minimises the need for primary resources (Ecorys, 2016).

2.1.2. Circular Economy in the current practise of waste management

The need of addressing the EoL phase of an asset in order to move towards a circular economy has been adopted by the sector. Because of the high impact of the sector on the environment, the construction industry is one of the priority sectors of the European Union for the transition towards a CE (European Environment Agency, 2016). This is stated in the Circular Economy Package, which is adopted by the European Commission and is translated to a circular action plan. The key of moving towards a circular construction industry, according to the European Commission, is the waste and \( CO_2 \) emission reduction. According to the European Commission, there are large gains to be made in identifying, collecting and recovering valuable materials at the EoL phase of assets in the construction industry (European commission, 2017). Therefore the commission proposed a non binding guideline on construction waste to support the transition of CE in the construction industry. The opinion of the EU is that a good waste management is the key for a circular construction industry. The major issue that needs to be overcome, according to the commission, is the lack of confidence in waste management and the trust in the quality of recycled materials. The proposed guideline will lead to good waste management and will therefore help to overcome these obstacles. According to the
protocol, good waste management in the construction industry can be achieved by improving:

- waste identification, source separation and collection
- waste logistics
- waste processing
- quality management
- policies and framework conditions.

(Ecorys, 2016) The protocol provides guidelines for different actors in the construction sector. The guidelines that help to improve the first three points are meant for the practitioners of the construction waste industry. The guidelines that help to improve the latter two points are meant for policy makers and governance. The approach of the protocol is therefore to improve the waste management on two levels. On the one hand, improving the practise of processing waste can lead to higher quality of the processed materials which can increase the rate of reuse of construction waste. On the other hand policies and regulations can influence the practise of waste management. For example, raising taxes on landfill and primary resources could create an incentive for the market to aim for more recycling of their waste (Ecorys, 2016). This non binding guideline can contribute in reaching the target set in the Waste Framework Directive which states that by 2020 70% of the construction and demolition waste needs to be re-used, recycled or recovered (Directive, 2008). The Netherlands have even set a more ambitious goal of a recycling percentage of 95% (Circle Economy, 2015).

The Dutch government wants to contribute in realizing the ambition of the European Union and therefore, proposed the programme “the Netherlands circular in 2050”. In this programme, special attention is given to the construction industry. The Dutch government tries to innovate the construction industry by entering into “Green Deals” with the market participants. Innovation and chain cooperation is the key of a successful transition towards a circular economy. The “Green Deal Cirkelstad” focus on the recycling and reuse of demolition waste in the construction sector (Ministerie van Infrastructuur en Milieu, 2016).

2.1.3. Level of circularity

The transition towards a circular construction industry can be realised by processing waste in such extent that it will re-enter the system. However, there are different levels of circularity to obtain and therefore different ways the materials re-enter the system can be distinguished.

Figure 2.1, at the beginning of the chapter shows multiple cycles of different sizes that all represent materials that re-enter the system. The larger the cycle, the more cost, effort and energy is used to get the material back in the system. These cycles show that there is a level of priority on how the materials will re-enter the system. Only focussing on processing waste that can re-enter the system, without taking into account the size of the cycle, is not enough for the transition towards a circular economy. The key concern of implementing CE in the construction industry is avoiding losses. To get a better understanding of what this means, an example from the concrete sector is presented. More than 95% of the concrete is being reused. However, almost everything of the concrete waste will be used as foundation under road constructions (Rijkswaterstaat, 2015). The consequence is that for the production of new concrete constructions, primary resources are needed. The concrete which is used for foundation purposes has lost its value as concrete and is called "down cycling”. This "down cycling” cannot be defined as circular because the aim of CE is preserving the residual value of return materials (CE100, 2016). Value preservation is one of the key enablers for a transition towards a circular infrastructure industry. Value preservation results in less input of primary resources because value preservation aims for keeping the same functionality and therefore prevents losses. Weighting the different ways how materials re-enters the system against each other results in some kind of hierarchy between the different end-of-life(EoL) strategies. There are different theories which establishes a priority order for waste treatment methods. The priority order for waste management is based on environmental impacts and fewer natural resources (which is the result of value preservation) (Planbureau voor de leefomgeving, 2016).
Theoretical framework
The Waste Framework Directive has three principles of waste hierarchy that should be applied as priority order in waste prevention and management:

1. prevention;
2. re-use & recycling;
3. improving and controlling final disposal.

(Directive, 2008)

The aim of waste management is to reduce the environmental impact. The high value preservation is important because less primary resources will be needed for the following cycle. This reduces the environmental impact.

There are many extensions and variance on this hierarchy, the so called R-models. All these models are similar and the main difference between the models is the amount of “R” included. The origin of the waste hierarchy is the “Ladder van Lensink”, introduced by a Dutch politician in 1979 (Planbureau voor de leefomgeving, 2016). The hierarchy in these R-models is based on the decomposition of the asset. The more an asset needs to be decomposed before it can be reused, the larger the cycle will be and therefore the less preferable. The different levels in decomposition is shown in figure 2.3.

For this research, the 10-R model of Prof. dr. Jacqueline Cramer is adopted (Cramer, 2014) This model, which is presented in figure 2.4, consists of 10 different levels of circularity. R0 to R2 do not apply for the EoL phase and waste management. R3 to R9 are in the scope of this research because all these levels are potential strategies for demolition materials.

The differences between the strategies in the hierarchy are small. The column next to the strategies provides the definition of the strategies. The difference lies in the adjustments that are made on the original product. The aim of the priority is to keep the original product as much as possible in the original form. The hierarchy goes from reuse on product level to the reuse on component level and the final stage is the reuse of energy which is generated by the incineration of the materials.

The list is easily to apply from the first glance, but the utility of the waste hierarchy as a guideline for waste management is not so straightforward as it might look.

Article 4 of the Waste Framework Directives says the following about the hierarchy: “The waste hierarchy generally lays down a priority order of what constitutes the best overall environmental option in waste legislation and policy, while departing from such hierarchy may be necessary for specific waste streams when justified for reasons of, inter alia, technical feasibility, economic viability and environmental protection.”

(Directive, 2008).

Article 4 does not give clear direction on the application of the hierarchy and leaves room for interpretation. According to Van Ewijk and Stegemann (2016), there are some limitations about the usefulness of the hierarchy in practise. One limitation is the doubt about the value of the hierarchy with regard to minimising environmental impacts and the use of primary materials. There is sometimes a contradiction between the two aspects which defines the priority level of the strategies: avoiding environmental impacts and using natural resources. The recycling process and transport causes sometimes more harm to the environment than fabricating primary materials (Haas et al., 2015). Besides, the interpretation of the hierarchy very much depends on the sector, product type and the scale (Van Ewijk and Stegemann, 2016).
The hierarchy informs the users in the direction rather than the end goal that should be reached. Therefore, the hierarchy provides a framework for stimulating circular thinking and decision-making rather than strict directions. With this in mind, the 10R model will be used as a framework for prioritising the waste management strategies and not as a strict hierarchy.

Further guidance for defining how circular different options of waste processing are, can be obtained by looking at the definition of circular economy. Three aspects arise from this definition that together identify the goal of CE:

1. Reducing leakage (material and energy)
2. Minimising CO\textsubscript{2} emission
3. Value preservation

Prioritising the waste management strategies can be done by taking these three goals in mind and to evaluate to which extent the waste management strategy contributes in reaching the goal of CE. Therefore, it is important to take the whole life cycle into account. This implies that for example a particular processing approach can have more CO\textsubscript{2} emission than another, but it is still the most favourable option because it will lead to an enormous CO\textsubscript{2} emission reduction in another phase of the life cycle. Moreover, taken these three aspects into account next to the 10R-model it will result in different types of trade-offs that will be made. For example, creating closed material cycle on regional scale becomes a more circular option when considering the three aspects instead of only the hierarchy from the 10R model. Moreover, closing the cycle on a regional scale is one of the drivers of the transition towards a circular construction industry (Kok et al., 2013).

---

<table>
<thead>
<tr>
<th>R0</th>
<th>Refuse</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Reduce</td>
</tr>
<tr>
<td>R2</td>
<td>Re-design</td>
</tr>
<tr>
<td>R3</td>
<td>Re-use: Re-use the same product by a different owner or other place.</td>
</tr>
<tr>
<td>R4</td>
<td>Repair: Repair and maintain a product so it can have the same functionality</td>
</tr>
<tr>
<td>R5</td>
<td>Refurbish: Restore modernize old products.</td>
</tr>
<tr>
<td>R6</td>
<td>Remanufacture: Use components of discard products for new products with the same functionality.</td>
</tr>
<tr>
<td>R7</td>
<td>Re-purpose: Use components of discard products for new products with different functionalities.</td>
</tr>
<tr>
<td>R8</td>
<td>Recycle: Process components to obtain the same or lower quality</td>
</tr>
<tr>
<td>R9</td>
<td>Recover: Burn the materials and generate energy</td>
</tr>
</tbody>
</table>

Figure 2.4: 10-R Model
2.2. Reverse Logistics

According to the Ellen McArthur Foundation, reverse logistics is one of the key enablers for CE (CE100, 2016). It should help to overcome the obstacles of implementing the principles of CE in the EoL phase of assets in the infrastructure. This paragraph elaborates on the theory of reverse logistics. First an explanation will be given on what RL exactly is. This is followed by a further explanation on how it can be the enabler of CE. RL is proven successfully in the manufacturing industry. In order to understand the application of RL in the construction sector, the characteristics will be compared with those from the manufacturing industry. Multiple researches have been conducted to point out the characteristics of RL in the construction sector. The aim of this research is to design a RL-model that supports decision-making in the infrastructure. Therefore, this section will end with discussing the theory on RL-model design. This will be based primary on the theory of Brito & Dekker (2014).

2.2.1. The characteristics of Reverse Logistics

There are many definitions for "Reverse Logistics" and they all have slightly different perspective on the essence of reverse logistics (De Brito and Dekker, 2004). For this research, the definition of the European Working group is used. The European Working Group on Reverse Logistics states the following definition of Reverse Logistics (RL):

"The process of planning, implementing, and controlling flows of raw materials, in-process inventory, and finished goods, from a manufacturing, distribution or use point to a point of recovery or point of proper disposal" (De Brito and Dekker, 2004). Where Forward Logistics(FL) involves the movement of materials from point of origin to the point of consumption, concentrates RL on the movement of materials from the point of consumption (end user) back to the market. Therefore, RL can not be seen as literally the reverse of the forward logistics (Hosseini et al., 2015). RL and FL together form the whole supply chain, which can be an open or closed-loop. The boundary between FL and RL is not always clear, because it is not always clear what the point of origin is or who the end user is (De Brito and Dekker, 2004).

The concept of RL has been developed in the manufacturing industry primarily to manage the products which were returned by the customers to the producer. RL was focused on solving problems when something goes wrong: consumers change their minds, the product is broken, etc. It was not intended as a systematic system which would standard be applied (Snyder, 2010). Only from the 1990's, RL has been recognised as an important part of the logistics which can be from great benefit for companies (Colligan, 2015).

RL does not only cover the collection and transportation of EoL materials, it also covers the value added activities which supports the re-entering of materials back in the system and therefore closing the loop CE100 (2016). The aim of RL is to collect and recover products to an extent that the recovered product obtains value and can re-enter the supply chain (De Brito and Dekker, 2004).

The activities included in the RL process are illustrated in figure 2.5. The first step is the collection of the materials, which involves bringing the products from the consumer to a central point. This activity follows by the inspection of the products and, based on the quality and the characteristics of the material, a decision will be made about the type of recovery. Recovery activities can be divided in two types: direct recovery and reprocessing activities. Reprocessing activities involves a more comprehensive process. The final activity is the distribution of the recovered materials. The type of distribution depends on the outcome of the recovery activity (De Brito and Dekker, 2004).
In the previous section, the term “waste management” has been used. Although waste management and RL are closely related, there are some differences which are worth mentioning. Waste management only includes the management of waste streams, while RL can include any type of streams. Moreover, waste management focuses on reducing the environmental impact of waste streams and RL focuses on both the environmental impact and the economic gains (Hosseini et al., 2014). Other studies, propose a RL-network to support the management of waste (Nunes et al., 2009). This will also be the approach in this research. To understand why and to what extent the principles RL can be applied in the infrastructure to support the transition towards a circular industry, it is important to get some insight in the principles of RL in the infrastructure.

**Waste management versus reverse logistics**

Some researchers state that one fundamental difference is that RL focuses on streams where there is new value to be recovered, while waste management only deals with streams without a potential value (De Brito and Dekker, 2004) (Hosseini et al., 2014). The waste framework directive contradicts this definition by including the waste hierarchy (in which the value recovering and preservation are potential options).

### 2.2.2. Reverse Logistics & Circular Economy

RL and CE have several similar characteristics. CE is a broader concept than RL because CE covers the whole supply chain, while RL only focus on the EoL phase. The purpose of RL is to recover the value of the product in order that it can re-enter the system. This is in line with the goal of CE (Ripanti et al., 2015).

To use RL as an enabler of CE, the principles of CE should be included in the design of a RL-system. The different levels of circularity can be introduced in the RL-system. The EoL strategies of CE can be implemented in the recovery step of the RL process. The strategies are divided between the direct recovery and the re-processing, whis is illustrated in figure 2.6.
The type of recovery influences the exact course of the RL process. The size of the loop can influence the type of the RL. Figure 2.7 shows the influence of the different levels of circularity on the RL process in combination with the forward supply chain. The levels of circularity not only influence the whole RL process, it also influences the length of the whole supply chain. It depends on the type of recovery where the construction waste re-enters the supply chain. This is according to the waste hierarchy and is also linked to the material cycles of Ellen Mc Arthur as shown in figure 2.1. Re-use is the most preferable option which results in the smallest cycle and the least recovery.

In the introduction, the financial obstacles have been mentioned as the key aspect which keeps the actors from moving towards a circular business. The reason for this are the financial uncertainties, which occur primarily on the micro-economic level. As stated before: circular business involves higher inventory costs. To avoid financial risks, one should know that the revenues can eliminate these additional inventory costs. However, there are uncertainties about the value of residual products due to the small market of second-hand products (Rijkswaterstaat, 2015). RL has been assigned as possible solution to overcome this obstacle. RL can be seen as an efficient and effective approach to organise the high value take back system of EoL materials.

In the field of RL, quantitative models have long been recognised as a useful approach to manage and optimise return flows. Quantitative models help to obtain a better understanding in the interactions and the
dynamics of the RL process (Dekker et al., 2004). Therefore, this knowledge can be used to include the principles of CE in the EoL phase of assets. Integrating CE in such a model has the consequence that quantitative analysis can be made to evaluate the impact of circular decisions in the system. It will provide an insight in the financial impact of circular decision on the return flow and therefore can help to eliminate the uncertainties (Ripanti et al., 2015). This could help decision-makers in making trade-offs on the implementation of circular principles. Moreover, such a quantitative model can help to create a cost-efficient take-back system that can accelerate the market for secondary resources (Kok et al., 2013).

2.2.3. Reverse Logistics in the infrastructure

Reverse logistics has emerged within manufacturing organisations as an effective measure for achieving environmental and economic goals. Hence, RL has not been adopted to such an extent in the construction industry (Hosseini et al., 2014). The construction industry differs a lot from the manufacturing industry and therefore the RL of the construction industry looks different. In order to design a RL-model for the infrastructure, it is important to understand the characteristics of RL in the sector. Several studies have been executed on the application of RL in the construction sector. The following paragraph will identify the characteristics of RL in the construction sector that are essential for the design of the RL-model. The characteristics will be identified by comparing the RL of the construction industry with the RL of the manufacturing industry. This comparison will be made on basis of the following four aspects which have been defined by previous studies as the essential viewpoints to define the characteristics of RL (De Brito and Dekker, 2004):

1. **Motivation for applying RL:**
2. **The processes carried out in the logistics to recover the value:**
3. **The characteristics of the return products:**
4. **The actors involved in the RL activities.**

1. **Motivation:**

   The motivation of RL can distinguish two types: The driving forces for executing the RL-process (receiver) and the reason for returning (sender) (De Brito and Dekker, 2004). The drivers for executing the RL-process in the construction industry do not really differ from the manufacturing industry. The main drivers can be classified in three categories: Economic, environmental and social divers.

   - **Economic:** The economic benefits comes from cost savings and additional revenues. The cost savings come from avoiding landfill, lower inventory costs and less transportation. The potential revenues come from the resale of valuable components or products. Although the inventory costs (e.g. processing costs, storage costs, deconstruction costs, etc.) are higher when implementing RL, different studies have shown that the overall cost of construction by implementing RL will be lower (Hosseini et al., 2014)(Hosseini et al., 2015)(Sobotka and Czaja, 2015)(Schultmann and Sunke, 2007).

   - **Environmental:** Due to the high environmental impact of the construction industry, construction enterprises face pressure to be more sustainable (Schultmann and Sunke, 2007). The major environmental drivers are the use of less materials, less energy consumption for production and transportation of materials and less waste that is generated (Hosseini et al., 2014). However an important environmental driver is of course the environmental regulatory requirements (Directive, 2008).

   - **Social:** The social drivers are the ones that help to win public favour. The construction industry has a bad public image (Rameezdeen, 2007). Improving the green image by the implementation of RL could result in higher competitiveness (Sobotka and Czaja, 2015).

The reasons for return for products in the construction industry differs from the ones of the manufacturing industry. In the manufacturing industry, there are multiple types of product return to define: Manufacturing returns, distribution returns and costumer returns. These returns will take place in different stages of the life cycle of a product and for different reasons.(De Brito and Dekker, 2004). The return flow for each stage is easy to predict. Therefore, the return flow can be well organised (Hosseini et al., 2014). The return of products in the construction industry will mainly place at the EoL of an asset, which can be the end of economical life or technical. Assets in the construction sector have often a long life time. The consequence of the product return at the EoL is that there is uncertainty about the quality of the returned asset and therefore it can not be organised up front (Hosseini et al., 2014).
2. Process

The activities of RL are already illustrated in figure 2.5. However, the execution of these activities in the construction industry differs from the manufacturing industry. To explain the characteristics of the process in the construction industry, the steps of RL are outlined in table 2.1 for the construction industry and the manufacturing industry.

Table 2.1: Comparing RL process of manufacturing industry and construction industry

<table>
<thead>
<tr>
<th></th>
<th>Manufacturing Industry</th>
<th>Construction Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collecting</td>
<td>Bringing products from customers to a central point. Occurs different phases of the life cycle.</td>
<td>Collecting will take place at the particular construction site. This occurs at End of Life phase. EOL can be economical or technical.</td>
</tr>
<tr>
<td>Inspection/Selecting/Sorting</td>
<td>At the place of recovery.</td>
<td>On-site or off-site. This will take place by deconstruction</td>
</tr>
<tr>
<td>Recovery</td>
<td>At manufacturer or at the place of repair.</td>
<td>Different recyclers or salvage yard.</td>
</tr>
<tr>
<td>Distribution</td>
<td>Back to the market</td>
<td>New project or manufacturer of new products.</td>
</tr>
</tbody>
</table>

The fundamental differences between the process in the construction industry and in the manufacturing industry lies in the beginning of the process. In the manufacturing industry, special locations can be assigned for the collection of returned products. For example, old mobile phones can be brought to an electronic store. A fixed RL-network can be designed from these collection points to the further locations of the process. In the construction sector, it is not possible to assign special locations for collection. The collection will take place at the construction site, which differs per case. This has as consequence that the RL-network differs per case (Hosseini et al., 2014). The inspection and selection of manufacturing products will take place at the place of recovering, which is chosen based on the reason why the product is returned. The inspection, selection and sorting of products in the construction industry will take place by the deconstruction, on-site or off-site.

To get a better understanding of the RL-process in the construction industry, the RL procedure for the construction industry has been illustrated in figure 2.8. The figure provides the RL-process construction industry in relation with the Forward Logistics (FL). The ideal situation is that nothing goes to landfill, which results in a Closed Loop Supply Chain (CLSC).
2.2. Reverse Logistics

Although it is not included in the process description, transportation and storage are important activities within the RL-process. The transportation and storage takes place between different activities, depending on the particular execution of the RL activities (Schultmann and Sunke, 2007). Because the RL-network of the construction industry is not fixed upfront, the transportation routes differ also per case. The same applies for storage facilities. It depends per case whether the return flow can be stored on-site or whether additional storage facilities are required (Sobotka and Czaja, 2015).

3. Product characteristics

The exact execution of the RL activities, very much depends on the characteristics of the products. The characteristics of returned products depends on the composition, deterioration and the use pattern (De Brito and Dekker, 2004).

The composition includes, among other things, the number of components, the heterogeneity, how components are put together and the size of the product. Manufactured products exist often of multiple components. A mobile phone has a battery than can be replaced easily when it is broken. Products in the construction industry are often large and have a heterogeneous structure. The size of the products influence the transportation options. The way that products are put together also influences the possibilities for reprocessing. Concrete, for example, is very difficult to decompose into the original components (cement, water and aggregates) (De Brito and Dekker, 2004).

The deterioration causes the main non-functionality of the product. This characteristic strongly influences the choice for certain recovery options. The deterioration describes whether or not the product has enough functionality left to make use of the product as a whole or as parts. The following question can be asked to determine the deterioration of a product: Do all the parts age equally? What is the value of a product, or its components, after lifetime? Can the product be reused as a whole or can only components be reused? (De Brito and Dekker, 2004). A concrete construction is a homogeneous product and will age as a whole, while a lamppost exist of different components which has a different lifespan. In the construction industry, a large volume of assets will often be released in once, because a whole construction will often be demolished in once. This results in large fluctuation in return flows. In the manufacturing industry, however, the products will be returned more fragmented, which results in a
more continuous return flow. The value left depends also on the demand for such products at moment of release. Because the manufacturing return flow is more continuous, it is easier to assess the value of the returned products. Due to the long life-time of assets in the construction industry, there is a wide variety in the functionality and the quality of the extracted materials (Hosseini et al., 2015).

The use pattern refers to the location, intensity, the duration of use and the type of user. The use pattern affects the collection phase because it says something about the sender of the returned product and the place where it can be collected (De Brito and Dekker, 2004). The location where the asset will be used in the construction industry is fixed. While in the manufacturing industry, the locations of use can change easily. The construction sector is known for the long lifetime of its products. There is no single user, like in the manufacturing industry. The products are used with a large amount in one (the whole road or bridge are used in one) by a large number of people. The duration of use in the construction sector is very long. Therefore, assets often cannot be returned to the manufacturer of the asset and there is often a lack of information harvesting (Hosseini et al., 2015).

4. Actors involved
The construction industry has usually more actors involved in the RL process compared to other industries. The EU C&D Waste management protocol (2016) defines the stakeholder of construction industry in the following three groups for actors:

(a) **Industry practitioners**: This includes the renovation companies, demolition contractors, construction products manufacturers, waste treatment, transport and logistics, and recycling companies, suppliers

(b) **Public authorities**: At local, regional, national and EU levels.

(c) **Clients**: This can be a government body or a project developer.

The general contractor or the subcontractor is mostly responsible for the C&D waste. The aim of the contractor is to keep the disposal cost as low as possible. Therefore, a high degree of C&D waste separation and selection is desirable. The contractor decides whether or not to bring the waste to disposal or a specialised reverse chain actor (like recycling companies or suppliers). It depends per project which actor is responsible for the transportation between the construction site and the next destination. The public authority is indirect involved by setting up directives and legislation, but can also be directly involved as project owner (e.g. client). For the manufacturing industry the division of tasks stays the same for a longer period of time, while in the construction industry it is different for every project. The temporal character of the RL network makes the application of RL more complex. The main structural difference between the construction and manufacturing industry regarding the RL is the organisation of the collection and the logistic processes from the construction site to the recovery facilities (Schultmann and Sunke, 2007).

2.2.4. Designing a RL-network
The previous paragraph has identified the characteristics of RL in the construction sector. These characteristics influence the design of the RL-model. This paragraph focuses on the type of RL-model that should be designed for this research. This is based on the characteristics of RL in the construction industry and the objectives of this research. After the type of model is indicated, the aspects that influence the model design will be discussed.

There are multiple types of RL-models and it depends on the decision issues that needs to be addressed, what type of model will be designed (Dekker et al., 2004). Dekker et al. (2004), has outlined several types of RL-models. There are models that focus on the physical flow, which includes models that focus on the transportation routing issues, internal logistics or focus on the design of the whole RL-network. The other type of models focus on planning. These include, amongst others, forecasting issues and analysing lot-sizing decisions (Dekker et al., 2004). Distinguish can also be made about the scale of operation. One can focus on modelling one part of the RL-process in detail to take the whole process into account on a more general level. The objective is to create a model that supports decision-making about the RL-network design in order to optimise the circularity of the return products and minimises the cost involved. The main determinants of the performance of a reverse flow is the location of production, facilities, storage, and the transportation links between these locations. Setting up a RL-network involves decision making on where to locate and how
to perform the different activities. Next to that, it involves decision making on how to link the different processes by the use of transportation and storage (Fleischmann et al., 2004) Therefore, it can be concluded that the most appropriate model for this research is a model that focuses on the physical flow and takes the whole RL-process into account.

There are some key issues that have been addressed in the previous paragraph and should be taken into consideration in the model design. One important characteristic of the construction industry that has been identified is the dynamic nature of the reverse flow. There is a high fluctuation in the release of assets in the construction industry. One of the most important challenges of the development of a RL-network is the fact that it is hard to forecast the reverse flows (Colligan, 2015). A forward flow can easily be predicted and planned. The processing costs, the revenues, destination and quality of the products are all known for the forward flow. The main uncertainty in a FL-network is the demand, because it is an external factor that variates (Fleischmann et al., 2004). For a reverse flow both the demand and supply variates. This result in the fact that the RL-network can not be totally standardised. The routing, process, destination and origin can be different for each project. The reverse flow has a high level of uncertainty due to the high variety of quantity, quality and timing of returned products (Hosseini et al., 2014). The aim of a model is to support the network design decisions while dealing with the uncertainties of a reverse flow (Fleischmann et al., 2004). The model should be able to match demand and supply under these dynamic circumstances. Matching demand and supply is not so easy for a reverse flow as it is for the forward flow. The quality and quantity of the supply should somehow be matched with the required quality and quantities. The moment when there is a demand for certain material could easily differ from the moment that a certain material comes available. To deal with these aspects, is important to define the starting point of the RL-network. To design such a RL-model for optimising the RL-network, it is important to define the starting point. Fleischmann et al. (2004) distinguishes two types of RL-models: "supply push" and "supply pool" models. These indicate whether there is a given collection (supply) which needs to be processed or whether the collection responds to the demand (pull). In this research, the focus is on EoL which means that the type of model is "supply push". This will have consequences for the approach on dealing with the uncertainties.

Table 2.2 illustrates for all the activities involved in the RL process the aspects which should be defined (decision variables) and the factors that influences the choice. It is also important to make decisions about the process between these activities. This means that storage and transportation are also part of the RL-network. Therefore, these activities have been included in the table as well. The decisions made are based on the quality and quantity of returned products, the potential revenues, the availability, accessibility of processing facility and the cost of different activities. Where and if the transportation and storage will take place in the whole process can differ per project. Hence these activities are accommodated under "supporting facilities". The types and characteristics of the returned products (which has been described earlier) is one of the most influencing factors when designing a RL-network. It is clear from the table that there are a lot of choices to make which means that there are a lot of potential RL-networks. The aim is to find the most optimal RL-network, which creates an efficient and effective take back system where the economic feasibility and environmental concerns are main drivers. The challenge of finding the optimal RL-network is the dynamic nature of RL, RL-networks are far from identical.
Table 2.2: RL-network design

<table>
<thead>
<tr>
<th>Process activities</th>
<th>Decisions</th>
<th>Factors that influence the decisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collection</td>
<td>• Approach of demolition&lt;br&gt;• Actor&lt;br&gt;• Location</td>
<td>• Type of project&lt;br&gt;• Regulations&lt;br&gt;• Use pattern&lt;br&gt;• Composition&lt;br&gt;• Costs&lt;br&gt;• Circular ambitions</td>
</tr>
<tr>
<td>Inspecting/ Selecting/ Sorting</td>
<td>• Location(s)&lt;br&gt;• Level of decomposition&lt;br&gt;• Actor</td>
<td>• Composition&lt;br&gt;• Deterioration&lt;br&gt;• Use pattern&lt;br&gt;• Costs&lt;br&gt;• Collection</td>
</tr>
<tr>
<td>Recovery</td>
<td>• Location(s)&lt;br&gt;• Level of circularity&lt;br&gt;• Actor</td>
<td>• Demand for certain products&lt;br&gt;• Deterioration&lt;br&gt;• Technical capabilities&lt;br&gt;• Regulations&lt;br&gt;• Circular ambitions&lt;br&gt;• Costs</td>
</tr>
<tr>
<td>Re-distribution</td>
<td>• Location(s)&lt;br&gt;• Residual value&lt;br&gt;• Actor</td>
<td>• Type of recovery&lt;br&gt;• Demand of market&lt;br&gt;• Deterioration&lt;br&gt;• Potential revenues</td>
</tr>
<tr>
<td>Supporting facilities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td>• Routing&lt;br&gt;• Type of transportation&lt;br&gt;• Between which activities&lt;br&gt;• Frequency&lt;br&gt;• Actor</td>
<td>• Composition&lt;br&gt;• Use pattern&lt;br&gt;• Capacity of different transportation types&lt;br&gt;• Potential revenues</td>
</tr>
<tr>
<td>Storage</td>
<td>• Location(s)&lt;br&gt;• Size of facility&lt;br&gt;• Duration&lt;br&gt;• Between which activities&lt;br&gt;• Actor</td>
<td>• Moment of demand&lt;br&gt;• Use pattern&lt;br&gt;• Costs</td>
</tr>
</tbody>
</table>

The following paragraph will focus on the modelling approach. The aim is to find the right modelling approach which fits best for modelling the RL of the construction industry and optimising the ambitions of CE.
2.3. Modelling approach

A RL-model contribute in better understanding of the interactions, dynamics and underlying trade-offs of the different RL processes (Dekker et al., 2004). Models are a simplified and idealised representation of the real world and therefore it cannot be guaranteed that the optimal solution found in the model will be the optimal solution for the real-world problem. Only when the model is a sufficient precise representation of the real situation, the conclusion obtained from the model will be valid for the real problem (Hillier, 2012). There are several promising techniques available for addressing RL-problems and it depends on the research objectives what kind of technique fits best. The aim is to find an approach to model RL where the principles of CE can be included and can take away the uncertainties concerning the supply & demand and the financial feasibility. This paragraph discusses alternative approaches that supports the design of RL-networks.

The method that has been examined as a suitable method for modelling this problem is Linear Programming (LP). This method is widely applied to solve logistics problems and can be adopted for this research due to the availability of the software.

2.3.1. Linear Programming

Linear programming is a widely used quantitative approach for designing RL-networks. LP is a commonly applied technique to optimise the supply chain (Hillier, 2012). LP is a tool for selecting alternatives in a decision problem. It can be applied in a wide variety of problem settings. LP is a method which is used for achieving an objective while having to deal with some constraints. The objective can be, for example, minimising the costs or maximising the profit. Objective and constraints are defined by linear relationships (Hillier, 2012).

According to Govindan et al. (2015), linear programming is the dominating modelling approach for the design and planning problems. It is widely applied in research about reverse logistics. LP is a suitable approach when there is a stable network design. Different studies have already showed that LP is an appropriate method to combine economically and environmental concerns (Fleischmann et al., 2004). It helps decision makers to decide amongst alternative courses of action.

The aim of this research is to support decision makers in optimising the RL-network. The objective of this research is not to test what the influence is of several factors on the functioning of a RL-network. This research will not focus on the policy making or evaluating a specific strategy of stakeholders within the supply chain. Therefore, it can be concluded that linear programming is the most appropriate method to use. LP is a suitable approach when there is a stable network design. Different studies have already showed that LP is an appropriate method to combine economical and environmental concerns (Fleischmann et al., 2004).

2.3.2. Applying Linear Programming

LP is developed by George Dantzig in 1947, who invented a method that that could be used to compute complex real-world problems. He proposed an algorithm to solve very efficiently and routinely a large and complex problem, which is called the simplex algorithm (Hillier, 2012). It was first applied to solve logistics problem in the Air Force. After that, it has been applied in all kind of sectors. Nowadays it is widely used to solve logistics, financial, scheduling, distribution and policy issues. The word “Linear” refers to the fact that all mathematical functions in the model must be a linear model. In a LP-model, all the mathematical functions need to be linear. This means that the objective and the constraints both should be linear functions (Hillier, 2012). The word “programming” is a synonym for planning.

The aim of LP is to find a best feasible solution, which is the feasible solution that has the most favourable value of the objective function (Hillier, 2012).

A linear function exists of a set of decision variables, parameters, the objective function and a set of constraints (Hillier, 2012). The standard approach to solve a LP-model, is to allocate limited resources \(m\) among competing activities \(n\) in an optimal way. The limited resources are for example limited number of labour, materials, machines, finance, etc. The activities are for example production, transportation, investing money, etc.
The aim is to maximise (or minimise) the objective function $Z$, which is the value of overall measure of performance. A standard objective function is:

$$Z = c_1 x_1 + c_2 x_2 + \cdots + c_n x_n$$

$x_j$ = *A decision variable* which shows the level of activity $j$ (for $j = 1, 2, \ldots, n$)

c$_j$ = *A parameter* which provides the contribution of activity $j$ to the objective function $Z$.

An objective function should be subjected to certain restrictions, which are the *functional constraints*:

$$a_{11} x_1 + a_{12} x_2 + \cdots + a_{1n} x_n \geq b_1$$
$$a_{21} x_1 + a_{22} x_2 + \cdots + a_{2n} x_n \geq b_2$$
$$a_{m1} x_1 + a_{m2} x_2 + \cdots + a_{mn} x_n \geq b_m$$

$b_i$ = A parameter which presents the amount of resource $i$ that is available for allocation to activities (for $i = 1, 2, \ldots, m$).

$a_{ij}$ = *A parameter* which presents the amount of resource $i$ consumed by each unit of activity $j$.

(Hillier & Lieberman).

Besides the functional constraints, there can also be *nonnegative constraints*:

$$x_n \geq 0$$

The mathematical function can be placed in the framework as shown in Table 2.3.

<table>
<thead>
<tr>
<th>Resource</th>
<th>Resource Usage per Unit of Activity</th>
<th>Amount of resource available</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Activity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 2 \ldots n</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$a_{11}$ \ldots $a_{1n}$</td>
<td>$b_1$</td>
</tr>
<tr>
<td>2</td>
<td>$a_{21}$ \ldots $a_{2n}$</td>
<td>$b_2$</td>
</tr>
<tr>
<td>:</td>
<td>$\ldots \ldots \ldots \ldots$</td>
<td>:</td>
</tr>
<tr>
<td>m</td>
<td>$a_{m1}$ $a_{m2}$ \ldots $a_{mn}$</td>
<td>$b_m$</td>
</tr>
<tr>
<td>Contribution to $Z$ per unit of activity</td>
<td>$c_1$ $c_2$ \ldots $c_n$</td>
<td></td>
</tr>
</tbody>
</table>

When applying LP in this research, the decision variables can be the amount of materials that will be processed. The parameters are uncontrolled input like cost per kilometre or re-manufacturing costs and quantities of supply and demand of the materials. A LP-problem could have more than one objective, which can be solved by, for example, goal programming. In this research the multiple objectives could be the environmental and economic objectives.

Because of the linear characteristic of the method, the technique is based on linear assumptions. Only when the following four assumptions are met, the problem can be solved by applying LP (Hillier, 2012):

1. **Proportionality**: A change in the constraint function will lead to a proportional change in the objective function, and the other way around.

2. **Additivity**: Every function in linear programming is the sum of the individual contribution of each product. There is no interaction between the decision variables.

3. **Divisibility**: Decision variables can have any value that satisfy the constraints.

4. **Certainty**: The value of each parameter is assumed to be a known constant.
These assumptions could be a drawback for applying the technique, because the reality is not always linear. The assumption of certainty is especially a drawback when applying LP for a RL-problem. As stated earlier, a RL-network has to deal with uncertainties which means that the parameters are not always known. Applying a sensitive or scenario analysis can help to overcome this problem. A sensitivity analysis is conducted to define the sensitivity of objectives to changes in the parameters. Scenario analysis will be conducted to predict the outcome by future changes.

The divisibility assumption does not hold for some situations because sometimes a part or all of the decision variables are restricted integers. Therefore a commonly used variant of LP can be applied: Integer Linear Programming (ILP) or Mixed Integer Linear Programming (MILP) (Hillier, 2012).

To study the sensitivity of the system to changes in these parameters, a scenario analysis can be applied. Different scenarios can be analysed which will depend on the availability and market demand.

The result will be a general framework which provides the opportunities and limitations for reusing materials. By illustrating the possibilities to create an economically feasible closed-material cycle, it hopefully gives the stakeholders in the cycle some incentive to move towards a closed material cycle.

2.3.3. Network model

The basic approach for applying LP is to allocate resources among competing activities. However, the proposed modelling objective of optimising a RL-network does not fit this framework. This does not include a single type of activity which needs to be allocated to a single type of resource. Therefore another approach should be to model the proposed problem. The model should aim for optimising the return flow of assets and help to design the RL-system. There is a wide variety of approaches for modelling a LP-problem. Different types of models are available to solve more efficiently problems with a special structure. To find the best modelling approach to solve this problem, a couple of important special types of LP-problems have been reviewed. The most common special types of LP-problems are the transportation problem, assignment problem and minimum cost flow problem. These types of LP-problems all involve networks (Hillier, 2012).

**network model**

Many linear optimisation models are network models, from which there are many different types. A network model provides a clear visualisation of the relationships between the components of a system. A network consists of a set of points which are connected by a set of arcs. The main components in a network model are the nodes (e.g. the points), the arcs which connects the nodes and the flows (the objects which needs to be transported) (Hillier, 2012). This is shown in figure 2.9.

![Network Model](image)

**Figure 2.9: Network model**

The proposed problem can be drawn in a network of nodes and flows. The problem can be seen as set of sub-problems, representing the different activities in the process, which are linked. The nodes represent the possible options (e.g. the type of transportation, the level recycling, etc.). The arcs represent the path between one option and the next option. The flow is the construction waste.
2.4. Conclusion

The aim of this chapter was to provide an answer to the first four sub-questions. The principles of CE can be implemented in the infrastructure in the design phase and EoL phase. Implementing the principles of CE in the EoL phase can contribute in reducing the amount of waste of the construction industry. The waste hierarchy can be a guideline for supporting the CE in the EoL phase. The waste management strategies can be prioritised by combining the waste hierarchy and the three aspects that define the goals of CE. RL could be an enabler for accelerating the CE in the construction industry. It is a good approach to deal with the obstacles that retain the actors from implementing circular principles in the EoL-phase of construction sectors. One of the major obstacles of implementing CE in the infrastructure, is the financial uncertainties. By introducing a RL-model, this obstacle can be overcome. A quantitative model supports the management of return flows. A RL-model can help to create a cost-efficient take back system. It provides an insight in the financial impacts of circular decisions. In order to reach this, it is important to identify the critical aspects that should be included in the model. RL in construction industry is complex comparing to the manufacturing industry. This is due to the dynamic nature of the construction industry. The characteristics of the products in the infrastructure, the diversity in locations and amount of products that are released in once make the construction industry less suitable for fixed RL-network design. The dynamic nature can be tackled by designing a model that could help to deal with these dynamics. LP is a good approach for designing such a model. It can combine environmental and economic concerns. The proposed problem can best be approached as a network problem. All the findings from the literature study can be combined into a framework that forms the base for the model design. The model exists of three parts: The first part includes the different aspects that influence the decisions made in a RL-process, which are called, in this framework, the input parameters. The second part are the sequence of activities that are involved in the RL-network. The choice should be made on how, where, when and by who certain activities will take place. This results in a unique RL-network which aims in reaching certain goals. The third part is the output of the model. The objectives of the model in this research is that the RL-network should include the principles of CE and should take away the financial uncertainties.

Figure 2.10 presents the framework for the RL-model.
3 Model
The knowledge obtained from the literature study will be applied to design a model. In the previous chapter the characteristics of circular economy in the construction sector have been discussed. It is explained how applying the theory of reverse logistics can improve the circularity in the EoL-phase of products in the construction industry. A RL-model which is general applicable and supports decision making in projects is found as the solution to improve the circularity at the EoL-phase. Linear programming has been assigned as the most suitable modelling approach for this problem. This chapter focuses on the design of the model, which builds on the framework obtained in the previous chapter. The aim of this research is to design a general model which can be applied for specific cases. This chapter has therefore two objectives: The first objective is to design a general LP-model based on the knowledge obtained in the theoretical framework. The second objective is to develop a guideline that helps decision-makers to transform the general model to a case specific model.

The first part of the chapter will focus on the structure of the model that arises from the framework obtained from the previous chapter. The second part describes the mathematical formulation of the general problem. The third part provides a guideline for the application of the model on specific cases.

3.1. Model framework

The process of reverse logistics for infrastructural assets has been described in the previous chapter. The aim is to improve the circularity of EoL waste by optimising this process. Two critical decisions are included in the optimisation of the RL-process: On one hand the decision about what the level of circularity will be and on the other hand about the design of the RL network. The model should support decision-makers in making these choices. Chapter 2 provides a framework from where the model will be further developed. The framework for the model design, (figure 2.10), consists of three elements: The input parameters, the process and the output. The input represents the parameters of the model, the process involves all the activities that will be performed in the reverse logistics of the asset and the output is the goal of the model. In this section, the framework will be used to develop the structure of the model. The first paragraph will elaborate more on the RL-process. The second paragraph will present the structure of the model which is based on the parameters and the relation between these. The third paragraph will elaborate on the objectives of the model.

3.1.1. Inventory of the process

The point of departure for the model is one single asset which has been extracted from a demolition project in the infrastructure. The asset owner is the decision-maker and should decide to which level of circularity the asset will be processed after demolition. Therefore, decisions should be made at each stage of the RL-process. The process starts at the construction site where the asset can be processed to some extent by separating and selecting the different products or elements of the asset or keeping the asset as a whole. After the activities at the construction site, the asset/products/elements should be transported to the next destination by using some type of transportation method. The asset can be send to a recycler or can be sold to a potential pur-
chaser when there is a demand for it. After recycling, the asset/product/material can be sold. Revenues from selling the products depend on the value of the final product. The aim of this whole process is to obtain the highest level of circularity at the lowest costs. The decision that will be made in every stage of the process depends on the available alternatives. For every type of asset and particular project there are different alternatives available. The amount of options and the type of options to decide on are case specific. Moreover, the costs and revenues are also case dependent. Therefore, the exact path of the model should be defined for every single case. Because the aim of this research was to design a model which is general applicable, a list of question in a particular order has been formulated that will help to find all the alternatives for a specific case. The sequence of questions forms the inventory of the logical process. The inventory of the process will help to obtain all the possible options which will lead to a material flow definition. A material flow definition is a network of all the possible options in the process. This is used to display the structure of certain decisions and the interrelationships between different alternatives and the possible outcomes. The inventory will help to see which options are left after for the next activity after choosing for a particular option on the previous activity. For example: choosing for a certain way of separating and sorting material at the construction site, has consequences for the possible types of transportation. Asking the question in sequence, will lead to a tree-shaped diagram which includes all the options for the process. The questions for the inventory of the process and the network of the material flow is shown in figure 3.1.

The sequence of the questions follows mostly the RL-process, but it starts with the end of the process. It is important to first define all the possible destinations for the demolition material and then to find out what all the possible ways are to get to these destinations. Therefore, the following question should be asked first:
"What level of circularity is technically feasible given the quality of the material of a demolition project?"
Each branch represents the possible levels of circularity (R1-R7). The questions that follow will be answered while having the intended level of circularity in mind. These following questions will be asked in the order of the process. The answers together are the input for the model. The answers will help to transform the general model into a case specific model. All these options which have been obtained by answering the set of question form the set of competing activities which are part of a linear model and have been mentioned in the previous chapter.

### 3.1.2. Structure

The structure of the model defines how the LP-problem will be modelled. There are different types of LP-problems that require different kinds of model structures. In the literature review, RL-problems have been identified as network problems. The proposed RL-problem can be drawn as a network system. The network system represents all the activities that are involved including the links between these activities. Figure 3.2 shows the network representation of the problem. The nodes represent the possible options (e.g. type of transportation, the level of recycling, etc.). The arcs represent the path between one option and the next option.

![Figure 3.2: Network representation of the system](image)

There are many types of network models, that have particular structures. The structure of the model is based on the theoretical framework. The theoretical framework points out the critical aspects of the problem and that should somehow be included in the model design.

### Input parameters

The input parameter as identified in the framework influence the structure of the model. The parameters can be defined after the exact process is designed. The parameters are variables that influence the choices that are made for certain activities in the process. For example: The choice for the destination of the material depends on the demand for such a material. Therefore, the parameters have an influence on the structure of the model. In the theoretical framework, the aspects that influence the RL-process have been identified. These aspects should be included in the model to obtain a reliable model. It is important to know what will influence the outcome of a model before designing the model. The input parameters that have been identified in the previous chapters are:
3.1. Model framework

- demand & supply
- distance
- material characteristics
- technical possibilities
- timing
- actors involved

The demand & supply and material characteristics influence the potential revenues. The more demand there is for a certain product, the higher the revenues. Timing refers to the moment that an asset will come available and the moment of a potential demand. Storage facilities can be needed to bridge this gap in time. The distance between different places in the network, the actors involved and the timing influence the cost of processing. The technical possibilities and the material characteristics can influence the potential level of circularity. The different parameters are all related to each other. These are all aspects that can influence decision-making and should therefore be taken into consideration when designing the structure of the model.

Transshipment model

According to the literature studies, matching demand and supply is one of the key challenges of RL. Therefore, it is essential to include this aspect in the model. The transshipment model is a type of network model that can include the demand and supply. A transshipment model is a variance of the transportation problem. The general objective of a transportation problem is to distribute the items from origins (sources) to a potential destination against the minimum costs. The origins have certain supply and the destinations have a certain demand. The general constraint for a transportation model is that the sum of the demands is equal to the sum of supplies. The distribution of one unit from a source to a destination has a price, which is a parameter. The transshipment problem is a variety of transportation problems where units are not being distributed directly from one or more sources to the destinations, but can first pass through intermediate nodes, which are called the transshipment nodes. These intermediate points can include other types of destinations or additional transfer points (Hillier, 2012). This fits the proposed network system that consists of multiple intermediate points. Writing the problem as a transshipment problem results in a system as shown in figure 3.3.

![Figure 3.3: General representation of the transshipment system](image-url)
The supply node is the origin, which is the demolition project. This node has a supply of certain quantity of units, which is in this case the amount of construction waste. The destination nodes have certain demand of units. In this study, there is one supply node, which represents the deconstruction project. The destination nodes represent the different levels of circularity (recycling, remanufacturing, reusing, etc.). The required assumption in a transshipment problem is that each source \( i \) (for \( i = 1, 2, \ldots, m \)) has a fixed supply of units and each destination \( j \) (for \( j = 1, 2, \ldots, n \)) has a fixed demand of units. The entire supply must be distributed to the destinations and all the demand must be received from the supply (Hillier, 2012). The remaining points are the transshipment nodes. In these transshipment nodes the inflow of units equals the outflow of units. The net flow of a node is defined by the outflow (supply) minus the inflow (demand). A transshipment problem has the following characteristics:

\[
x_{ij} = \text{flow through arc } i \rightarrow j.
\]

The given information includes:

\[
c_{ij} = \text{parameter which defines the contribution (often the costs) to } Z, \text{ per one unit flow through arc } i \rightarrow j,
\]

\[
b_i = \text{parameter which represents the net flow generated at node } i.
\]

The value of \( b_i \) depends on the type of node \( i \), where

- \( b_i > 0 \) if node \( i \) is a supply node
- \( b_i < 0 \) if node \( i \) is a demand node
- \( b_i = 0 \) if node \( i \) is a transshipment node.

The most common objective of a transshipment problem is to distribute units from each source to the destination by passing through intermediate points for the minimum cost. Therefore, the objective function of a transshipment problem will be:

Minimise \( Z \):

\[
Z = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij}
\]  

(3.1)

SubJECTED TO:

\[
\sum_{j=1}^{n} x_{ij} - \sum_{j=1}^{n} x_{ji} = b_i, \text{ for each node } i.
\]  

(3.2)

The problem of this research cannot meet the equality assumption, where the sum of the supplies is equal to the sum of the demands. The supply in this cases is one demolition project and the demand can be all possible markets. Therefore, the demand is way larger than the supply. This can be solved by introducing a “dummy source” to supplement the supply to such extent that it becomes equal to the demand. The parameter \( c_{ij} \) associated with the dummy source should be equal to zero because it should not influence the outcome of the objective function. The system with the dummy node is shown in figure 3.4.
Appendix A provides a demonstration on how to model a transshipment problem in excel. Because of the fact that the transshipment model has an equality assumption, matching the demand and supply could be taken into account. The demand nodes represent the different levels of circularity. P1 could be another project in the area where they need components of the demolition waste. In town A a road just has been demolished and one of the waste materials are concrete tiles, while town B just needs concrete tiles for a new road. The demand is exact because it is a single project. P4 instead, represents the market for a particular material which needs the components of the demolition waste. Therefore, the demand cannot be satisfied by one single demolition project.

Matching demand & supply is closely related to the timing aspect. In order to match the demand and supply, the moment that the material will become available should be the same as the moment that the material is needed. Therefore, time should be taken into account in the model. When the demand and supply matches in terms of quantity but not with respect to timing, option for storage could provide a solution. Therefore the costs for storage per month for a certain quantity could be included in the cost parameter.

Locating different facilities can also be included in this network approach. The value of the cost parameter could partly be depend on the distance between different facilities.

### 3.1.3. Objectives

The output, as been described in the previous chapter, represents the goal of the model. The goal is important for defining the objective function of the model. The standard objective function of a transshipment problem is to minimise the cost of distributing all the units from the origin to the destinations. However, the objective for the proposed problem is twofold. The asset owner wants to maximise the circularity of the demolished asset while keeping the cost as low as possible. Having two objectives for a problem means that somehow trade-off should be made between the two objectives when searching for the optimal solution.

An objective function needs to be constructed that defines the ultimate objective. Therefore, a quantitative measure of performance should be developed. To design a model, an objective function should be constructed which is the mathematical formulation of the objectives. The objective function can be obtained by developing a quantitative measure of performance. The quantitative measure of performance for the financial objective is easy to develop. The quantitative measure of performance for this objective is cost. The
parameter $c_j$ can be defined in terms of money, just as it has been done in the example. Developing a quantitative measure of performance for the circularity objective is more complicated. Circularity is something abstract, not tangible like costs. However it is important to design a right measure of performance because this will lead to the optimal solution. It can be concluded that there are two problems which need to be solved here: The first relates to multiple objectives that should be included in the model. And the second relates to developing a quantitative measure for circularity.

A problem with multiple objectives is called a multi-objective optimisation problem. There are several approaches to imply multiple objectives in a LP-model. Multi-objective problems can be solved according to the linear programming method by applying goal programming. The approach of linear goal programming is to establish a target value for each objective function which needs to be achieved. Goal programming can be categorised by preemptive or non-preemptive goal programming, depending on whether the different objectives are of comparable importance or not (Hillier, 2012). For the problem concerning the cost objective and circular objective it can be said that it is a non-preemptive goal programming problem. The drawback of this approach is that a target value should be defined for each objective.

Another approach for modelling a multi-objective optimisation problem is to optimise both objectives simultaneously. Optimising two objectives at the same time could lead to more than one solution. An optimal solution for a multi-objective problem is a solution where there is no feasible solution that improves one objective without sacrificing the other objective. Solving the model with these two objectives results in multiple non-dominated solutions. The set of non-dominated solutions are called "Pareto optimal" solutions, which are the most optimal solutions. The line indicates the boundary for all the feasible solutions of the multi-objective problem, which is called the Pareto frontier (Wang et al., 2011). A hypothetical example of the Pareto optimal solution for the proposed problem is shown in figure 3.5.

**Weighted sum method**
The aim is to maximise the circularity and minimise the costs. The points on the line are the Pareto optimal solutions. The point above the line are less preferable solutions. The decision maker can select one of the the non-dominated solutions that is the most suitable. To generate the Pareto solutions one can apply the weighted-sum method. The weighted-sum method transforms the multiple-objective problems into a single-objective problem. The single-objective function is the sum of the objective functions multiplied by weighting coefficient. Solving the problem for different values of the weighting coefficient will result in a Pareto solution. The weighted-sum method is an easy to apply method when trade-offs should be made between competing objectives. The drawback of applying the weighted sum-approach is that the simplex method will always pick a corner solution. This can result in large jumps in solutions when the weighting coefficient are only changed slightly, whereas large changes of weighting coefficient can result in no changes of the solution (Grodzevich and Romanko, 2006). Despite this drawback, the weighted-sum method seems to be a suitable approach for this research.

**Circularity weighting factors**
Applying this method brings us to the second problem that needs to be solved: Developing a quantitative measure of performance for the circularity objective. The previous chapter has already mentioned criteria to value circularity. Circularity can be obtained by minimising the leakage of resources and energy, the CO$_2$ emission and by maximising the value preservation. When applying the weighted-sum methods, the circularity should be defined in terms of the parameter $c_{ij}$. This means that $c_{ij}$ will become a parameter which defines the circularity contribution to "Z" per one unit flow through arc $i \rightarrow j$. CO$_2$ emission is an aspect which can easily be defined this way, every activity has some amount of CO$_2$ emission. However, this will
not cover the whole circularity objective. There are two drawbacks of this approach; The first is the fact that when the parameter is being defined as the amount of CO\textsubscript{2} emission, only one aspect of the circularity is included. The other aspects concerning the leakage and the value preservation should then be included in a different way. The second drawback is that minimising the CO\textsubscript{2} emission in the EoL-phase of a product, does not imply that it automatically results in a reduction of CO\textsubscript{2} emission in the whole life cycle of the product.

In a circular economy, the aim of reusing products and materials is to avoid the CO\textsubscript{2} emission of producing and obtaining primary resources. For example: In the production of concrete, the most CO\textsubscript{2} emission comes from producing the cement (Lieshout and Nusselder, 2016). Reusing cement contributes greatly in reducing the CO\textsubscript{2} emission over its life cycle, even when the process of obtaining cement from the concrete waste causes more CO\textsubscript{2} emission than other types of processing the concrete waste. Therefore, it can be concluded that CO\textsubscript{2} as quantitative measure of performance is not sufficient to satisfy the circularity approach. Another approach could be to include the circularity objective. In the previous chapter, the 10-R model has been introduced as a tool to prioritised different processing approaches. This 10-R model could be a guideline to define which outcome is more preferable concerning the circularity than the other. A level of circularity can be assigned for each possible outcome of the process, which is based on the 10-R model. As mentioned in the previous chapter, the 10-R model is only a guideline and should be interpreted differently for each project. The levels of circularity should therefore be defined for each project and material type independently, based on criteria that defines the circularity. The level of circularity which will be used is based on the weighting factor that is applied by Antea Group to value different levels of circularity in their "resource passport". This implies that outcomes can be valued on a scale between -1 to 4. Material that is processed as waste will score -1 and products that are reused directly as a whole will score 4.
3.2. General model formulation

In the previous section, the characteristics of a transshipment model have been explained and the general design of the model has been described. In this section, the structure and the mathematical formulation of the proposed model that addresses the optimisation of material flow after demolition will be presented. Figure 3.6 presents the structure of the proposed model.

The exact network of nodes and arcs is case specific and will be obtained by the inventory activity. Node $i$ is the starting point of the case and represent the asset that should be processed. The inventory of the process starts after defining node $i$. The first question indicates the types of purchasers and together with the fifth question it will define all the nodes $q$. The second question will define the quantity of nodes $j$ and the arcs moving to these nodes. The third question determines whether the connection between node $k$ and node $q$ can be made. The fourth question defines all the nodes $n$. The sixth question determines all the arcs moving to nodes $q$. The last question defines all the nodes $k$ and the arcs moving from and to these nodes. This results in a complex network of nodes and arcs.

The flow diagram distinguishes three types of nodes: origin, transshipments and destination nodes. The symbol $i$ represents the origin nodes $O_i$ with the net flow of $b_i > 0$. The symbols $j, k, n$ represent the transshipment nodes $D_j, T_k$ and $R_n$, with $b_j, b_k, b_n = 0$. However, nodes $j$ and $n$ are special types of transshipment nodes. Despite the fact that the quantity of inflow equals the quantity of outflow (just like regular transshipment nodes), the type of material inflow differs from the outflow. The processing activities result in further decomposition of the de-constructed asset. Figure 3.7 shows the inflow and outflow of nodes $i$ and $n$.

Figure 3.6: Flow diagram of the proposed transshipment model

Figure 3.7: The processing and recycling activities will change the products
The symbol \( q \) represents the destination \( P_q \) with \( b_q < 0 \). Because the point of departure of this model is a single asset of one project that needs to be demolished, it follows that \( I = 2 \). The first node is the proposed asset and the second node is the dummy node. The arcs represent the type of nodes that could be linked.

The mathematical formulation of the objective function and the constraints will be explained in the following sub-paragraphs. Appendix B provides an overview of all the parameters, variables and indices that are used in the model.

### 3.2.1. Objective function

The decision variables are shown in figure 3.6. The decision variables \( X \) denote the amount of material/product flow in tons. The decision variables \( N \) denote the quantity of transportation units. As stated in the previous paragraph, there are two goals to achieve: minimising the costs \( z_1 \) and maximising the circularity \( z_2 \). Both functions will first be discussed separately and thereafter they will be combined into one function.

**Minimisation of cost:**

The objective function of minimising the cost of the RL-process can be formulated as follow:

\[
\text{minimise } z_1
\]

\[
z_1 = \sum_{j=1}^{I} c_{ij}^p X_{ij}^p + k_j Y_j
\]

\[
+ \sum_{j=1}^{I} \sum_{k=1}^{K} \sum_{m=1}^{M} c_{jkm}^d B_{jkm} X_{jkm}^d + \sum_{k=1}^{K} \sum_{q=1}^{Q} c_{qkm}^p N_{km}^p
\]

\[
+ \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{m=1}^{M} c_{nqm}^r X_{nqm}^r + \sum_{q=1}^{Q} c_{pq}^r X_{pq}^r
\]

\[
\text{subject to: }
\]

This objective function minimises the cost for processing the construction waste and maximises the revenues from selling the processed materials. The process includes variable costs (\( €/\text{unit} \)) and fixed costs (€). The first costs arise at the construction site, when the first processing activities will take place. This includes the variable costs \( c_{ij}^p \) of processing the quantity of demolished asset \( i \) according processing activity \( j \) \( (X_{ij}^p) \). The processing activities also include fixed cost \( (k_j) \) for renting/using the processing equipment at the construction site, which only occurs when the processing activity will take place, denoted by the binary variable \( y_j = 1 \).

Processing activities result in new materials or components that are obtained from the original asset. For example, processing reinforced concrete results in a quantity of steel and a quantity of concrete.

A suitable type of transportation has to be selected to transport the obtained material to a recycler or purchaser. A transportation unit can transport one or more types of materials. Loading material \( m \) that has been obtained from processing activity \( j \) into transportation type \( k \) involves the variable cost of loading \( c_{jkm}^d \). The parameter \( b_{jkm} \) denotes whether or not a transportation unit is suitable to ship material \( m \). The costs for moving one transportation unit \( N \) to a recycler \( (c_{km}^p) \) or purchaser \( (c_{km}^w) \) depends on the transport distance and the type of transportation unit. The decision variable \( X_{knm}^r \) denotes the quantity of material \( m \) that is being transported by transportation type \( k \) to recycler \( n \). The costs of processing this flow at the recycler is denoted by the cost parameter \( c_{knm}^r \). The decision variable \( X_{qkm}^p \) denotes the quantity of material \( m \) that is being transported by transportation type \( k \) to purchaser \( q \) to who it will be sold directly. When there is a
gap between the moment of release and the moment that the purchaser needs the material, additional costs are involved for storing the material in the meantime. The costs for storing material \((c_{kqm})\) depends on the length of time that the material needs be stored and type of material \(m\). The revenues obtained from selling the materials \((r_{kqm}^p)\) can be abstracted from the variable costs of storing.

Just like the processing activities at the project site, new materials will be obtained from the processing activity at the recycler. These new obtained materials can be sold to a purchaser. Decision variable \(X_{nqm}^p\) denotes the flow of material \(m\) that has been processed at recycler \(n\) and will be sold to purchaser \(q\). The parameter \(g_{nqm}\) denotes whether or not a material that has been generated from the processing activity at the recycler can be sold to a particular purchaser. The costs involved for this flow are the potential costs for storing the processed material before it can be sold \((c_{nqm}^s)\) and the costs of transporting the material from the recycler to the potential purchaser \((c_{nqm}^t)\). The revenues from selling the material, \(r_{nqm}^s\), will be subtracted from these costs.

The decision variable \(X_{iqm}^z\) denotes the dummy flow. This is the quantity of unsatisfied demand of material \(m\) that is sent from dummy node \(i\) to purchaser \(q\). This flow should not influence the result of the optimisation problem. Therefore, the cost \(c_{iqm}^z\) is always zero.

**Maximisation of circularity**

The objective function of maximising the circularity can be formulated as follows:

\[
\text{maximise } Z_2:
\]

\[
Z_2 = \sum_{k=1}^{K} \sum_{q=1}^{Q} \sum_{m=1}^{M} e_{qm} X_{kqm}^p + \sum_{n=1}^{N} \sum_{q=1}^{Q} \sum_{m=1}^{M} e_{qm} X_{nqm}^s
\]

The value of circularity \(e_{qm}\) depends on the outcome of the RL-process. The value that is given depends on the type of material \(m\) and how it will be used by purchaser \(q\). Therefore, the outcome of this objective function only depends on the quantity of the decision variables \(X_{kqm}^p\) and \(X_{nqm}^s\), which represents the flow of material \(m\) that will be sold to purchaser \(q\). The total value of circularity is the sum of the total amount of material \(m\) at purchaser \(q\) multiplied by its level of circularity.

**Combined objective function**

By applying the weighted sum method, the two optimisation problems can be combined into one. This new objective function is the sum of the two objectives multiplied by the weighting coefficient \(w_i\). The two objective functions have contradicted objectives, one objective is minimising, while the other is maximising. However, maximising a function is equivalent to minimising its negative. Combing the objective functions \(Z_1\) and \(Z_2\) will result in the following function:

\[
\text{minimise } Z:
\]

\[
Z = w_1 Z_1 - w_2 Z_2
\]

Where \(w_i \geq 0\), \(\forall i = 1, ..., k\) and \(\sum_{i=1}^{k} w_i = 1\).

Running the model with different values for the weighting coefficient provides a Pareto frontier and therefore, will help to evaluate the cost of circular solutions. The full mathematical formulation of the combined objective function can be formulated as follows:
3.2. General model formulation

\[
\text{minimise } Z: \quad Z = w_1 \left( \sum_{j=1}^{J} c_{ij}^{o} x_{ij}^{o} + k_j y_j \right)
\]
\[+ \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{m=1}^{M} c_{jk}^{d} b_{km} x_{jkm}^{d} + \sum_{k=1}^{K} \sum_{n=1}^{N} c_{kn}^{w} x_{kn}^{w} \]
\[+ \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{m=1}^{M} c_{knm}^{l} x_{knm}^{l} + \sum_{n=1}^{N} \sum_{q=1}^{Q} c_{knq}^{p} x_{knq}^{p} \]
\[+ \sum_{k=1}^{K} \sum_{q=1}^{Q} \sum_{m=1}^{M} (c_{kqm}^{p} - r_{kqm}) x_{kqm}^{p} \]
\[+ \sum_{n=1}^{N} \sum_{q=1}^{Q} \sum_{m=1}^{M} (c_{nqm}^{l} + c_{nqm}^{p} - r_{nqm}) g_{nqm} x_{nqm}^{l} \]
\[+ \sum_{q=1}^{Q} c_{iqm}^{z} x_{iqm}^{z} \]
\[= w_2 \left( \sum_{k=1}^{K} \sum_{q=1}^{Q} \sum_{m=1}^{M} e_{m} x_{kqm}^{p} + \sum_{n=1}^{N} \sum_{q=1}^{Q} \sum_{m=1}^{M} e_{m} x_{nqm}^{p} \right) \]
\[\text{subject to: } \sum_{j=1}^{J} x_{ij}^{o} + \sum_{q=1}^{Q} \sum_{m=1}^{M} x_{iqm}^{z} = s_i, \quad i = 1, 2 \quad (3.7)\]
\[\sum_{n=1}^{N} x_{nqm}^{z} + \sum_{k=1}^{K} x_{kqm}^{p} + \sum_{l=1}^{I} x_{iqm}^{z} = d_{qm}, \quad \forall q = 1, 2, ..., Q, \quad \forall m \quad (3.8)\]
\[\sum_{i=1}^{I} s_i = \sum_{q=1}^{Q} \sum_{m=1}^{M} d_{qm} \quad (3.9)\]

These three constraints are related to the demand and supply of the problem. The demand and supply are predetermined quantities. Constraint 3.7 denotes that all the supply available should be processed. Constraint 3.8 denotes that the demand of purchaser \( q \) for material \( m \) should be satisfied. The total amount of supply should be equal to the sum of the demand of the purchaser for all the materials (constraint 3.9). The quantity of the dummy flow \( x_{iqm}^{z} \) will balance the mismatch between demand and supply in order to meet constraint 3.9.

Because this problem has been designed as transshipment problem, all the nodes that are not source or destination nodes should have a net flow of zero. The following constraints are defined to meet this requirement:
\[ \sum_{i=1}^{I} a_{ijm} X_{ij}^o = \sum_{k=1}^{K} X_{jkm}^d \quad \forall j = 1, 2, ..., J, \forall m \] (3.10)

\[ \sum_{j=1}^{J} X_{jkm}^d = \sum_{n=1}^{N} X_{knm}^r + \sum_{q=1}^{Q} X_{kqm}^p \quad \forall k = 1, 2, ..., K, \forall m \] (3.11)

\[ \sum_{m' = 1}^{M} \sum_{k=1}^{K} d_{nm'm'} X_{kmn'} = \sum_{q=1}^{Q} X_{nqm'} \quad \forall n = 1, 2, ..., N, \forall m' \] (3.12)

As has been stated before, nodes \( j, k, n \) are transshipment nodes, which means that the inflow should be equal to the outflow. Constraint 3.11 denotes that the inflow of material \( m \) should be equal to the outflow of materials \( m \) in node \( k \). This does not apply for the flow through nodes \( j \) and \( n \). These two nodes represent the processing activities at the project site and at the recycler. Processing involves (further) deconstruction of the asset into separate materials or components. The parameter \( a_{ijm} \) denotes the percentage ratio of material \( m \) that is obtained from asset \( i \) by the process activity \( j \). The same applies for \( d_{nm'm'} \), which is the percentage ratio of material \( m' \) that is obtained from material \( m \) by the recycling activity.

The following constraints are capacity constraints:

\[ \sum_{m=1}^{M} X_{knm}^r \leq C_k N_{kn}^r \quad \forall k = 1, ..., K, \forall n \] (3.13)

\[ \sum_{m=1}^{M} X_{kqm}^p \leq C_k N_{kq}^p \quad \forall k = 1, ..., K, \forall n \] (3.14)

The quantity of material that will be shipped by one transportation unit \( N \) should be smaller than the capacity \( C_k \) of transportation type \( k \).

The following constraint is regarding the fixed costs:

\[ \sum_{i=1}^{I} X_{ij}^o \leq M Y_j \quad \forall j = 1, 2, ..., J \] (3.15)

The fixed cost \( k_j \) is included if activity \( j \) is undertaken at any positive level. \( M \) is a large positive number and \( Y_j \) is a binary variable denoting whether activity \( j \) takes place \( (Y_j = 1) \) or not \( (Y_j = 0) \). Constraint 3.15 will ensure that \( Y_j \) will only be zero when \( X_{ij}^o \) is zero.

As has been discussed in the previous paragraph, the materials obtained from activity \( j \) cannot all be transported together by the same transportation unit. The same applies for the materials obtained from activity \( n \), that cannot be all sold to the same purchasers. Parameter \( b_{jkm} \) denotes whether material \( m \) obtained at activity \( j \) can be transported by transportation unit \( k \) \( (b_{jkm} = 1) \) or not \( (b_{jkm} = 0) \). Parameter \( g_{nqm} \) denotes whether material \( m \) obtained at recycler \( n \) can be sold to purchaser \( q \) \( (g_{nqm} = 1) \) or not \( (g_{nqm} = 0) \). This will lead to the following constraint:

\[ X_{jkm}^d = 0 \quad \forall j, k, m \in b_{jkm} = 0 \] (3.16)

\[ X_{nqm}^s = 0 \quad \forall n, q, m \in g_{nqm} = 0 \] (3.17)

This will ensure that there will be no material flow when \( b_{jkm} \) and \( g_{nqm} \) is zero.

The following constraint provides the non-negativity, the integer and the binary constraints:

\[ X_{ij}^o, X_{knm}^r, X_{kqm}^p, X_{nqm}^s, X_{iqm}^z \in \mathbb{R}^+, \quad N_{kn}^r, N_{kq}^p \in \mathbb{N}, \quad Y_j \in \{0, 1\} \] (3.18)
All the decision variables should be positive because there cannot be a negative material flow. The decision variables that denote quantity of transportation units should be integers. \( y_j \) is a binary variable denoting whether the activity \( j \) will take place or not.

### 3.2.3. Solving approach

The proposed model meets all the linearity assumptions and therefore it can be diagnosed as a Mixed Integer Linear Programming model (MILP). The problem is mixed integer because the model includes both integer and non integer variables. The aim of the model is to find the optimal solution for each of the objective functions separately and secondly to balance these two objectives by changing the values of the weighting coefficient. Therefore, a decision maker can see what it will cost extra to improve the circularity of the waste. The model will be computed in Excel 2016 by using the add-in Analytical Solver Platform 2016-R3. This is a premium version of the basic Excel add-in Solver. This premium version can solve larger problems within less time. The excel add-in uses the Simplex method to solve linear problems.

### 3.2.4. Assumptions and limitations

As the model is a simplification of the real world, some assumptions have been made.

- In this model, the variables do not evolve over time. Time only is taken into consideration to calculate the cost parameter of storage. The time that it takes to demolish, transport and recycle will be neglected.

- One major obstacle of reusing products/materials/components is the uncertainty about the quality. A product in the construction sector has a long lifetime. Hence, information about the product is often missing by the time of demolition. Uncertainty about the quality results in the fact that purchasers often prefer primary resources over secondary resources. The assumption made for this model is that the input of the model will provide clear information about the substance composition and quality of the extract materials. The purchaser will be certain about the quality and will prefer the secondary resources as much as the primary.

- The model calculates the optimal solution for the waste stream of one type of product (e.g. concrete, street-lights, etc.). Mixed streams have not been taken into consideration. Because the process is being modelled as a single flow, the option of combining different assets in processing activities and transportation is not included. Mixing streams could possibly lower the costs of processing.

Besides these assumptions concerning the structure of the model, there will be assumptions as well for the data input. This will be mentioned in the next chapter for the specific cases.
3.3. The application of the model

This chapter has proposed a model design that is derived from the theoretical framework. The aim of the proposed model is to include all the critical aspects to successfully include the circular principles in waste management of construction projects. It will be possible to include the aspects like matching demand & supply, timing and location options by approaching this problem as a transshipment problem. The proposed model is general applicable for all kinds of materials and projects. Adjustments should be made to run the model and to find an optimal solution for a particular problem. The exact layout of the model, including all the nodes and arcs, will be different for each project and material type. By answering the inventory questions, the decision maker can transform the general model to a case specific model. The inventory of the process leads to the identification of all the nodes. After the nodes have been defined, the level of circularity for each potential outcome should be defined based on the priority. Finally the data should be collected to define the values of the cost and other parameters. After these three steps the model can be run and the outcome can be evaluated. Running the model for multiple values for the weighting coefficient will provide the Pareto solutions. The decision-maker can select the solution from the Pareto frontier which fits best his strategy. Figure 3.8 provides a summary of the steps to take in order to find the optimal solution for a particular problem.

![Flowchart of the steps to take by the decision-maker](image)

The next chapter will focus on the practical implementation of this model. Two different test cases will be used to test and validate the utility of the model.
4 TEST CASES
Test cases

To evaluate the applicability of the model, two test cases will be presented in this chapter. The steps as proposed in the flowchart in the previous chapter (3.8) will be followed for each test case and the result of these steps will be evaluated. The aim of this chapter is to test the applicability of the model and to validate its structure. Moreover it will test the performance of the mathematical model. By testing the model and its application, conclusions can be drawn whether or not the model meets its expectations:

- Is the model general applicable?
- Does the proposed RL-process applies for the assets in the infrastructure?
- Will the proposed guideline and process inventory questions lead a correct and complete model?
- Provides the outcome of the model an answer about the economical feasibility of applying the principles of CE in the EoL phase of an asset?
- To which extend does it support decision-makers in making decisions about the EoL waste management of their assets?

This chapter only will provide an outline of the performed test cases and the obtained results. The next chapter will discuss the applicability of the model.

The test cases involve a type of asset which is part of a demolition project in the infrastructure. Therefore, assets have been chosen that are widely used in the infrastructure. The goal of this research was to design a model which is general applicable for all types of products in the infrastructure. To be able to draw a conclusion about the general applicability of the model, the characteristics of the two assets should be very different. The two assets that have been selected based on the variety of the following characteristics:

- **Decomposition:** Does the asset consist of different elements that are easy to separate? Or does it require special machines?
- **Quantity:** The size of the material flow, from the asset, after demolition.
- **Size per unit:** What is the volume of the asset? Is it easy to transport or does it require special types of transportation?
- **Components of the asset:** Is the asset made out of components or elements that are also used in other assets?

The assets that have been chosen are lampposts and concrete, which are both widely used in the infrastructure but differ on each of the points above. The point of departure for both case studies is a demolition project where a particular asset is being removed. The problem for the decision-makers is to optimise the deconstruction activities at the project site, the transportation, the recycling and disposal processes of the demolition waste. The decision-maker is the project owner.

Information for this case study is collected from literature and expert interviews. The interviews had two purposes: First to understand the process of waste management for that specific asset, which is needed for the
inventory of the process. Second to collect data which is used as input for the model. Appendix C provides the interview protocol that has been used and an overview of the interviewees. The models in this case study have been solved in Microsoft Excel 2016, by using the Excel add-in Analytical Solver, version 2016-R3, that can solve linear, integer, and non-linear problems in Excel (Excel Solver, 2017). This chapter consists of two parts: The concrete case and the lampposts case. The structure of both parts are in line with the steps of the flowchart. It starts with some background information about the asset, the current practise of waste management and the role of circular economy. The parts will finish with the modelling results.

4.1. Concrete

Concrete is the most used product in the construction industry (Frenay et al., 2015). In 2010 37,700 kton concrete was used in the construction sector and about 14,000 kton was released. More than 40% of the total amount of concrete used in the Netherlands is used for infrastructural projects. Concrete is responsible for 5% of the CO2 emission in the world and 1,7% in the Netherlands (Bijleveld et al., 2013). Because of the high impact of concrete (both on CO2 emission and amount of resources used), the industry has decided to act together to improve the sector. The Green Deal "Sustainable Concrete supply chain" has been signed in 2012 by the governance and multiple companies in the concrete sector (Bijleveld et al., 2013). The aim of this deal was to take actions in order to have a fully sustainable concrete chain by 2050. Different actions have been taken in order to reach this goal. The idea of the green deal is that collaboration between all the stakeholders in the chain is the key to a circular concrete chain. The aim is to make sustainable changes in the production of concrete, design of concrete structures, the use of concrete, the demolition and recycling of concrete. For the EoL phase, the focus lies on recycling techniques and regulation in order to make it easier to reuse concrete waste (Ministerie van Infrastructuur en Milieu, 2016). In general, concrete is made out of cement, water and aggregates (sand and rubble). Segregation of primary resources from the concrete is technically very difficult which means that reusing all the primary resources again and again is not (yet) possible. When a construction consists of prefab concrete elements, these elements could be reused as a whole for the same purpose. However, in-situ concrete can not be reused as a whole. The only element which can be separated easily is the reinforcement steel, which can be part of a concrete construction. The reinforcement steal can be melt down and used as steel for all kinds of purposes. Whether concrete elements include reinforcement steal or not depends on the purpose of the concrete. About 85% of the concrete used in the infrastructure is not for constructive purposes and therefore has no reinforcement steal (Bijleveld et al., 2013). The current practise of concrete waste management is to crush concrete blocks after demolition and recycle the crushed concrete to an extend that it can be used for foundation purposes or as aggregate for the production of concrete. About 95% of the concrete waste is used for foundation and elevation purposes (Rijkswaterstaat, 2015). A small percentage of concrete waste is being used as secondary aggregates which can replace primary aggregates like gravel. New techniques are under development to extract cement stone from concrete rubble, which can be used for the production of cement. This technique is called C2CA and is developed by TU Delft in collaboration with different companies (Lieshout and Nusselder, 2016).

A demolition project of a concrete construction starts with a project owner. For infrastructure projects this is almost always a government body. The project owner assigns a contractor to demolish the construction. This contractor can hire a sub-contractor for demolition or do it by them self. After demolition, the contractor is responsible that the waste will be brought to an accredited waste treatment company. The waste treatment company is responsible for processing the concrete waste. (interview Jasper Passtoors). Figure 4.1 illustrates the life-cycle of concrete with different ways to reuse concrete at the EoL.
The test case

Because there was no project available that could be used for this test case, the test case is a hypothetical situation. We consider a large demolition project of a roundabout and a part of a road in Huizen, a city in the province Noord-Holland which is situated next to a waterway. 5200 ton of unreinforced concrete will be extracted from the construction site and needs to be processed. The project owner, the municipality, has to decide how the concrete will be processed. The decision on how the concrete waste will be processed will be made by applying the model. The approach will be according to the flowchart that is shown in the previous chapter (3.8).

4.1.1. Step 1: Process definition

The aim of the first step is to specify the structure for the model. This can be done by answering the process inventory questions, as has been described in chapter 3. Answering these questions will lead to a design of the model where all the nodes and the connecting arcs are defined.

- **What are the potential levels of circularity, based on the quality?**
  The potential way of reusing concrete from demolition projects has been briefly described in the introduction. There are five potential destinations for concrete waste:
  1. Prefab concrete elements as a whole;
  2. Reusing cement stone for the production of cement;
  3. Aggregates for the production of concrete;
  4. Foundation purposes;
  5. Reusing the remelted steel for all kinds of new products.

  This case includes in-situ, unreinforced concrete. Therefore, the first and last options are not a potential destination for the concrete. The other three destinations are technically feasible for the concrete waste of this test case. For this test case the assumption has been made that the C2CA technique that makes it able to extract cement stone from concrete waste is already on the market.

- **Which of the processing activities can be done on the construction site?**
  Different activities can take place on the construction site for processing concrete. The construction needs either to be demolished or de-constructed before it can be transported to the next location. The
concrete should be separated from the other materials in order to be reused as a separate material flow. The construction will be demolished with the use of a demolition hammer. This results in concrete blocks. These blocks could either be directly loaded in the transportation unit or it could be further processed on the construction site. Further processing means crushing the concrete waste so that it will become concrete rubble with the use of a mobile crusher. Additionally, it can even be further recycled to granulate and fine segment by using the mobile recycler.

- **Can the product/component directly be reused at another project?**
  When the concrete only will be demolished at the construction site, it requires further processing before it could be reused. The rubble which is a product of the mobile crusher, can be used for foundation purposes or can be processed further in order to be used for other purposes. The mobile recycler can extract the fine segment and granulate from the concrete waste. About 40% of the output will be granulate. This can be directly used as aggregates for the production of new concrete. The fine segment cannot be reused directly. The fine segment (60% of the output), needs to be mixed with other material before it can be used for foundation purposes. Fine segment, can in theory, be used as sand replacement for the production of concrete. However, the quality requirements are high and therefore in practise is hardly applied yet (interview BCM consultancy).

- **If yes, what are the locations of the potential purchasers?**
  The use of a mobile crusher and the mobile recycler results in ready to use products. The granulate can be send to concrete suppliers or to a project site where they can produce the concrete on site. Two of the three selected projects have a demand for granulate. Foundations are used at project sites. All the selected projects demand the foundation materials. Figure 4.2 shows all the locations of the recycler, suppliers and projects.

- **If no, what are the locations of the potential processing facilities?**
  The concrete waste which has not been processed on the construction site should be brought to a recycler. The rubble which comes from the crusher can also be brought to a recycler for further processing. There are many concrete recyclers in the Netherlands. However, not at all recycling stations are able to process the concrete waste into the same type of material. As has been described in the introduction, there are new techniques under development to extract cement stone from concrete rubble. The C2CA installation is located in Hoorn, where the company “GBN Goep” is located. The process of getting secondary aggregates from concrete is something which can be done by more recycler. The secondary aggregates can be made from concrete rubble and the concrete demolition waste which has not crushed yet. This can be done at a recycler in Amsterdam, Utrecht or it can be send to Hoorn. The same location can be used for crushing the concrete waste when it has not been crushed yet on the project site.
· **Does it need to be stored before?**
  All the recyclers have the capability to store the processed materials at the recycling location. Therefore, no additional costs are included. Recyclers usually store the recycled materials and wait until the prices rise of that particular material (interview BCM consultancy). Therefore, the storage is part of the activities of recycler. The selected projects that need materials need it right away and therefore, no additional storage is required.

· **What are the possible options for transportation?**
  There are different options for transportation which have all different characteristics. There are two main types of transportation units: The vehicle and ship. Within these categories there is a variety. For this case three types of transport has been taken into consideration: Two types of vehicles and one type of ship transportation. The large vehicle has the capacity of 30 ton, which is the maximum capacity according to the regulations. The smaller vehicle has the capacity of 20 ton. For the transportation over water, a new type of ship has been selected. It is a ship that is already used for construction project in the city of Amsterdam (interview Jasper Passtoors). It has a maximum capacity of 130 ton, which is smaller than regular transportation ships. Transportation by ship will only be possible when the origin and destination is located near a water. The recycling centre in Hoorn where the installation is to extract cement stone from the concrete waste is located near the water way. The recycling centre in Amsterdam is also located next to a waterway. The loading costs are higher for transportation by water compared to vehicles. All the locations can be reached by the truck. The transportation routes will be the same for both types of trucks. The route of the ship will be different.

The cost of transportation can change in the future. To reduce the CO2 emission in cities, municipalities have started to make demands about transportation methods in the city. This involves that in cities only electrical vehicles are allowed and not the regular trucks. This has as consequence that the materials, when they have to be transported far away, will be passed over to the original truck outside the city. This additional activity involves extra costs.

Figure 4.3 provides an overview of the process of concrete waste flow after demolition for this case study. This scheme can easily be transformed in a network of nodes and arcs. This network results in a MILP model with 127 continuous variables, 39 integer variables, 3 binary variables and 87 constraints excluding the binary, non-negativity and integrality constraints.
4.1.2. Step 2: Circularity weighting factors

The weighting factors will be added to obtain the circularity objective. The circularity weighting factors will be assigned to the final materials that are the result of the RL-process. The value of the weighting factor is based on their level of circularity. Table 4.1 provides the interpretation of the 10-R model for concrete.

Table 4.1: Interpretation of the R-model for concrete

<table>
<thead>
<tr>
<th>Level of Circularity:</th>
<th>General definition</th>
<th>In relation to concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>R3 Re-use:</td>
<td>Re-use the same product by a different owner or location.</td>
<td>Reusing the concrete construction on the same location by different owner.</td>
</tr>
<tr>
<td>R4 Repair:</td>
<td>Repair and maintain a product so it can have the same functionality.</td>
<td>Repair and maintain the concrete construction to extend its lifetime.</td>
</tr>
<tr>
<td>R5 Refurbish:</td>
<td>Restore modernize old products.</td>
<td>Modernise the concrete construction. This is not really applicable for concrete.</td>
</tr>
<tr>
<td>R6 Remanufacture:</td>
<td>Use components of discard products for new products with the same functionality.</td>
<td>Use concrete elements for a new construction.</td>
</tr>
<tr>
<td>R7 Re-purpose</td>
<td>Use components of discard products for new products with different functionality.</td>
<td>Due the particular application of the product it is difficult to change functionality of concrete elements.</td>
</tr>
<tr>
<td>R8 Recycle:</td>
<td>Process components to obtain the same or lower quality.</td>
<td>This includes all types of processing activities where the processed components are used for foundation purpose, as aggregates or as cement stone.</td>
</tr>
<tr>
<td>R9 Recover:</td>
<td>Burn the materials and generate energy.</td>
<td>This is being avoided in the concrete industry.</td>
</tr>
</tbody>
</table>

All the potential end results of the waste flow of this case study are level "R8", recycling. However, the different end results are not equally circular. Further distinction should be made by applying the circular economy criteria to esteem the potential outcomes: Reduce energy and material leakage, minimising CO₂ emission and value preservation.

For all the potential destinations, the concrete waste will not end up as disposal. This means that the materials will stay in the economic cycle. However, when the concrete waste will be used for foundation purposes, the material will not stay in the concrete cycle. The consequence of this is that using materials for foundation purposes does not reduce the input of primary resources in concrete. Nevertheless, it reduces the input of primary resources for foundation purposes. When the concrete waste is used as aggregate for concrete and as cement stone for the production of cement, the materials will stay in the material cycle. The amount of cement stone that can be extracted from the concrete waste by the use of the C2CA technique is 6% (Lieshout and Nusselder, 2016). The residual flow is concrete rubble which can be used as aggregates (40%) and fine segment which can be used in foundation (54%). The amount of rubble for granulate purposes, what can be extracted from the concrete waste is 40%. The residual flow, the fine segment, can be used as foundation (Frenay et al., 2014). However, the fine segment cannot directly be used for foundation purposes. It should be mixed with a more coarse material to meet the technical requirements for foundation materials (interview BCM). Therefore, it can be concluded that fine segment has no value. The fine segment can be used, when it meets quality requirements, as replacement of sand in concrete (CE Delft, IVAM & Rebel, 2016). Currently,
Test cases

The extraction of cement stone from the concrete waste scores best on the criteria of minimising the material leakage. Nevertheless, the other two should be taken into consideration as well. The production of CO2 emission is probably the biggest issue of the construction sector because concrete is responsible for a significant amount of CO2 emission. 60% of the environmental impact of concrete comes from the production process (Cement&BetonCentrum, 2008). It is clear from figure 4.4 that the high level of CO2 emission from the production process is due to the production of cement. Furthermore, the transportation of materials contributes to the CO2 emission for 26%. The high level of CO2 emission from the production of cement is the reason that a lot of research is done on ways to extract cement stone from the concrete waste (Lieshout and Nusselder, 2016). For this test case, the application of the C2CA techniques is used, but there is also another technique in development which is called the Smart Crusher. The recycling of cement stone generates substantial environmental benefits.

The last criteria which should take into consideration is the value preservation. The perception of value preservation will change over time. The expectation is that the value of foundation material will go down due to saturation of the market. The saturation can partly be explained by decline in the construction of new roads. Besides that, foundation can be reused over and over. The aggregates on the contrary, will rise in value over time. The primary aggregates, especially gravel, will become more scarce in the future and therefore will rise in value. The main location where gravel extraction takes place in the Netherlands, will close at the latest by 2022. Furthermore, the governance does not provide permission for extraction of gravel on a large scale any more (Frenay et al., 2014). The expectation for cement stone is that the prices will rise due to the closing of the mining location of limestone in the Netherlands in 2018. Resources for cement production will be imported from other countries which will lead to higher prices due the transportation costs ((Stichting ontwikkelingsmaatschappij ENCI-gebied, nd).

Based on the analyses, the cement stone gets the highest weighting factor (3 out of 4), followed by granulate (2 out of 4) and the lowest weighting factor will be given to concrete rubble that and fine segment for foundation purposes (1 out of 4). Fine segment should be mixed with other concrete waste before it can be used for foundation purposes. When the fine segment can be applied in producing concrete, the weighting factor will be the same as for granulate (2 out of 4).

4.1.3. Step 3: Data collection

In the first step the arcs and nodes have been defined. The second step resulted in values for the circularity weighting factor. In this step, the values of all the other parameters should be defined. This involves the cost and the general parameters. From the interviews it became clear that it is difficult to collect data for the model because either companies assume the data to be confidential or to be too complicated, especially regarding the cost parameters. This complexity is caused by the dependency of the value on multiple aspects. Therefore, assumptions have been made regarding the cost parameters. The parameters are obtained from literature research and by asking different stakeholder of the concrete industry. To value the processed materials, the assumptions has been made that the value will be equal to the primary resources. When granulate can replace the aggregates, it has the same value as aggregates. Although these values fluctuate, it is easy to find this data. The technology of C2CA is not yet further developed. The current value of the cement stone is zero, because it replaces a stream in the cement production which has no value. As soon as it has been proven

![Figure 4.4: CO2 footprint of concrete production (adopted from Vos and Plaggemans (2016))](image-url)
that the extracted cement stone can be used as filler, the value will rise enormously. The same applies for fine segment. Currently is has no value, because additional materials are needed in order to be able to use it for foundation purposes. However, when it can be used as sand replacement in the production of concrete, the value will rise. Both options have been taken into consideration when running the model. A representation of the excel spreadsheet with the collected data is shown in Appendix E.

4.1.4. Step 4: Running the model

The solving time of the model is negligible. The model is run for two scenario’s, based on the potential innovations and changes in the industry of concrete. The first scenario will be the basic scenario. The obtained data will be used to simulate the process as has been described in the previous steps. This includes that cement stone has value and fine segment does not. In the second scenario, the fine segment will have value due to the technical innovations. The model have calculated the optimal solution in each scenario for different values of the weighting coefficient $w_i$ (Where $w_i \geq 0, \forall i = 1, ..., k$ and $\sum_{i=1}^{k} w_i = 1$).

4.1.5. Results

Figure 4.5 shows the optimal solutions for both scenarios.

The basic scenario provides a Pareto frontier and the other scenario does not. Applying the weighting coefficient for the first scenario results in the two extreme outcomes. The Pareto points in between have been obtained by setting constraints to the value of circularity, instead of applying the weighting coefficient. The feasible values for circularity in the first scenario are between 1 and 2. The reason for this is that the value of circularity is an average. The most circular end product is cement stone. However, only a small percentage of the concrete can become cement stone. The remaining part can only be reused for purposes with a lower value of circularity.

There is only one optimal solution for the second scenario, for each value of $w_i$. This means that the most optimal solution for the circularity objective is equal to the most optimal solution for the cost objective. The RL-process with the minimum cost involved has the highest circularity. In this scenario, the fine segment can be reused for purposes with a higher level of circularity. Therefore, the highest level of circularity that can be obtained in this scenario is 3.1. The value of fine segment will increase when it can be reused in the production of new concrete. Therefore the revenues will increase. The results shows that technical innovations will
lead to higher revenues and more circularity in the construction sector.

The model did not only provide information about the minimum costs and the maximum level of circularity, it also provided information about the most optimal RL-network. The most optimal RL-network designs for the two scenarios will be discussed.

**Scenario 1: Basic scenario**

The first scenarios has multiple optimal solutions, which means that there are multiple optimal RL-network designs. The two extreme solutions will be discussed. The first RL-network is the one where the weighting coefficient of cost is one and the weighting coefficient of circularity is zero. The result is shown in figure 4.6.

The optimal RL-network from a cost perspective is to process the concrete at the project site into concrete rubble and use it for foundation purposes. In this scenario, the option with the least transport distance is the optimal solution. The transportation and recycling costs outweigh potential revenues. Keeping the distance as short as possible will be beneficial for the costs.

The optimal RL-network for the circularity objective is shown in figure 4.7.

The RL-network design differs a lot from the previous one. The materials will be recycled at the construction site. The fine segment, which is 60% of the waste flow, will be transported by boat to the only recycler that can perform high value recycling. Cement stone will be extracted from the fine segment by applying the C2CA technique. The cement stone will be sold to a cement supplier. Cement stone has a high residual value. However, the quantity of cement stone that can be extracted is only 6% of the total waste stream. The fine segment is the residual stream with no value. The granulate (40% of the waste flow) will be transported by
4.1. Concrete

trucks and directly applied to make new concrete at the nearest project. The granulate will provide revenues.

**Scenario 2: Scenario with value for sand**
The expectation is that the value of fine segment will increase due to technical innovation. Technical innovation will make it possible to use the fine segment as sand replacement for the production of new concrete. Therefore, it will obtain the same value as sand. The network-design is the same for each value of the weighting coefficient. The RL-network is shown in figure 4.8.

![Figure 4.8: RL-process according to the second, with value for sand](image)

The most optimal RL-network for the second scenario is almost the same as the RL-network of the basic scenario where only the circularity objective is taken into consideration. The only difference is the fact that, in this scenario, the fines segment will be sold to a concrete supplier. For this scenario, both the circularity and the cost objective have been optimised. This means that the revenues from the fine segment are high enough to make this the most favourable option from a cost perspective. From this result it is clear that technical innovation will lead to more financial benefits.

The expectation is that the prices for resources for the production of concrete will rise in the future and that value of foundation material will decrease. This will make the above RL-network even more beneficial.

The transportation factor influences the output of all scenario’s. It is beneficial to perform the recycling activities on the construction site because it reduces the transportation costs. This is shown in both scenarios. For transportation over longer distances the boat was always the best option. This will become even more visible when the municipalities introduce the transportation requirements in the city, as described in the previous paragraph. This will not change the RL-network design.
4.2. Street lights

In the Netherlands there are about 3.5 million street lights (Openbareverlichting.nl, 2017). This makes the Netherlands one of the most luminous countries in the world. Street lights exist of multiple elements. It depends on the interpretation which elements are part of the street lights. In this case it is assumed that the asset “street lights” includes the armatures, the poles and the lamps. Figure 4.9 provides a clear overview of all these elements.

In the recent years, sustainability has become an important topic in the field of street lights. The focus has been primarily on the energy reduction in the sector. The reason for the focus on energy consumption lies in the fact that street lights consume a lot of energy. In 2011 the street lights were responsible for about 60% of the energy consumption of municipalities (Taskforce Verlichting, 2011). In 2013 the sector has signed the Dutch Energy Agreement, in which goals have been set for the reduction of energy consumption in the Netherlands (SER, 2013). This agreement resulted in the transition to LED lighting for street lights.

It is only recently that the material cycle has gained attention in the sector of street lights. The sector associations of public lighting has adopted the ambitions of the governance to reduce the use of primary resources. The association has started with collecting and sharing information on how to reduce the input of primary resources and how to avoid waste in the sector (OVNL, 2017). Despite the fact that closing the material cycle has just recently set on the agenda, there are already some practices that successfully have adopted the principles of circular economy. There are some suppliers in the field of street lights who have started a take back system in order to obtain high quality recycling. One example is SAPA, who takes back aluminium poles and remelts the aluminium to make new poles (Bordes, 2017). Another example is the company Ziut, who enables people (who have poor jobs prospects) to work to separate all the valuable materials from the armature (Ziut, 2016).

In the field of asset management, street lights are always divided in three parts: the pole, the armature and the lamp. There is a wide variety of street lights. The pole can be made from multiple materials like steel, aluminium and wood. The armatures and lamps also come in all shapes and sizes. The armatures and lamp include material like copper, plastic, glass, steal, aluminium and iron (Vos and Plaggemans, 2016). The three components all have a different lifetime. A pole has a life time of around 40 years. The life time of an armature is between 15 and 20 years. The lifetime of the lamp differs. It used to be 5 years, but now with the rise of the LED-lighting the lifetime can be 20 years. This means that in the life time of a street light, the lamp has been replaced four times and the armature twice. However, the transition towards the LED-light has changed the life time of the lamp from five years to fifteen/twenty years. The municipalities are owner of 95% of the street lights in the Netherlands (Energieakkoord, 2017). The installation, maintenance and replacement of the street lights is done by a contractor which is assigned for the job multiple years by the municipality. The street lights will be demolished at its technical EoL or when it no longer meets the aesthetic requirements. The maintenance contractor will remove the street lights or will assign a subcontractor to do this. Elements of the street light that are still in good condition are sometimes stored and used as spare parts for maintenance purposes (interview Sjaak Roosenboom). The other parts of the street lights are brought to an external recycler or will be brought to the contractor, where it will be demolished. What will happen after this process depends on the element and type of material. Since 2014 it is legally obligated to separate armatures and lamps and recycle them (art. 4.1 Bouwbesluit 2012). The materials can be recycled and used in other industries or be used again for the construction of new street lights. Some materials are send to landfill. Figure 4.10 provides a visualisation of the life-cycle of street lights.
The test case

For the test case we consider a project in Pernis, a district of Rotterdam. The poles of the street lights in this district have reached their technical EoL age of 40 years. Therefore, the street lights should be removed and new street lights will be placed. After inspection, the municipality has decided to remove the following items:

- 175 street lights as a whole (8 metres);
- From 30 street lights only the armatures and the lamps;

Since the street lights are 40 years old, the poles are theoretically at their technical end-of-life. Stabilisation test have been performed and it seemed that the poles could be used safely for at least five more years. Due to aesthetic reasons the poles will still be removed. All the poles are made from galvanized steel. The armatures have not yet reached their life-time of 20 year. However, not all armatures are in good condition. After inspection it has been decided that 50% of the armatures are still in good condition and can be reused. The lamps in the armatures have all reached their EoL. The lampshade of the armatures are made from polycarbonate and the casing is made from aluminium. The maintenance contractor is responsible for the replacement.

4.2.1. Step 1: Process definition

Similar to the concrete case, the process of the street lights will be defined by answering the process inventory questions.

- **What are the potential levels of circularity, based on the quality?**
  The street lights can be seen as multiple individual products, which can have different qualities. One street light can be in poor condition while the other is still in good condition. The same applies for the different components in the product (eg. armature, lamp and street light). Figure 4.11 provides an overview of the decomposition of the asset.
There are multiple potential destinations for the different components of the street lights.

1. Reuse the street light as a whole;
2. Reuse the pole;
3. Reuse the armature;
4. Reuse the electronic devices from the armature;
5. Reuse the lamp;
6. Reuse elements of the armature for new armatures.
7. Reuse the remelted steel for all kinds of new products;
8. Reuse the materials from the armature for all kinds of new products;
9. Reuse the materials from the lamp for all kinds of new products.
10. Landfill

As stated before, 50% of the armatures can be reused again. However, it can only be placed at places where the same type of armature is used. Although the poles have reached their EoL, they are still in good condition and can be used for the purpose of street light for a couple more years. 50% of the street lights can be reused as a whole. The lamps have reached their EoL and can therefore not be reused as a whole. Therefore, all the proposed options can be included for this case except the reuse of lamps.

• **Which of the processing activities can be done on the construction site?**
  The street lights will be removed from the ground at the location or, in case of removing only the armature, this element will be decoupled from the pole. There are multiple options from there: All three components (lamp, armature and pole) can be separated at the construction site and be transported separately. The armatures and lamp can be transported separately from the poles, or the street lights can be transported in one. When the poles will be transported separately, there are two options: The poles can be cut in pieces on the construction site or the poles can be transported in one piece.

• **Can the product/component directly be reused at another project?**
  All the poles can be used directly for another project. 50% of the armatures can also be used again for another project. Furthermore, 50% of the street lights can directly be reused at another project.

• **If yes, what are the locations of the potential purchasers?**
  The types of armatures from this project is a type of armature that is widely used in Rotterdam. These armatures are not fabricated any more. The armatures can be used as spare parts for the city of Rotterdam. The same applies for the poles. The municipality uses all the available armatures as spare parts,
4.2. Street lights

but they do not need so many poles. Therefore, there is a maximum of poles that are needed as spare parts. Besides, there is another project in The Hague, which is 35km away, where they need 40 new armatures of the same type. The town Hook of Holland wants 40 street lights that can replace other for a couple of years. Due to the sea air at Hook of Holland, the street lights have a shorter life time. The municipality has planned a replacement of street lights in this district in three years. However, some of the street lights need to be replaced now. Therefore, they can use the discard street lights for the street light that cannot rest for another three years. The town Noordwijk needs 50 street lights for five years for the same reason.

• **If no, what are the locations of the potential processing facilities?**
Further decomposition can take place at the contractors or at a recycler. The contractor enables people with poor job prospective to do the further decomposition. There are two recycling options for the armature: The armatures can be recycled by machines, which results in a recycling level of 80%. The second option is that the armatures will be first be taken apart by hand before it will be recycled by machines. This extra step results in the fact that elements of the armature that are still in good quality can be selected and reused again. This results in a recycling rate of 96%. The armatures and lamps can also be send to WeCycle, an organisation that recycles lamps and armatures. This organisation will collect the armatures and lamps without additional fee at the project location. A recycling fee is paid at the time of purchase of new products (interview Gied van Hoorn, Lightrec). The poles can be brought to a metal trader when the poles are demolished and cut into pieces.

• **Does it need to be stored before?**
The armatures which are used as spare parts, can be stored until needed. The armatures can be stored at the recycling centre of the municipality or it can be stored at the storage location of the contractor. No additional costs are included. The same applies for the poles. The capacity for poles at the storage facility in Rotterdam is 10 and the capacity of the storage facility at the recycler is 20. The towns Noordwijk and Hook of Holland can use the whole street lights right away. Figure 4.12 provides an overview of the locations involved.

![Figure 4.12: Overview of the locations involved](image)

• **What are the possible options for transportation?**
All the materials will be transported by vehicles. There are two types of vehicles available for the transport of street lights as a whole: A small vehicle with a capacity of 10 street lights and a large vehicle with capacity of 50 street lights. The armatures (with or without lamp) can be transported by a small vehicle with the capacity of 50 armatures or it can be transported by a vehicle with the capacity of 250 armatures. The poles can be transported by a vehicle with the capacity of 50 poles. It can also be trans-
ported by a container vehicle when the poles will be cut in pieces. This vehicle has a capacity of 80 units.

Figure 4.13 provides an overview of the process of street light flow after demolition for this test case.

Adjustments to the general model should be made in order to transform the proposed process to a MILP-model. As shown in figure 4.11, the asset can be clearly dived in products, components, elements and materials. The asset exists of 175 street lights and 30 armatures. Each street light consists of one armature, one lamp and one pole. These components consist of single elements, etc. Therefore the flow cannot be expressed in weight (tons or kilograms), but should be expressed in units. Therefore, parameter $a_{ijm}$, that defines the percentage of material $m$ that is obtained from asset $i$ by the processing activity $j$ does not apply for this case.

One street light can deliver one lamp, one pole and one armature. The flow constraint will be therefore:

$$X_{ijm1} = \sum_{k=1}^{K} X_{jkm2}, \quad \forall j = 1, 2, ..., J \forall m.$$  

The supply constraint of the dummy requires also a change. The supply of the dummy cannot be the demand minus the supply.

$$d_{qm} - \sum_{n=1}^{N} X_{nqm} + \sum_{k=1}^{K} X_{kqm} = X_{zqm}, \quad \forall q = 1, 2, ..., Q \forall m.$$  

Because the flow will be defined by units, all the variables should be integers. There will be two supply nodes instead of one. One for the street lights and one for the single armatures. As had been stated in the previous paragraph, only 50% of the armatures can be reused again. Therefore, 50% of the street lights can end up as street lights again and 50% of the armatures can be used as armatures again. This requires an additional constraint.
This network results in a MILP model with 87 integer variables, 6 binary variables and 64 constraints excluding the binary, non-negativity and integrality constraints.

### 4.2.2. Step 2: Circularity weighting factors

The interpretation of the 10-R model for the case of street lights is shown in table 4.2.

Table 4.2: Interpretation of the R-model for street lights

<table>
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<td>Repair and maintain a product so it can have the same functionality.</td>
<td>Repair the street light by replacing the lamp, recover the electronics, etc.</td>
</tr>
<tr>
<td>R5 <strong>Refurbish:</strong></td>
<td>Restore modernise old products.</td>
<td>Modernise the street lights by placing a more sustainable lamp, add more sustainable coating, or modernise the armature.</td>
</tr>
<tr>
<td>R6 <strong>Remanufacture:</strong></td>
<td>Use components of discard products for new products with the same functionality.</td>
<td>Reuse the armature, pole or lamp for a new function.</td>
</tr>
<tr>
<td>R7 <strong>Re-purpose</strong></td>
<td>Use components of discard products for new products with different functionality.</td>
<td>Electronics, cables can easily be used for another function. Poles and armature will be more difficult due to its specific design.</td>
</tr>
<tr>
<td>R8 <strong>Recycle:</strong></td>
<td>Process components to obtain the same or lower quality.</td>
<td>Materials such as copper, steel, aluminium, glass and plastic can be recycled and used for all kinds of products.</td>
</tr>
<tr>
<td>R9 <strong>Recover:</strong></td>
<td>Burn the materials and generate energy.</td>
<td>All the materials that have no value will be burned.</td>
</tr>
</tbody>
</table>

The potential end results of this case have the circularity level R3, R6, R7, R8 and R9. Before assigning the circularity weighting factors on these levels, the potential end results should be assessed against the three CE criteria. Reusing the street light at another location falls into level R3, Re-use, which is the highest level. Reusing the street lights means no material leakage and the only CO2 emission is caused by the transportation. The value of the street light is low because it already has passed its theoretical life-time. On the other side, it does not loose any value by replacing it. The drawback of this destination is that after a couple of years, the street lights have to be demolished. Reusing the street light as a whole can be seen as extending the life-time of an asset.

Reusing the components of the street light such as the pole and armature belongs to level R6, re-manufacture. A street light can be easily decomposed. Reusing components in terms of circular economy is almost similar as reusing the whole asset. Because the different components are easily to extract from the street light, the material and energy loss is minimal. The CO2 emission is only caused by transportation and it prevents the CO2 emission from producing new components. For the criteria value preservation it goes the same as for the option of reusing the street light as a whole. Therefore, it can be concluded that reusing components will get the same circularity weighting factor as reusing the asset as a whole.

Using small elements such as cables, electronics, lampshades and the covers for any purposes falls into level...
R7, re-purpose. Extracting these elements from the components should be done at the recycling place by hand and machines. This means that there is some energy leakage. This potential destination scores high for the criteria of value preservation and CO2 emission.

Recycling the materials of the asset falls under R8, recycling. Recycling means that multiple processing activities are required before it can be used again for the same purposes. These activities cause CO2 emission and energy leakage. Most of the materials in the asset have a high recycling rate, which means that the material leakage is low. Recycled materials decrease in value because it loses its function.

Sending the materials to landfill where it will be burned falls into level R9, Recovery. Sending the materials to landfill results in 100% material leakage, a 100% loss of value and additional CO2 emission. In this case, recovery has not taken into consideration.

This analysis results in the following circularity weighting factors:

- Reusing the street light as a whole: 4
- Reusing the components: 4
- Reusing the elements: 3
- Recycling: 1

4.2.3. Step 3: Data collection

The values used for this test case can be found in Appendix F. The project location and quantities come from a project of the city of Rotterdam. The global parameters were obtained by interviews with specialists in the field of street lights and documents. For confidentiality reasons it was difficult to obtain exact values of cost parameters. The processing costs on the project site has been found in documents. The recycling costs are estimations based on man hour and use of machinery. The value of the materials after processing are the today's market value of these materials. The value for the second hand products and components (street lights, armatures and poles) are based on the remaining life time.

4.2.4. Step 4: Running the model

The solving time of the model is negligible. Different scenarios are applied to the model. The first scenario is the basic scenario, as described in this section. In the second scenario, the quality constraints that allows only 50% of the armature to be reused are ignored. In the third scenario the quality constraints and the demand constraints are both left out. The model has calculated the optimal solution in each scenario for different values of the weighting coefficient \( w_i \) (Where \( w_i > 0, \forall i = 1, \ldots, k \) and \( \sum_{i=1}^{k} w_i = 1 \)).
4.2.5. Results

Figure 4.14 shows the optimal solution for each scenario.

What is striking is that there is no Pareto frontier. For each of the scenario there is only one optimal solution, for each value of \( w \). This means that the most optimal solution for the circularity objective is equal to the most optimal solution for the cost objective. The RL-process with the minimum cost involved has the highest circularity. This means that implementing circular principles leads to direct cost savings. For the basic scenario, the highest circularity possible is 2.6. This is due the fact that there is a limitation on the quantity of products that can reach a high level of circularity, due to the quality constraints. For the second scenario the maximum level of circularity is 3. There is no quality constraint, but there is still a maximum demand for products with a high circularity level. The last scenario does not have any quality constraints and it assumes that there is an unlimited demand. The highest level of circularity to be reached than is 3.8. It is clear that the higher the circularity is, the lower the processing costs are.

To obtain an insight in the RL-process, the most optimal RL-network designs for the three scenarios will be discussed in the following paragraph.
Scenario 1: Basic scenario

The first scenario represents the most optimal RL-network for the situation as has been described in the previous paragraphs. Figure 4.15 represents this network.

The majority of the street lights are removed as a whole and 50% is sent to other municipalities to be reused. The other street lights which have been removed as a whole are sent to the recycler where the components will be further separated. A part of the poles will be used as spare parts and stored at the recycler. The poles that are left after the demand of the storage at the recycler has been satisfied, will be cut into pieces and sent to the metal trader. The armatures that have been separated from the poles will be high value recycled. This means that the elements of the armatures that can be reused will be collected before the armatures will be processed by machines.

The minority of the poles are separated at the construction site into armatures (with lamp) and poles. The poles are stored in Rotterdam and the armatures are sent to the recycler with the other armatures. At the recycler the lamps will be taken from the armatures. The armatures will partly be high value recycled and partly be used as spare armatures. All the lamps are collected by the organisation WeCycle. All the armatures and street lights that are of sufficient quality are being reused as a whole.

Figure 4.15: RL-process according to the basic scenario
Scenario 2: Without quality constraints
The basic scenario assumes that only 50% of the armatures can be reused again. The next scenario assumes that all the armatures have sufficient quality to be reused again. The network is shown in figure 4.16

![Diagram showing RL-process when there are no quality constraints](image)

The main difference between this scenario and the basic scenario is that all the street lights and armatures are being reused until the demands are satisfied. The lamps are collected by WeCycle. More processing activities take place at the project site compared with the basic scenario. This is because it reduces the transport distance. The armatures can be stored near the project location. Further difference is that there is no high value recycling of armatures involved. The poles that are left after all demands for poles or street lights have been satisfied are brought to the metal trader.
**Scenario 3: Without quality constraints and with unlimited demand**

The final scenario is performed to check what the optimal network would be when there are no constraints concerning demand or quality. The result is shown in figure 4.17.

The most optimal network design, from circular and financial point of view, is the reuse of street lights and armatures as a whole. Where the products are being brought to the nearest purchaser.

It is clear from the outcomes that the more products can be processed according to a high level of circularity, the more cost saving there are.
5 DISCUSSION
Two different types of assets, concrete and street lights, were applied to the model. This chapter will discuss the outcome of both test cases, including a comparison between the test cases. The aim of this discussion is to draw conclusions on the general applicability of the model. The chapter will first evaluate both test cases separately. This evaluation consists of three parts. In the first part, the results obtained from running the model will be discussed. Secondly the applicability of the proposed guideline will be discussed. Finally the applicability of the mathematical structure will be evaluated. Based on the observations of both test cases, the general applicability of the models will be discussed in the final section of the chapter. Moreover, the limitations and opportunities of the model will be given.

5.1. Concrete

To model has been tested on a test case where concrete waste was being proposed. This section will provide a reflection on the case as described in the previous chapter.

5.1.1. Model result

There is not a wide variation in the possible level of circularity for the whole waste stream. This is due to the fact that the final circularity is the average of the circularity of all flows. There is only a small amount of the total flow that can become material with a high circularity level. The transportation distance has a high impact on the outcome of the model due the high cost of transporting concrete. It can be concluded that when designing a RL-network for concrete waste, the distances should be as short as possible. There are almost 200 concrete suppliers in the Netherlands (Betonplatform, 2014) and it is assumed that there is about the same number of recyclers in the Netherlands. Therefore, it should be possible to reuse the concrete waste in the region. Moving as much as possible processing activities to the construction site will also reduce the transportation distances and therefore the the costs. Further investments and innovations in new transportation methods over water, like the electrical boat, could improve the reverse logistics of the demolition concrete. High value reuse of concrete is not yet financially the most favourable option. selling concrete waste obtained enough revenue to become financially most favourable option. Improving the circularity by one level lead to a substantially decrease in revenue due to the higher processing costs. However, this will change when fine segment will become widely applicable for sand replacement. The expectation that the value of primary resources will increase and the price of foundation materials will decrease will also benefit the financial feasibility of circular solutions in the RL-process of concrete. The outcome provides an insight on the financial feasibility of applying the principles of CE in the EoL phase of concrete. It provides also an insight on the aspects that influences the feasibility.
5.1.2. Applicability of the guideline

The test case has been solved by following the proposed steps from the flow chart. This has been done by answering the process inventory questions, applying the circularity weighting factors, collecting the data and finally run the model and evaluate the results. The question is if this is the right approach to come to a model that could help decision-makers in making decisions about the EoL waste management of their asset. The inventory questions follows the RL-process of assets in the construction industry. By everlasting these question, the applicability of the proposed RL-process can be evaluated as well. By answering the question, all the options for the RL-process of concrete have been collected. However, the collected options are not always available. The inventory of the process starts with the question about the potential destinations of the concrete waste and their level of circularity. There are not many different options for concrete currently, but there are a lot of developments on recycling techniques. When taking these innovations into account, there are multiple options as potential destinations for the concrete. Which processing activities can take place at the construction site depends on multiple factors such that there is often no choice left. Especially in infrastructure projects it is often due to the time limitations that there are no processing activities possible on the construction site. Closing a road causes hindrance and therefore it is important that the demolition process on the construction site will be as short as possible. For that reason, project owners and contractors will choose to do as much activities as possible somewhere else (interview BCM consultancy). Another aspect that limits the options for processing activities at the construction site for concrete projects, is the location of the project. In urban areas it is often not allowed to use the mobile crusher or mobile recycler due to the noise pollution. Besides, in urban areas, there is often not enough space to perform recycling activities at the construction site (Interview BCM consultancy). In practise, the vehicles with the capacity of 30 ton will always be used for large construction projects. This is the maximum capacity allowed on the road and therefore always beneficial. Using boats for transporting concrete waste is not a common applied method of transportation. However, this model helps to get some insight of potentially more preferable transportation methods. Storage is always available at the construction site. The potential storage facilities for concrete are all located at the recycler. In the test case, more storage facilities could have been included to test the influence of opening special storage facilities for concrete that goes from one project directly to another without additional recycling. As stated before, there are many recyclers, concrete suppliers and potential projects. The model could easily be extended by including more options. This could help to design the optimal RL-network where locations are close and the demand and supply will fit best. It can be concluded that the proposed RL-process fits overall the RL-process of concrete and therefore the inventory questions are applicable. However, in practise it turns out that not all the activities of the RL-process have many possibilities to choose from.

Applying circularity weighting factors, depending on the level of circularity to the potential outcomes, helps to evaluate the potential outcomes. It provide a clear overview on what the additional cost would be to obtain a better level of circularity. Therefore, decision-makers will have a clear view on the consequences of implementing circular principles in their waste management.

Collecting all the available data is difficult and time consuming. Different stakeholders are involved who all have a part of the information. To optimise the input of the model, all stakeholders should share their information. This is unfortunately not realistic. It is assumed that the profit of the project owner equals the revenues from the material minus the cost of processing. It should be noted that in practice not all the costs are paid by the project owner. The recycler gets paid for processing the materials and later sells the processed materials. The higher the value of the processed material, the lower the recycling costs will be.

5.1.3. Applicability of the mathematical structure

The proposed mathematical model fits the RL-process of concrete. Therefore the RL-process of concrete could easily be applied to the mathematical model. All concrete is composed of the same main materials. The main materials can differ, but there are no big differences. Hence, the models for each concrete case will be similar to this one. The model of the test case is small, but can be extended by adding additional processing locations, potential projects and other purchasers. A demolition project where concrete is being demolished involves also other assets. The model could be extended by including all the assets of the demolition project. Nevertheless, the weighting coefficients applied on the objectives did not lead to expected results. Only two vertex where found as possible solutions. Small changes in the value of weighting coefficient leaded to large jumps in the outcome. This hurdle have been overcome by changing the circularity objective into a con-
5. Discussion

Running the model for different values of the circularity constraints have obtained the intermediate results. It can be concluded that the overall mathematical formulation fits the concrete case very well. Only the weighting coefficients do not lead to the required outcomes.

5.2. Street lights

To model has been tested on a test case where street lights in Rotterdam where being replaced. For this case a mixed of street lights and single armatures had to be processed.

5.2.1. Model result

Contrary to the concrete case, the transportation distance does not have a high impact on the outcome of the model. High level recycling is always the most cost efficient option. This is even more beneficial than having the armatures after demolition being picked up by WeCycle without additional fee. For each scenario the optimal solution for the cost objective was equal to the optimal solution for the circularity level. Moreover, the more circularity can be obtained, the more the processing cost decrease. The reason for this is that street lights can easily be dismantled. Street lights can easily moved from place and change of owner. Street light is a product that can easily be decomposed into components that can easily be used again. The EoL of an asset does not always implies the EoL of a product. Moreover, the reason of demolition is not always because of technically disability of the street light. Besides, the different parts of street light can easily be extracted and have certain value. This results in many opportunities of reusing street lights. Therefore, it can be concluded that applying the principles of CE in the EoL phase is financially feasible. The maximum feasible level of circularity to be obtained depends on the quality of the demolished street lights and the demand for secondary products. An average circularity level of 4 cannot be obtained due to the fact that the lamps in this case could only be recycled by WeCycle, there was no quality left for reuse. The outcome provides interesting knowledge for decision-makers that have circular ambitions. These ambitions can be fulfilled when the exchange of products between municipalities will be improved.

5.2.2. Applicability of the guideline

Street lights can have all shapes and sizes. Therefore, the first inventory question, about the potential destination of the asset and its material, is case specific. Because the street lights are easily to decompose and to be reused in parts, there is a wide variety of potential destinations for the lights. The option of reusing street lights for a couple of years in other cities is an approach which is currently not used in the field of street lights. However, this could be an option that could be further investigated and has the potential of improving the circularity in the field of street lights. Using the components as spare parts is the current procedure of municipalities. The requirement of the municipality is that all the armatures that are still working will be used as spare parts for maintenance work in the city (interview Peter Wijnands). The decomposition activities can take place at the construction site. Further processing activities requires installations which are not available at the construction site. Poles and armatures are seen as two separate products with a whole different market. After the decomposition of the pole and armature, these products will be processed separately by different stakeholders. According to laws it is obligatory to hand in the armatures and lamps to WeCycle or to other processing facilities that have the right certificate. This is due to the fact that electronic devices have special processing requirements. In practise, many demolition contractors will process the materials them self to obtain the materials, even when they are not certificated (interview Gied van Hoorn). The assumption for this case has been made that the contractor has the right certificates for processing armatures and lamps. There are not many options for the type of transportation in the field of street light and transportation does not influence the RL-process of street lights. Therefore, it can be concluded that transportation is not a critical aspect in optimising the RL-process of street lights. Due to the volume of the material and size of the products, storage facilities are not a critical aspect in the RL-process. There are always possibilities for storage at the contractor or at the storage facilities of municipalities. No additional cost are included. Because the storage of street lights is not a cost item, the timing of demand and supply is not an important factor. It can be concluded that the RL-process of street lights fits the proposed general process.
Applying the level of circularity on potential approaches of processing EoL street lights, depends on whether the armatures are assumed to be separate products or not. This shows the subjectivity of the levels of circularity. Moreover, reusing a street light, pole or armature only results in extending the life-time for a couple of more years. At the end, everything should still being recycled. This means that it is not possible to obtain a high level of circularity infinite.

Poles and armatures are seen in the sector as two separate industry. Data obtained on the processing activities are from both industries. There is a wide variety in types of street lights, therefore data is often very case specific. The data can be obtained from the three main stakeholders involved: The project owner (the municipality), the contractor and the manufacturer (armatures and poles). The contractor is responsible for the whole RL-process of street lights. Minimising costs and maximising revenues will benefit the contractor. It can be stated that such a model could support the contractor in making decisions about the RL-process.

5.2.3. Applicability of the mathematical structure

Several adjustments had to be made to the mathematical structure in the case of the street lights. The most important adjustment was the flow constraint and the unit type. The flow had to be expressed in units instead of weight and the flow capacity does not fit the transshipment model where the inflow equals the outflow. A street light consists of many materials. The model has simplified this structure by not mentioning all the materials separately. When optimising the EoL phase of each single materials, all these materials should be defined separately. The proposed model is a very small model. There are two ways of extending the model. The first option is to zoom in to the processing activity of street lights where each material will be defined separately. The second option is to combine different maintenance projects and optimise the exchange of products or components. There is a wide variety of street light designs which are made of different materials. Only the pole can be made out of five different types of materials already. This implies that the model can look very different for each street light case.

The weighted-sum method did not provide another solution than when the two objective function were solved separately. However, this could be different when applying the model to another case in the street light industry.

5.3. General

Street lights and concrete are two very different assets in the field in infrastructure. For both cases, the model provided a clear insight on the financial feasibility of applying circular principles to the EoL processing approaches. Applying the weighted-sum method should have obtained a Pareto frontier. However most of the cases, the optimal solution for the circularity objective was equal to the optimal solution for the cost objective. The reason for this "positive" outcome could be that there are no inventory cost include and additional cost that are involves for managing the waste process not the regular way. When there where multiple optimal solution, only the vertex solution where shown. There are other solution techniques available that can help to overcome this problem.

The model design seems to fit the concrete case better than the case of the street lights. For the street lights, more adjustments had to be made. Besides, there are more opportunities for developing and extending the model for the concrete case. The strength of the model is that it can support matching demand and supply and that it can help to evaluate the financial feasibility of multiple approaches of processing the EoL phase of an asset. The model can help in designing the most optimal RL-network. Moreover, the model has proven to be a good tool to evaluate different scenario whereby decision-makers could be better prepared for the future. The model can easily be extended, which makes it interesting to apply for a whole project instead of a single asset. The RL-process can generally be applied for all kinds of assets in the field of infrastructure. Drawback of this general application could be that critical aspects in the RL-process of a certain asset can be easily overlooked. A limitation of the applicability of the model is that it is difficult to collect all the necessary data due to the lack of transparency in the construction sector. More reliable data would lead to more reliable outcomes.

Despite this limitations, the model has proven to be a valuable tool for decision-makers to analyse their waste management strategies. The model provides an answer about the financially feasibility of applying the principles of CE in the RL-process of assets from the construction industry.
CONCLUSIONS & RECOMMENDATIONS
Conclusions & Recommendations

6.1. Conclusions

The aim of this research was to develop a model that supports decision-makers in the infrastructure with optimising the circularity of the return flow of their asset while minimising the costs. The model should be generally applicable for all kinds of assets in the infrastructure. Circularity involves the principles of circular economy. Circular economy is a regenerative system that aims for a closed material and energy cycle. Closing the material and energy cycle can be obtained by avoiding waste and energy leakage and minimising the input of resources. The current system is based on linear principles of take, make and dispose. The transition towards a circular system requires a different economic system and a redesign of the current business cases. The construction industry uses more than 50% of the primary resources and is responsible for a large amount of $CO_2$ emission. Therefore, large gains can be obtained when the construction industry will move towards a circular economy. Despite the fact that CE can provide major benefits on environmental, economic and technical level, there all still some obstacles that withhold the industry from a big transition. The main obstacle that keeps the construction sector away from moving towards a circular economy, is lack of a secondary market due to the undeveloped take-back system. This results in the fact that it does not seems to be financial feasible to apply the principles of circular economy in the sector. Reverse logistics (RL) have been recognised as the potential enabler for accelerating the circular economy in the construction industry. RL is the process of planning, implementing and controlling material flow from the point of consumption to the point of recovery and back to the market. The activities involved in the RL-process of a construction project includes the collection, inspection and selection, recovery and redistribution of the material. Many RL-models have been developed to optimise the return flow of goods. However hardly any of these models are designed for the construction sector which focuses on the economic implications in combination with the environmental concerns. This research tries to fill this research gap by designing a RL-model which is applicable for the construction sector.

6.1.1. Model framework

To create a model that optimises the circularity of a return flow, it is important to understand what circularity means for the the return flow. Improving the circularity at the End-of-Life (EoL) phase of assets involves minimising the waste. Minimising waste can be obtained by reusing the material to such an extent that the least primary resources are needed for the next life cycle. Improving the circularity at the EoL phase of an asset can be done by reducing the material and energy leakage, minimising $CO_2$ emission and preserving the value. To prioritise multiple waste strategies based on its circularity, the 10-R model can be applied. The 10-R model provides a hierarchy of waste processing strategies. The rule of thumb of this hierarchy is that the more the product will remain intact, the higher the level of circularity. However, this is not always the case. To obtain a more realistic level of circularity, the 10-R model should be used in combination with the three aspects that define the goals of circularity.

Reverse logistics in the infrastructure have some special characteristics. These characteristics should be iden-
6.1. Conclusions

Identified because it influences the structure and design of the model. One important characteristic of the construction industry that has been identified is the dynamic nature of the reverse flow. There is a high fluctuation in the release of assets in the construction industry due to the volume of the asset. This results in fluctuation in the demand and supply for secondary materials in the construction sector. The type of product that should be processed differs a lot from other industries. Often assets in the construction sector are large and not easy to move. Therefore, the design of the RL-network is case specific. It is not possible to design a fixed network of facility locations. The reverse flow has a high level of uncertainty due to the high variety of quantity, quality and timing of returned products. The model should deal with these dynamics of the sector.

Linear programming (LP) has been found to be the most suitable approach for modelling the problem of this research. LP is a method that is widely used to model logistics problems. Linear programming is known as an application to optimise problems. For this case, linear programming will be used to optimise the circularity of the reverse logistics process of materials in the construction industry while minimising the costs. The proposed problem has been identified as a network problem. This network problem can be transformed into a transshipment model. A transshipment model can design a RL-network where the demand and supply will be matched. Therefore the model deals with the dynamic nature of the construction industry. The model has two objectives: minimising costs and maximising circularity. The decision-maker should make a trade-off between these two objectives. Therefore the weighted-sum method will be applied. By adding weighting coefficient the two objective can be combined in one objective function. The results of the model will be the Pareto optimal solutions. These are solutions from where it is not possible to improve one objective without making sacrifices to the other objective. The obtained model is a general applicable RL-model which will be solved by applying LP. To make the model general available, a guideline has been developed on how to apply the model for a specific case. This guideline consists of multiple steps that should be taken to solve a specific model. These steps involve the inventory of the RL-process, defining the level of circularity, collecting the data, running the model and evaluating the outcome.

6.1.2. Application of the model

The applicability of the model and the guideline have been tested on two different types of assets in the infrastructure. The first test case was about concrete. From the outcome could be concluded that transportation has a high influence on the financial feasibility of applying the principles of circular economy in the EoL phase of concrete. Technical innovations and more scarcity of resources will make the implementation of circular principles financially more feasible. The reverse logistics process of concrete can easily be transformed in the proposed mathematical model. However, the weighted-sum method did not provide all the feasible solutions.

The second case was about street lights. It was clear from the outcome that transportation had hardly any influence on the outcome of the model. Furthermore, it seemed that the most circular approaches of processing the street lights were also financially the most favourable options. Street lights can easily be decomposed into separate components which have all different lifespans and quality. Therefore it can be concluded that a circular return flow of street lights, that is financially feasible, can be obtained when there will be more exchange of street lights and components between municipalities. To transform the RL-process of street lights in the proposed mathematical model, some adjustments have to be made.

From these two test cases it can be concluded that the model is general applicable. The model can support matching demand and supply and it can help to evaluate the financial feasibility and circularity of multiple approaches of processing the EoL phase of an asset. Therefore trade-off's can be made between circularity and costs. This will reduce the uncertainties that prevent the market to move towards a circular economy. The model is able to support the design of the most optimal RL-process. The model has proven to be a good tool to evaluate future scenario’s. It is possible to extend the model such that it can be applied to a whole project instead of a single asset. The provided guideline makes it easy to apply the model in practise.
6.1.3. Limitations

Although the model has proven to meet the objectives of this research, there are some limitations of the model that should be mentioned. The model is a simplification of the reality, which means that some aspects that may influence the course of the RL-process are not included. The model assumes an ideal situation in which aspects such as regulations and external factors have not been taken into consideration. The limitation of a general applicable model is that critical aspects in the RL-process of a certain asset can easily be overlooked. Another limitation of the model, concerning the applicability, is that it is difficult to collect all the necessary data due to the lack of transparency in the construction sector. Unreliable data results in an unreliable outcome. More transparency in the supply chain is required to improve the model.

This research has obtained a basic model that combines economic implications with the environmental concerns in the infrastructure. This model has the potentials to be further developed and extended.

6.2. Recommendations

Recommendations can be given for further research, which are based on the conclusions of this study. The recommendations are listed below.

- **Conducting a more depth research**
  This research resulted in a basic framework for a model that supports circular decision making in processing the assets at the end of life. However, this framework requires further development. This research has taken the whole RL-process into account, from disposal to redistribution, on a general level. Further research could focus on one or two of the steps of this process and include a more depth research.

- **Investigating the potential of storage facilities for concrete waste**
  Further research could only focus on the "storage" aspect of the RL-network. This is an undeveloped area within the reverse logistics and requires more research (Circle Economy, 2016). Special storage facilities could improve the RL-network design and improve the match between supply and demand.

- **Including time**
  The aspect "time" has not be taken into account in the model. Including time in the model could help to obtain long-term strategies for the RL-network.

- **Extension of the model**
  This research focuses on the reverse flow of one material type. In practice, a demolition project has to deal with multiple materials. Further research should focus on combining all materials in one model.

- **Life cycle**
  Future studies could focus on the optimisation of other parts of the life cycle. A combination of those studies could lead to more knowledge regarding the whole life cycle. When the whole life cycle could be combined in one model, more reliable statements can be made about the circularity.

- **Measure circularity**
  Future studies could focus on tools to measure circularity which can be included in the model. Consequently, the objective function of the model could maximise the circularity.

- **Weighted-sum method**
  The weighted-sum method has some weaknesses when the problem is solved with the simplex method (which is the solving approach of Excel) (Grodzevich and Romanko, 2006). Future research could use different solution techniques to obtain a better result from the multi-objective problem.


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Formulating transshipment model in Excel

The excel add-in “solver” provides a method for solving shortest-path problems. This add-in relies on the general simplex method (Excel Solver, 2017). Figure A.1 shows the spreadsheet formulation of the system as described in the previous paragraph.

In the first place the assumption has been made that the demand equals the supply, therefore, no dummy node is included. Column J listed all nodes of the system. The first node is the supply node and the last two nodes are the destination nodes. The requirement for the net flow of all nodes are listed in the supply/demand column. Because the net flow is calculated by subtracting the inflow from the outflow, the supply node has a positive net flow. The demand nodes have, for that reason, a negative net flow. The intermediate node should have a net flow of zero. The columns D and E together are listing the arcs. column D presents $i$, the start of the arc and column E points $j$, the end of the arc. The “cost” of moving one unit from one node to another is listed in column H, which is a parameter $c_{ij}$. The objective is to minimize the total value of cell F23, which presents the total cost of the transshipment:

$$Z = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij}$$  \hspace{1cm} (A.1)

The cells F3:F19 listing the decision variables $x_{ij}$, which is the amount of units that will be transshipped through a particular arc. The net flow, which is listed in column K, is defined by subtracting the outflow from the inflow of a particular node. The constraint of this problem is that column K should be equal to the net
flow requirements. Running the model provides the optimal solution as shown in figure A.2. The yellow arcs represent the chosen path which provides a right solution for the given problem.

![Figure A.2: Solved model in excel](image)

In the described excel model, the supply as equal to the sum of all demands. As have been described in the previous part, this is not the case in this research. The demand represents all possible destinations for the demolition waste, while the supply represents one demolition project. Therefore, a dummy node has been added to obtain a feasible solution. The net flow of this dummy node is determined by subtracting the total demand by the supply. The dummy node is directly linked with the demand nodes. The unit cost, $c_{ij}$ of the arc from the dummy node to the demand nodes will be zero. The new excel form is shown in figure A.4.

![Figure A.3: Spreadsheet formulation of model with dummy node](image)

The demand of R3 and R4 have been changed for this example to 200 and 100. The supply is still 50. This results in a mismatch of 250 units between demand and supply. Therefore, the supply of the dummy node
will be 250. This results in a different optimal solution for the system. The chosen path is represented in figure 6.

Figure A.4: Solved model with dummy node
Mathematical formulation

The following tables provide an overview of all the indices, variables and parameters used for the mathematical model. The employed indices are provided at table B.1

<table>
<thead>
<tr>
<th>Indices</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i = 1, 2$</td>
<td>demolished asset and dummy node</td>
</tr>
<tr>
<td>$j = 1, \ldots, J$</td>
<td>type of processing activities at the project site</td>
</tr>
<tr>
<td>$k = 1, \ldots, K$</td>
<td>type of transportation</td>
</tr>
<tr>
<td>$n = 1, \ldots, N$</td>
<td>processing facility</td>
</tr>
<tr>
<td>$q = 1, \ldots, Q$</td>
<td>final purchaser</td>
</tr>
<tr>
<td>$m = 1, \ldots, M$</td>
<td>material</td>
</tr>
<tr>
<td>$m' = 1, \ldots, M'$</td>
<td>material that is obtained in the recycling step</td>
</tr>
</tbody>
</table>

The decision variables which are used in the formula are provided in table B.2:

<table>
<thead>
<tr>
<th>Decision variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_{ij}$</td>
<td>quantity (unit) of the demolished asset $i$ which will be processed at construction site according to activity $j$.</td>
</tr>
<tr>
<td>$X_{ijmq}$</td>
<td>dummy node: quantity (unit) of unsatisfied demand of material $m$ that is sent from dummy node $i$ to purchaser $q$.</td>
</tr>
<tr>
<td>$X_{jkm}$</td>
<td>quantity of material $m$ (unit) that has been processed by activity $j$ and will be loaded into transportation type $k$.</td>
</tr>
<tr>
<td>$X_{knm}$</td>
<td>quantity of material $m$ from transportation unit $k$ that is processed at recycler $n$.</td>
</tr>
<tr>
<td>$X_{kpqm}$</td>
<td>quantity of material $m$ from transportation unit $k$ that will be directly be sold to purchaser $q$.</td>
</tr>
<tr>
<td>$X_{nqm}$</td>
<td>quantity of material $m$ from recycler $n$ that will be sold to purchaser $q$.</td>
</tr>
<tr>
<td>$Y_j$</td>
<td>binary variables denoting if activity $j$ will be performed.</td>
</tr>
<tr>
<td>$N_{km}$</td>
<td>integer variables that defines the number of transportation units $k$ that will bring materials to the recycler $n$.</td>
</tr>
<tr>
<td>$N_{kq}$</td>
<td>integer variables that defines the number of transportation units $k$ that will bring the material to purchaser $q$.</td>
</tr>
</tbody>
</table>

The parameters are the required input for a specific case. Tables B.3 and B.4 provide the cost parameters and the general parameters.
### Cost parameters

- $c_{ij}$: variable cost of processing the deconstruction waste $i$ at the project site according activity $j$ (€/unit).
- $c_{dkm}$: variable cost of loading material $m$, which has been processed according activity $j$, in transportation unit $k$ (€/unit).
- $c_{kn}$: variable cost of transporting one transportation unit $k$ to recycler $n$ (€/unit).
- $c_{knm}$: variable cost of processing the material $m$ from the transportation unit $k$ at recycler $n$ (€/unit).
- $c_{nqm}$: variable cost of moving the materials $m$ from recycler $n$ to purchaser $q$ (€/unit).
- $c_{nk}$: variable cost of transporting the transportation units $k$ to purchaser $q$ (€/unit).
- $c_{nqm}$: variable cost for storing material $m$ from recycler $n$ before selling it to purchaser $q$.
- $c_{kqm}$: variable cost for storing material $m$ from $k$ before selling it to purchaser $q$ (€/unit).
- $c_{z}$: cost of moving material $m$ from dummy node $i$ to destination $q$ (always €0,/-unit).
- $k_{d}$: fixed cost for using/renting processing equipment for activity $j$ (€).
- $r_{nqm}$: revenues from selling material $m$ from recycler $n$ to purchaser $q$ (€/unit).
- $r_{kqm}$: revenues from selling material $m$ of transportation unit $k$ right away from the construction site to purchaser $q$ (€/unit).

### General parameter

- $a_{ijm}$: percentage of material $m$ that is obtained from asset $i$ by the process activity $j$ (%).
- $d_{nmm'}$: percentage of material $m'$ that is obtained from processing material $m$ from recycler $n$ (%).
- $C_k$: capacity of transportation unit $k$ (tn).
- $s_i$: supply: the total amount of the demolished asset that is available at $i$ (tn).
- $d_{qm}$: demand: the total amount of required material $m$ of purchaser $q$ (tn).
- $b_{jkm}$: parameter denoting whether material $m$ obtained at activity $j$ can be transported by transportation unit $k$ ($b_{jkm} = 1$) or not ($b_{jkm} = 0$).
- $g_{nqm}$: parameter denoting whether material $m$ obtained at recycler $n$ can be sold to purchaser $q$ ($g_{nqm} = 1$) or not ($g_{nqm} = 0$).
- $e_{q}$: the level of circularity of using material $m$ at final purchaser $q$, which is assigned according to the waste hierarchy.
- $w_1$: the weighting coefficient for the objective function of cost minimisation.
- $w_2$: the weighting coefficient for the objective function of circularity maximisation.

The mathematical formulation of the model has the following objective function:
Minimize Z:

\[
Z = w_1 \left( \sum_{j=1}^{f} c_{ij}^o X_{ij}^o + k_j Y_j \right) \\
+ \sum_{j=1}^{I} \sum_{k=1}^{K} \sum_{m=1}^{M} c_{jkm}^d b_{jkm} X_{jkm}^d + \sum_{k=1}^{K} \sum_{n=1}^{N} c_{kn}^w N_{kn}^w \\
+ \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{m=1}^{M} c_{knm}^l X_{knm}^l + \sum_{n=1}^{N} \sum_{q=1}^{Q} c_{kn}^p N_{kn}^p \\
+ \sum_{k=1}^{K} \sum_{q=1}^{Q} \sum_{m=1}^{M} c_{kqm}^v \left( r_{kqm} - r_{kqm}^v \right) X_{kqm}^v \\
+ \sum_{n=1}^{N} \sum_{q=1}^{Q} \sum_{m=1}^{M} \left( c_{nqm}^s + c_{nqm}^f - r_{nqm}^f \right) g_{nqm} X_{nqm}^f \\
+ \sum_{q=1}^{Q} c_{iqm}^s X_{iqm}^s \\
- w_2 \left( \sum_{k=1}^{K} \sum_{q=1}^{Q} \sum_{m=1}^{M} e_{m} X_{kqm}^p + \sum_{n=1}^{N} \sum_{q=1}^{Q} \sum_{m=1}^{M} e_{m} X_{nqm}^s \right)
\]  

(B.1)
Subjected to:

\[
\begin{align*}
\sum_{j=1}^{I} X_{ij}^o + \sum_{q=1}^{Q} \sum_{m=1}^{M} X_{iqm}^z &= s_i, \quad i = 1, 2 \quad (B.2) \\
\sum_{n=1}^{N} X_{nqm}^s + \sum_{k=1}^{K} X_{kqm}^p + \sum_{i=1}^{I} X_{iqm}^z &= d_{qm}, \quad \forall q = 1, 2, ..., Q, \ \forall m \quad (B.3) \\
\sum_{i=1}^{I} s_i &= \sum_{q=1}^{Q} \sum_{m=1}^{M} d_{qm} \quad (B.4) \\
\sum_{i=1}^{I} a_{ijm} X_{ij}^o &= \sum_{j=1}^{J} X_{jkm}^d \quad \forall j = 1, 2, ..., J, \ \forall m \quad (B.5) \\
\sum_{j=1}^{I} X_{jkm}^d &= \sum_{n=1}^{N} X_{knm}^r + \sum_{q=1}^{Q} X_{kqm}^p \quad \forall k = 1, 2, ..., K, \ \forall m \quad (B.6) \\
\sum_{m=1}^{M} \sum_{k=1}^{K} d_{nmk} X_{knm}^r &= \sum_{q=1}^{Q} X_{nqm}^s \quad \forall n = 1, 2, ..., N, \ \forall m' \quad (B.7) \\
\sum_{m=1}^{M} X_{knm}^r &\leq C_{k kn} \quad \forall k = 1, 2, ..., K, \ \forall n \quad (B.8) \\
\sum_{m=1}^{M} X_{kqm}^p &\leq C_{k kq} \quad \forall k = 1, 2, ..., K, \ \forall n \quad (B.9) \\
\sum_{i=1}^{I} X_{ij}^o &\leq M Y_j \quad \forall j = 1, 2, ..., J \quad (B.10) \\
X_{jkm}^d &= 0 \ \forall j, k, m \in b_{jkm} = 0 \quad (B.11) \\
X_{nqm}^s &= 0 \ \forall n, q, m \in g_{nqm} = 0 \quad (B.12) \\
X_{ij}^o, X_{knm}^r, X_{kqm}^p, X_{nqm}^s &\in \mathbb{R}^+, \quad N_{kn}^r, N_{kq}^p \in \mathbb{N}, \quad Y_j \in \{0, 1\} \quad (B.13)
\end{align*}
\]
Interview protocol

To make the test cases as realistic as possible, it is important to obtain an insight in the practise of waste management for both materials. Therefore, experts interviews have been conducted for this research. The goal of the interviews is to gain information about the material flow to firstly, be able to design the specific model for the test case and secondly to be able to define the values of the parameters.

The interview type which is common to use for expert interviews are unstructured or semi-structured interviews (Baarda et al., 2007). As the goal of the interview is to generate input for the model, a semi-structured interview is chosen. The questions are not fixed in advance for a semi-structures interview, but the subjects do. Due to the fact that the questions are not fixed in advance, unexpected subjects can be added during the interview. The subjects will be treated in logical sequence and a new subject is introduced by the same first question (Baarda et al., 2007). The advantage of a semi-structured interview is that the researcher can ask supplementary questions to gain specific knowledge. The disadvantage of this type of interview is that the interview has a lower validation than a structured interview (Baarda et al., 2007).

The structure of an interview follows the process of the material. A general interview schedule is composed which follows the structure of the model. The interview will start with some general questions to introduce the subject. Subsequently, questions are asked for each section about the choices that can be made. Closed questions are asked about costs and distances, although the interviewee might not be able to answer directly. If the question can not be answered, the interviewee might be able to respond after the interview. The interviews will be recorded to increase the reliability of the interview.
Table C.1: Structure of the interview

<table>
<thead>
<tr>
<th>Section</th>
<th>Questions</th>
</tr>
</thead>
</table>
| General                  | What processes are involved from demolition to processing of the materials?  
• How can demolition waste be re-used?  
• Which parties are involved in processing demolition?                                                                                       |
| Construction site        | How exactly will demolition take place at the construction site?  
• Which parties are involved in the demolition at the construction site?  
• Activities  
• How are the costs composed?  
• Indication for the costs  
• How is demolition waste separated at the construction site?  
• Which products and product components are in the demolition waste?  
• Quantities                                                                                                                                     |
| Transport                | How is the transport of demolition waste organised?  
• Distribution of materials for transport  
• Transport type  
• Which parties are involved in the transport  
• What are the costs  
• What are the distances                                                                                                                                 |
| Recycler/waste processor | What can be done with the demolition waste?  
• Where does the demolition waste go to?  
• What are the residual values and which ones are the most valuable?  
• What are the costs for dump?  
• Which parties are interested in demolition waste?  
• What are the advantages/disadvantages of using demolition waste instead of primary materials?                                              |
The table C.2 provides an overview of all the experts which have been interviewed for this research.

Table C.2: Approached experts

<table>
<thead>
<tr>
<th>Name</th>
<th>Organisation</th>
<th>Case</th>
<th>Part of the chain</th>
<th>Expert</th>
<th>Appointment</th>
<th>Focus subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jasper Passtoors</td>
<td>Municipality of Amsterdam</td>
<td>Concrete</td>
<td>Project/asset owner</td>
<td>In dealing with the transition towards a more sustainable concrete chain</td>
<td>3th of May</td>
<td>General</td>
</tr>
<tr>
<td>Dirk van Zoest</td>
<td>J P van Deenen</td>
<td>Concrete</td>
<td>Contractor</td>
<td>Worked on a successful project where concrete from a demolition project was used for the construction of a new building.</td>
<td>4th of May</td>
<td>- Practical experience</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Activities on construction site</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Transport</td>
</tr>
<tr>
<td>Spint Roussemoons</td>
<td>Municipality of Almere</td>
<td>Street light</td>
<td>Project/asset owner</td>
<td>Technical consultant for public lighting</td>
<td>30th of May</td>
<td>General</td>
</tr>
<tr>
<td>Renate Huisman</td>
<td>GBN</td>
<td>Concrete</td>
<td>Recycler</td>
<td>Planner for demolition/recycling projects</td>
<td>10th of May</td>
<td>- CICA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Recycling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Demolition</td>
</tr>
<tr>
<td>Leonie Duijnstee</td>
<td>GMP-group/Pyro</td>
<td>Concrete</td>
<td>Demolition contractor, recycler and transporter</td>
<td>Concrete waste treatment</td>
<td>8th of May,</td>
<td>- Transport</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>by telephone</td>
<td>- Recycling</td>
</tr>
<tr>
<td>Peter Wijngaard</td>
<td>Municipality of Rotterdam</td>
<td>Street light</td>
<td>Project/asset owner</td>
<td>Coordinator of a replacement project for street lights in Rotterdam</td>
<td>30th of May</td>
<td>General</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Test Case</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Project site</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Recycling</td>
</tr>
<tr>
<td>Richard Gestel</td>
<td>City Tec</td>
<td>Street light</td>
<td>Maintenance contractor</td>
<td>In responsible for maintenance and replacement of the street lights in Rotterdam</td>
<td>16th of May</td>
<td>- Test Case</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Project site</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Recycling</td>
</tr>
<tr>
<td>Guus Vorhout</td>
<td>BCM-consultancy</td>
<td>Concrete</td>
<td>Demolition consultancy</td>
<td>Director of demolition consultancy company</td>
<td>8th of September</td>
<td>- Demolition</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Transport</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Recycling</td>
</tr>
<tr>
<td>Jan Schiphorst</td>
<td>Gemeente &quot;W&quot; recyclinggroup</td>
<td>Concrete</td>
<td>Recycling</td>
<td>Director of the recycling company</td>
<td>Email conversation</td>
<td>- Recycling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Demolition</td>
</tr>
<tr>
<td>Hak van der Sleen</td>
<td>Gemeente</td>
<td>Street light</td>
<td>Consultant in circular asset management</td>
<td>Consultant on circular asset management for street light</td>
<td>5th of May,</td>
<td>- Recycling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>by telephone</td>
<td>- General</td>
</tr>
<tr>
<td>Cor van Aalens</td>
<td>Stichting Lichtsl. Nederland</td>
<td>Street light</td>
<td>Recycling</td>
<td>Director of Dutch recycling foundation</td>
<td>3rd of May,</td>
<td>- Recycling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>by telephone</td>
<td>- General</td>
</tr>
<tr>
<td>Sjaak de Jong</td>
<td>Van Joosdijk Infra</td>
<td>Street light</td>
<td>Maintenance contractor</td>
<td>By telephone</td>
<td></td>
<td>- Transportation</td>
</tr>
</tbody>
</table>

In order to develop an optimal model, experts have to be interviewed from different disciplines. The focus for the model is the process from demolition to recycling, which is investigated for two different materials: Concrete and street light. The selection criteria for the interviewees are therefore:

- Interviewees have knowledge on concrete and/or street light
- Interviewees are stakeholder in the chain: project owner, transporter and recycler

The table below was conducted to keep an eye on whether experts have been interviewed from different parts of the chain.

Table C.3: Approached experts

<table>
<thead>
<tr>
<th></th>
<th>Concrete</th>
<th>Street light</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project owner</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Deconstruction contractor</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Transporter</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Recycler</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>General/object-expert</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Not all approached interviewees are directly involved in the chain. The interviewees Coriolis and the municipality of Amsterdam have no direct role in the chain, but do have knowledge on the chain. There is a possibility that an interviewee is not able to answer all questions. For these cases, the snowball method is applied. This implies that the interviewee is asked if he or she knows someone who fulfils the criteria (Baarda
et al., 2007). This will help to gain knowledge on the whole chain. As can be seen in the scheme, the list of approached experts will not lead to information about the whole chain. The questions asked to the interviewee depend on the role of the interviewee in the chain. The table below provides an overview of all the experts that have been approached.
Sources for the test cases

Concrete test case


Street lights test case


Model input concrete case
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total amount of demolition concrete (tn)</td>
<td>5200</td>
</tr>
<tr>
<td>Costs for activities at the construction site (€/tn)</td>
<td>Demolition (€/tn) Demolition &amp; Crusher Demolition &amp; mobile recycler</td>
</tr>
<tr>
<td></td>
<td>0.50 € 1.50 € 1.75 €</td>
</tr>
<tr>
<td>fixed cost for activities at the construction site (€)</td>
<td>400.00 € 400.00 €</td>
</tr>
<tr>
<td>Loading cost (€/tn)</td>
<td>Boat (€/tn) Truck 20 tn (€/tn) Truck 30 tn (€/tn)</td>
</tr>
<tr>
<td></td>
<td>0.20 € 0.05 € 0.05 €</td>
</tr>
<tr>
<td>Processing cost at recycler</td>
<td>High value recycling Medium value recycling Low value recycling</td>
</tr>
<tr>
<td>Concrete waste</td>
<td>3.18 € 3.00 € 2.00 €</td>
</tr>
<tr>
<td>Concrete rubble</td>
<td>2.68 € 2.50 €</td>
</tr>
<tr>
<td>Granulate</td>
<td>2.95 € 1.50 €</td>
</tr>
<tr>
<td>Reinforced</td>
<td>2.40 € 0.90 €</td>
</tr>
<tr>
<td>Construction site option 1</td>
<td>100% 0% 0% 0% 0%</td>
</tr>
<tr>
<td>Construction site option 2</td>
<td>0% 100% 0% 0% 0%</td>
</tr>
<tr>
<td>Construction site option 3</td>
<td>0% 0% 100% 0% 0%</td>
</tr>
<tr>
<td>Recycler option 1 (low value recycling)</td>
<td>0% 0% 0% 40% 0%</td>
</tr>
<tr>
<td>Recycler option 2 (medium value)</td>
<td>0% 0% 0% 40% 40%</td>
</tr>
<tr>
<td>Recycler option 3 (high value)</td>
<td>0% 0% 0% 40% 100%</td>
</tr>
<tr>
<td>Recycler option 4 (high value) with the input from fine segment</td>
<td>0% 0% 0% 0% 100%</td>
</tr>
<tr>
<td>Capacity of transportation unit</td>
<td>Boat (max 130tn) Truck (max 20 tn) Truck (max 30tn)</td>
</tr>
<tr>
<td>Concrete blocks</td>
<td>100 15 24</td>
</tr>
<tr>
<td>Granulate</td>
<td>120 19 28</td>
</tr>
<tr>
<td>Fine segment</td>
<td>130 20 30</td>
</tr>
<tr>
<td>Rubble</td>
<td>125 18 27</td>
</tr>
<tr>
<td>Supply of origin</td>
<td>Concrete: km distance by road km distance by water</td>
</tr>
<tr>
<td>Location</td>
<td>Project Location</td>
</tr>
<tr>
<td>Potential recyclers:</td>
<td>Huizen GNP-group Hoorn Paro Oskam B.V. Betoncentrale Almere</td>
</tr>
<tr>
<td>Final Purchaser</td>
<td>Distance from (km): Huizen GNP-group Hoorn (C2CA) Paro Oskam B.V. Betoncentrale Almere</td>
</tr>
<tr>
<td>concrete rubble (foundation purposes)</td>
<td>Project 1 10 60 40 60 20 30 Project 2 40 50 25 30 20 Project 3 20 50 25 20 20</td>
</tr>
<tr>
<td>Current store</td>
<td>GNP-group Hoorn Oskam B.V. Betoncentrale Almere GNP-group Hoorn Oskam B.V. Betoncentrale Almere</td>
</tr>
<tr>
<td>Fine segment</td>
<td>0 0 0 0 0</td>
</tr>
<tr>
<td>Transportation, €/Unit (from project location)</td>
<td>GNP-group Hoorn Paro Oskam B.V. Project 1 Project 2 Project 3 ENCI Ijmuiden Mebin Hoorn Dyckerhoff Almere Mebin Amsterdam Oskam B.V. Betoncentrale Almere</td>
</tr>
<tr>
<td></td>
<td>truck 20tn truck 30tn boat 130tn</td>
</tr>
<tr>
<td>Concrete blocks</td>
<td>600 800 1000</td>
</tr>
<tr>
<td>Granulate</td>
<td>800 1000 1200</td>
</tr>
<tr>
<td>Fine segment</td>
<td>600 800 1000</td>
</tr>
<tr>
<td>Cement stone</td>
<td>600 800 1000</td>
</tr>
</tbody>
</table>
Model input street light case
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total amount of whole street lights</td>
<td>175</td>
</tr>
<tr>
<td>Total amount of only armatures</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Costs</th>
<th>Armature (pole stays)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>€</td>
</tr>
<tr>
<td>Street light as a whole (D1)</td>
<td>70.00</td>
</tr>
<tr>
<td>separate pole from armature (D2)</td>
<td>105.00</td>
</tr>
<tr>
<td>separate pole, armature (D3)</td>
<td>100.00</td>
</tr>
<tr>
<td>armature as a whole (D4)</td>
<td>25</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Transportation cost</th>
<th>Armature (pole stays)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>€</td>
</tr>
<tr>
<td>separate armature &amp; lamp (D4)</td>
<td>5.00</td>
</tr>
<tr>
<td>Cutting steel</td>
<td>3.00</td>
</tr>
<tr>
<td>Medium value recycling (D5)</td>
<td>3.00</td>
</tr>
<tr>
<td>High value recycling</td>
<td>9.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WeCycle</th>
<th>Armature (pole stays)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>€</td>
</tr>
<tr>
<td>armature &amp; lamp (D4)</td>
<td>0</td>
</tr>
</tbody>
</table>

| Revenue Weighting factors |
|---------------------------|----------|
| Pole (70 kilo) steel recycling | 1.25 |
| Street light as a whole | 2 |
| Pole as a whole | 1.75 |
| Armature | 1.75 |
| Polycarbonate panel | 1.25 |
| Lamp (negative) | 1.25 |
| Copper/ armatuur | 1.25 |
| Aluminium | 1.25 |
| Cables | 1.25 |
| Polystyrene | 1.25 |
| Small part like screws and lustre terminal | 1.25 |

| Processing cost at recycling |
|-----------------------------|----------|
| Armature & lamp (D4)  | 0 |
| Cutting steel | 5.00 |
| Medium value recycling (D5) | 3.00 |
| High value recycling | 9.50 |

<table>
<thead>
<tr>
<th>Capacity of transportation unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large trucks for armatures (250)</td>
</tr>
<tr>
<td>Small trucks for street lights (10)</td>
</tr>
<tr>
<td>Big trucks for pole (50)</td>
</tr>
<tr>
<td>Small trucks for armatures (50)</td>
</tr>
<tr>
<td>Big trucks for street lights (50)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Locations:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Location:</td>
</tr>
<tr>
<td>Pernis Rotterdam</td>
</tr>
<tr>
<td>Storage in Rotterdam</td>
</tr>
<tr>
<td>Recycler</td>
</tr>
<tr>
<td>Steel recycler A simons haven</td>
</tr>
<tr>
<td>Steel recycler B Vondelingshaven</td>
</tr>
<tr>
<td>Noordwijk</td>
</tr>
<tr>
<td>Hoek van Holland</td>
</tr>
<tr>
<td>Den Haag</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total amount of whole street lights</td>
</tr>
<tr>
<td>Total amount of only armatures</td>
</tr>
<tr>
<td>Costs for activities at the construction site (€/unit)</td>
</tr>
<tr>
<td>Transportation cost (€/unit)</td>
</tr>
<tr>
<td>Processing cost at recycling</td>
</tr>
<tr>
<td>Capacity of transportation unit</td>
</tr>
<tr>
<td>Locations:</td>
</tr>
<tr>
<td>Project Location:</td>
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<tr>
<td>Potential recyclers:</td>
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