Supply chain mapping for concrete recycling

The design of a closed-loop supply chain concerning
the integration of novel technologies
in conventional concrete production in the Netherlands

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PREFACE

This work represents the conclusion of my Master Thesis Project and fulfills the final requirement for my graduation at the Management of Technology program at the Delft University of Technology, Faculty of Technology, Policy and Management. I am grateful for all the experience that I gained, and the support that I received in order to achieve this milestone.

The accomplishment of this research could not be realized without the guidance of some very unique people. First of all, I would like to express my gratitude to my supervisor Ir. Marcel Ludema for his thoughtful insights and his continuous encouragement. Marcel was always available to answer the questions that I posed and inspire me to incorporate new aspects in my research. I would also like to express my warm thanks to the other members of the graduation committee, Chairman Dr. Ir. Lori Tavasszy and Dr. Maarten Franssen, for their critical feedback since their opinion, proved to be of decisive importance.

Special thanks to Prof. Dr. Peter Rem and Ing. Peter Berkhout from the 'Resource and Recycling Laboratory' in the Faculty of Civil Engineering, for introducing me to the concept of concrete recycling and giving me the opportunity to contribute to their research. They helped me when my work was in a dead-end and their recommendations were essential for the formulation of my final results. They shared with me not only confidential data but their valuable knowledge, and they invited me to meetings were experimental results from an industrial scale were presented.

Many thanks to all the interviewees and participants in my questionnaire survey. They were willing to share their experiences and viewpoints about concrete recycling as well as the new technologies in the construction sector.

The motivation behind my decision to choose the specific project lies in two friends of mine, who convinced me for the interest of concrete as the most important material in the urban environment, and at the beginning of my research, they shared their enthusiasm and expertise with me. This work would not exist without them.

Furthermore, I would like to express my hearty feelings for my 'family' in Delft because they made my stay in this 'village' outstanding. Without them, this journey would have been completely different and I feel so lucky about meeting them. They were the most important part of my life during these two years. Special thanks to my ex- and current flatmates for their tolerance, they know why. Love you guys!

Above all, I would like to thank my family for all their love and belief in me. Their motivation and support all these years was vital, and even if I have moved some thousands of kilometers away from my home, thank you for reminding me that when you try hard, you will succeed.

I hope you enjoy reading this report.

Yours sincerely,

Kelly Kalioupi

SUMMARY

Supply chain mapping for concrete recycling

Concrete is the second most consumed material after water and shapes the largest area of the built environment in the Netherlands. It is on the verge of becoming a circular material since the fundamental knowledge for affordable high-grade applications from old concrete has already been introduced. More precisely, the development of technologies that can separate End-of-life (EoL) concrete into its constituents, facilitates its recycling and reuse into new building materials and not in the landfill. During the reporting period, the emphasis lies on organizing the EoL concrete flow, arranging a system for quality control, as well as developing additive manufacturing in order to turn concrete recycling into a commercial success. Therefore, in this report attention is being given on the analysis of the material flows of conventional concrete and the integration of recycled materials in the process of production.

This topic focuses on three promising technologies that can crush and separate concrete at an advanced level by ensuring high-quality outputs; i) Crusher – Smart Dismantling and Demolishing, ii) Advanced Dry Recovery (ADR) technology and iii) Heating Air Classification System (HAS). The problem of EoL concrete treatment in the Netherlands, in combination with the insufficient communication concerning the three mentioned technologies for concrete recycling, lead to the thesis' objective: '*The design of a closed-loop supply chain concerning the integration of novel technologies into the conventional concrete production in the Netherlands.'* In order to reach this objective, a design approach is being developed and design activities are being realized throughout the thesis report. The problem definition and the design stages are in line with pilot testing and experimental results from the 'Resource and Recycling Laboratory' in the faculty of Civil Engineering in the Delft University of Technology, wherein the technologies are under development. This report consists of six chapters in which the five developed design stages are thoroughly explained.

In Chapter 2, the stage of 'Conceptual Design' is discussed. The current industry conditions and related concepts concerning the production of concrete are described. Dutch companies' reports in the demolition and construction sector are valuable tools since the focus shifts in the Netherlands. With regard to the material production, the two identified categories, that set the foundations for the following stages of 'Detailed Design' and 'Evaluation', are the i) prefabricated concrete and the ii) site-cast/ ready-mixed one. The findings indicate that concrete production requires multiple control testing in various stages of its manufacturing in order to lead to a high-quality end material. Additionally, the literature study signifies that construction logistics costs are responsible for the highest part of concrete's final price and the three main distinguished activities are; i) procurement, ii) transportation and iii) loading.

Chapter 3 formulates the solution to the main research problem. The knowledge of developed and developing technologies in the Construction Sector (CS) has not been well-accumulated in academic research papers. Moreover, not only the theoretical research on the field is immature but also the empirical research that has been completed or is on-going remains largely unknown. Hence, expert unstructured interviews constitute a useful methodology in order to overcome the scientific limitations. More precisely, interviews with professors and researchers from the 'Resource and Recycling Laboratory' led to a deeper understanding of the current state of development of concrete recycling. Concerning the exploratory

results of this chapter, the volumes of inputs, and outputs of the three referred technologies are presented and the way the novel technologies can close the conventional loop is depicted. These technologies are working either in line or separately. More specifically, the Crusher technology is operating with a speed of 150 tons/h and crushes EoL concrete into coarse aggregates (30% EoL) and aggregates with a smaller diameter, which constitutes the input of ADR technology (70% EoL). To continue with, ADR removes the fine and light contaminants from aggregates (crusher's output) with a speed of 50 -120 tons/h; ADR coarse recycled aggregates (60% of the input) and ADR rotor & ADR ariknife (40% of input – HAS input) are separated. HAS splits the cementitious powder from the sandy part and delivers products with a minimum amount of contaminants. The moisture is evaporated (5-8% of input) and the outputs are divided into ultrafine particles (20% of input) and fine particles (72-75% of input). Its operating speed is 3 tons/h. Regarding these technologies, the highest interest is attributed to the last referred one, since it can replace additives (e.g. fly ash) as well as a percentage of limestone in cement, and can result in lower CO_2 emissions. Finally, feasible options concerning circular concrete management are recommended. A 'Concrete-to-concrete Recycling Plant', which consists of mobile technologies that separate and control the quality of concrete, is proposed and two extreme cases based on its location lay the groundwork for the 'Detailed Design' of the next chapter; i) Recycling plant is operating near mortar supplier or near prefabricated concrete industry and ii) Recycling plant is operating at the demolition site.

It is worth mentioning that mapping the supply chain is essential for supply chain analysis and the identification of trade-offs. Accordingly, in Chapter 4 the 'Detailed Design' stage of the research approach is developed. Six extreme cases regarding the conventional and closed-loop concrete production are examined in line with the identified categories of concrete; three of them concern the prefabricated concrete and the other three the site-cast/ ready-mixed one:

- Case 1: Prefabricated concrete production
- Case 2: Prefabricated concrete production with a 'Concrete-to-concrete Recycling Plant' operating near prefabricated concrete industry
- Case 3: Prefabricated concrete production with a 'Concrete-to-concrete Recycling Plant' operating at the demolition site
- Case 4: Site-cast/ Ready-mixed concrete production
- Case 5: Site-cast/ Ready-mixed concrete production with a 'Concrete-to-concrete Recycling Plant' operating near mortar supplier
- Case 6: Site-cast/ Ready-mixed concrete production with a 'Concrete-to-concrete Recycling Plant' operating at the demolition site

The SCOR Model formulated by Supply-Chain Council is selected as a supply chain mapping tool and is designed in Levels 1, 2 and 3 in order to illustrate the complexity of concrete production and its modifications with the integration of technologies for concrete recycling to the market. After a comparative analysis, it is observed that when the final product is not conforming to the project's specifications, the production of prefabricated concrete is the only category that includes return processes. Additionally, it requires more Engineer-to-order processes and consequently, more stakeholders are involved in the production of concrete. Concerning the cases related to the closed-loop approach, transportation in the vicinity of the recycling plant is schematically presented and differences are emphasized in truck shipments of raw materials as well as in inventory.

In chapter 5, the ‘Evaluation’ stage is elaborated and two different perspectives are examined for the feasibility assessment of a ‘Concrete-to-concrete Recycling Plant’. In terms of the first perspective, a calculation model is developed. The focus is on combinations of costs, quality and time in order to examine the possible ways of concrete recycling. Essentially, it summarizes and combines information that is included in the aforementioned cases. Regarding the financial findings, the recycling plant requires an investment of 1M€. Nonetheless, mortar companies and demolition centers could collaborate and operate in terms of Circular Economy (CE) in order to overcome the initial financial barrier and take advantage of the materials’ prices. Afterward, the plant could bring environmental benefits since CO_2 emissions could be reduced significantly if the amount of CaO in the recovered finer fraction from the recycling process is used in cement production. It is calculated that a ton of recycled cement paste can save at least 500 kg of CO_2 emissions in cement production. In addition, a Value Stream Mapping for the processes executed on a ‘Concrete-to-concrete Recycling Plant’ is developed with a selected example of a building constructed by 13,000 tons of concrete. The value-added time calculated equal to 211 days. Hence, it is worth mentioning that 152 days (72% of the total duration), are attributed to HAS operation. Consequently, it is recognized that there is space for improvement in the operating speed of the HAS technology. One step further and through considering the model results, points of difference in recycling plant’s location reveal that the ‘Case 2: *Prefabricated concrete with a Concrete-to-concrete Recycling Plant operating near the prefabricated concrete industry’* and ‘Case 5*: Site-cast/ Ready-mixed concrete with a Concrete-to-concrete Recycling Plant operating near the mortar plant’* are the most efficient ones for each category of concrete production respectively. Fewer transportation movements are realized and the main problem of HAS’ operating time has been overcome since the technological outputs are leveraged immediately without storage. Lastly, the geographic area of the Netherlands has the appropriate size (41,543 km^2) for materials’ transshipment around the country and fosters the integration of a ‘Concrete-to-concrete Recycling Plant’ to concrete production.

The second approach refers to an organizational perspective. Aiming to analyze the current potentials of the market, as well as the enablers and stoppers of introducing the new technologies in the CS, questionnaires were designed and distributed to several stakeholders in the concrete value chain. The impact of the novel technologies on the market conditions and the viewpoints of the involved actors are summarized with the developed schemes of Porter’s Five Forces model in the industry of concrete, cement, and aggregates. The position of Recycled Aggregates (RA) in each industry in correlation with the power of the relevant stakeholders (Stake/ Power/ Knowledge (SPK) Framework & Power-Interest grid), as well as the received questionnaire answers, formulate the feasibility level of introducing novel technologies in the CS. It is observed that RA have a different role in each industry. More precisely, the stakeholders with great influence in the production process of concrete (cement and concrete producers) are in favor of using recycled materials. On the other hand, aggregate extractors do not support the above-mentioned technologies since they will substitute part of their production. However, their low power in the sector constitutes the use of RA and the development of a ‘Concrete-to-concrete Recycling Plant’ feasible.

To sum up, the result of this research is a feasibility assessment of integrating technologies for concrete production in the CS based on a design approach. This project creates an overview regarding the potentials of concrete recycling in accordance with the feasible logistics trade-offs as well as the current market situation. Over and above, it composes supplementary research for the ‘Resource & Recycling Laboratory’ in the faculty of Civil Engineering in TU Delft, through targeting to complete the picture of circular concrete and finally introduce RA to concrete production.

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- ADR: Advanced Dry Recovery
- AF: Aggregate Fraction
- CCC: Construction Consolidation Centers
- CDW: Construction and Demolition Waste
- CE: Circular Economy
- CLC: Construction logistics coordinator
- CS: Construction Sector
- EoL: End-of-life
- HAS: Heating Air Classification System
- ILC: Integrated Logistics Concept
- JIT: Just-in-time
- KPIs: Key Performance Indicators
- RA: Recycled Aggregates
- RL: Reverse Logistics
- SCM: Supply Chain Management
- W/C: Water to Cement

CHAPTER 1. INTRODUCTION – RESEARCH FRAMEWORK

Construction and demolition projects are described by two major features that lead to environmental pressure. Regarding the rising urban population, there is an increasing requirement for building materials aiming to provide new infrastructure as well as preserve the current one. Additionally, the activities in the CS require the management of large amounts of waste streams.

Concrete constitutes the most widely used artificial material from the moment that is invented (de Brito and Saikia 2013). Its waste is characterized as a critical stream since its volume is noteworthy in the built environment and limited management alternatives are currently identified. Concerning the European Union, there are more than 450 million tons of Construction and Demolition Waste (CDW) per year and the percentage of EoL concrete is equal to 40-67% of this volume (Turk et al. 2015). Even if the Netherlands is one of the countries with a high level of concrete-rubble recycling, the current regime is not sufficient (Hu et al. 2013).

While the management of CDW is a common issue on a global scale, this research focuses on the Netherlands. This research targets to improve EoL concrete exploitation through examining currently developing technologies that leverage CDW in order to produce high-quality recycled materials. Concrete recycling is translated into the fact that EoL concrete is converted back to cement paste powder for producing new cement and to sand and gravel for new mortar. Since EoL concrete emerges mainly in the urban environment, the production of recycled sand and gravel (85-90 mass % of the recycled products) will diminish the transportation movements within a city. The main obstacle in such a project concerns the organizational perspective. The existing market situation influences impressively the integration of the technologies for concrete recycling into concrete production. Each industry involved in concrete manufacturing has a different role and its stakeholders affect accordingly the recycling expectations. The concrete industry consists of a large number of concrete producers and is characterized by several types and grades of concrete. Nevertheless, it is highly correlated with the supply of its components since it is not a virgin material. RA constitute one more supplier in the concrete industry and enlarge the options of mortar and prefabricated concrete manufacturers. The following chapter describes the background and the exact methodology used in this thesis by identifying the main research problems.

1.1 Research Background

Circular Economy in the Dutch Constructor Sector

While modern cities occupy only 3% of the land surface area worldwide, their residents consume more than 75% of the globe's natural resources to cover their needs (Kubbinga et al., 2018). Global human population growth in correlation with an international trend towards the creation of resource-intensive processes have resulted in major social and environmental changes. It is estimated that the demand for infrastructure and buildings is going to surge from 54% in 2018 to over 60% by 2025 (Kubbinga et al., 2018). As a result, the necessity for raw materials will rise in the upcoming years. Currently, an abundance ends up as wastes, losing their value, polluting the environment and impacting the climate (Government of the Netherlands, 2017).

In the concept of resilience cities, practices such as urban metabolism and CE as well as the analysis of the flows of materials within cities are essential for a circular viewpoint. Numerous efforts are made in the geographical region of the Netherlands driven by a shared ambition of accelerating the transition to a CE, aiming to utilize raw materials more effectively and profitably. The challenging nature of this transition in a constantly changing word leaves, unsurprisingly, room for improvement. Attention should be shifted not only in quantity but also on quality and value. The management of raw materials, products, and services in a sustainable and intelligent manner seems vital for the reduction of CO_2 emissions (Government of the Netherlands, 2017).

Regarding that concern, the sector with the greatest interest, not only from an environment but also from a financial perspective, is the CS. It is both a major user of materials as well as a primary producer of waste (Agamuthu, 2008; Li, 2015). More specifically, in the Netherlands, 50% of the raw materials used, 40% of total energy and 30% of the total water consumed are attributed to it. The CDW constitutes 40% of the Dutch wastes (Table 1.1 – Figure 1.1) and the sector is responsible for 35% of CO_2 emissions. Though the reuse of CDW is quite widespread, in many situations, the materials are not reused at the same or a higher level (The Ministry of Infrastructure and the Environment & the Ministry of Economic Affairs, 2016).

Table 1.1 *Source of waste in the Netherlands by weight (CBS, PBL & Wageningen UR, 2012)*

Source of waste	% by weight
Traffic and transportation	2
Energy supply	2
Water supply; sewerage, drinking water	3
Agriculture, forestry, and fishing	4
Services	9
Households	15
Industry	25
Construction and demolition	40

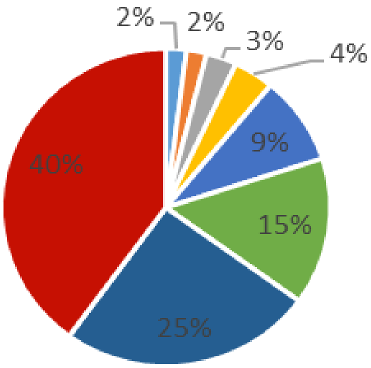

Figure 1.1 Percentage of wastes in the Netherlands by weight (CBS, PBL, Wageningen UR, 2012)

Concerning the Construction 2020 strategy in the European Union, the Waste Framework Directive targets for the upcoming year, to a minimum percentage of 70% by weight of 'non-hazardous' CDW. This strategy refers to recycle, re-use and material recovery through closing the loop of product lifecycles and bringing environmental as well as financial benefits (Directive, 2008).

A *'Circular Economy in the Netherlands by 2050'* shares the aspiration of efficient use of raw materials that will strengthen the earning capacity of the Dutch Economy. At the same time, climate and other environmental ambitions will be realized. New opportunities for innovation are created in the CS, which emphasize energy savings as well as CO_2 emissions decrease (The Ministry of Infrastructure and the Environment & the Ministry of Economic Affairs, 2016). This work contributes to the Dutch vision by examining the potentials of a specific material; the EoL concrete.

Concrete recycling as an object of study

The broader problem that this thesis tackles by focusing on concrete recycling is the construction waste streams. Concrete is not a virgin material but an artificial one, with the highest volumes of consumption since it is invented (De Brito & Saikia, 2013). It shapes the built environment with a yearly consumption of more than 900 million tons in Europe, the USA and Japan alone (CSI, 2009). Around 3 tons of concrete per year are used individually on earth (U.S. GEOLogical Survey, 2007). The concrete production causes significant environmental impacts, and more specifically it is responsible for a percentage of 6-7% of the CO_2 emissions worldwide (Shi, Jiménez & Palomo, 2011). In the Netherlands, from cradle to grave, concrete's use corresponds to 35% of the CO_2 emissions of the sector and 1.7% of the total CO_2 emissions (Circular Economy, 2015). Attributable to its everyday use and the contemporary inadequate management alternatives, the concrete from demolition projects constitutes a critical concern. Additionally, it is worth mentioning that a big amount of concrete's negative environmental impact is attributed to the transportation of bulk concrete since logistics plays a significant role in the concrete supply chain.

Table 1.2 *Construction and Demolition Waste composition by weight (BioIS, 2016)*

Waste Category	min % by weight	max % by weight
Concrete and Masonry	40	84
Concrete	12	40
Masonry	8	54
Asphalt	4	26
Other (mineral)	2	9
Wood	2	4
Metal	0.2	4
Gypsum	0.2	0.4
Plastics	0.1	2
Miscellaneous	2	36

Based on Müller's research (2006), the amount of concrete used in the second half of the 21st century in the Netherlands is going to be equivalent to the amount of EoL concrete. As a consequence, the recycling EoL concrete into new concrete is the ideal EoL waste management option. Additionally, in the Dutch CS, concrete is crushed as a base for road construction; a low-value application for high-quality material. The effective reuse of concrete will only become truly interesting if all raw materials could be reused at a high-quality level for circular design. The current average recycling rate of CDW for EU-27 is only 47% and there is still a significant loss of potentially valuable materials all over Europe (Pacheco-Torgal, 2013).

Technologies that leverage EoL concrete

Considering the urgency and importance of CDW recycling and reusing, the European Commission has taken initiatives towards the sustainable treatment of EoL concrete based on innovations and sustainable concrete recycling processes. Advanced Dry Recovery (ADR), as well as Heating Air Classification System (HAS), are two worth-referring technologies that can separate EoL concrete's raw materials through maintaining their mechanical properties (Lotfi et al, 2014; Lotfi et al., 2017). These technologies enable the materials to be reused appropriately in the building sector and consequently, they promote the key point of CE.

The last decade, three EU-projects have been developed or are currently developing by targeting to close the conventional concrete loop; the C2CA Project – '*Concrete to Cement and Aggregates'*, ("Home | C2CA", 2019), the HISER Project - '*Holistic Innovative Solutions for an Efficient Recycling and Recovery of Valuable Raw Materials from Complex Construction and Demolition Waste'* ("Home | HISER Project", 2019) and the 4-year H2020 VEEP Project - '*Cost-effective recycling of CDW in high added value energy-efficient prefabricated concrete components for massive retrofitting of our built environment'*, ("Home | VEEP Project". 2019). Technologies ADR and HAS are part of these projects and contribute to keeping resources within the economy when EoL concrete no longer serves its functions.

Construction supply chains

The literature study guided the current thesis to the necessity of a logistics analysis regarding the complexity of concrete's supply chain. The term 'traditional Supply Chain Management (SCM)' was first described as a purchasing and logistics concept (Cooper & Ellram, 1993). Nevertheless, it is directly connected to operations, and more specifically the performance of the material and information flow among the involved stakeholders (Defee & Stank, 2005; Cooper, Lambert & Pagh, 1997; Hines et al., 2000; Hult et al., 2007). Christopher (2005) developed the most popular definition of SCM, which is formulated as *'the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole'*. An important aspect of SCM is that it focuses on multiple customer-supplier relationships, starting with the extraction of raw materials until the delivery to the final customer or consumer (Harland, 1996).

According to Vidalakis, Tookey, and Sommerville (2011), the impact of logistics on raw materials' purchase price can be reduced through a supply chain approach. The examination of transportation of construction materials facilitates the recognition of potential savings, while it extends the scope of logistics outside the project environment aiming to include the involved actors.

The focus on diminishing the impacts of products and processes as well as the new industry standards led to the design of closed-loop supply chains where investment in resources is required. To be more specific, the understanding of information flows and the right distribution of products is essential. Another factor of equivalent importance is a collection system that harvests the product at its EoL (Loomba & Nakashima, 2012). Additionally, collaboration among the involved actors should not be absent (Kumar & Malegeant, 2006).

One step further, according to Sobotka, Sagan, Baranowska & Mazur (2017), Reverse Logistics (RL) is: *'a closed-loop approach that uses remanufacturing, refurbishment, repair, reuse or recycling to recover products and process materials after the point of consumption ending with energy recovery, and finally disposal'.* They plan and organize supply chains, incorporate physical flows of waste and accompany the information. Nevertheless, inadequate attention has been paid to RL's interpretation (EMF, DPDHL, & CU, 2015). This comprises requirements such as asset tracking, optimized product, and material flows as well as waste handling regulations. Highly optimized logistics is the only solution to the preservation of the residual value of return products (EMF, DPDHL, & CU, 2015).

1.2 Research Problem

In 2003, the Dutch environment had excessive demolition rates, which were higher than many other European countries. The renovation of urban cities as well as the low rates of occupancy led to a surge in demolition projects. At this very moment, the existing dwellings were unable to cover the resident's needs and a number of construction projects developed after the demolished ones (Meijer, Itard & Sunikka-Blank, 2009). With reference to a landfill ban implementation in 1997, four years later, the Dutch CS reached a recycling rate equal to 95% of CDW, and as a result, the concrete waste stream retrieved for recycling (Hu, Kleijn, Bozhilova-Kisheva & Di Maio, 2013). However, thus far, the percentage of recycled CDW is used for low-quality applications, such as road filling, and the main concern which arises is that high-quality applications reach a rate equal to 2% (Bakker, Di Maio & Rem, 2013; Hu et al., 2013). In parallel, cement production is responsible for a high percentage of CO_2 emissions in the urban environment and this rate can be reduced only if recycled materials replace a part of cement's raw materials. Therefore, one of this thesis' main problem is concrete-rubble recycling in the geographical region of the Netherlands.

Problem Statement 1: Construction projects do not leverage EoL concrete, whereas at the same time new concrete is produced and CDW is exploited in low-quality applications.

Aiming to take advantage of EoL concrete, novel technologies should be introduced to the constructor sector. The already referred technologies, ADR and HAS, are currently developing in the 'Resource and Recycling Laboratory' in the faculty of Civil Engineering in TU Delft. Nevertheless, more research is still required since their application is going to change entirely the conventional supply chain, as well as relevant logistic concepts. Additionally, a number of stakeholders are opposed to their use and their afterward integration to the market. After thorough discussions with Prof. Dr. Peter Rem and Ing. Peter Berkhout, who are currently researching that aspect in concrete recycling, the following problem statement identified.

Problem Statement 2: Insufficient communication of the novel technologies for concrete recycling in the CS.

With reference to the 'Construction and Demolition Waste Protocol' in Europe, proper management of significant wastes that are originated from construction and demolition projects have a positive impact in terms of sustainability and the quality of life. The correct handling of hazardous waste, the improvement of source separation, the examination of available options on-site as well as the increase of confidence in the quality of recycled materials (European Commission, 2016) constitute the backbone of the current thesis project.

Although in the Netherlands, the waste management is among the most mature elements of the CE initiatives of Dutch companies, RL is considered to be the most complex one; a fact signifying that further research is necessary. De Angelis, Howard and Miemczyk (2018) worked on the relationship between SCM and CE, and they identified the knowledge gap on the practical aspects of introducing supply chain systems in a real-world context. Moreover, concerning industrial symbiosis, the exchange of by-products, materials, and energy between companies that are located in the same geographic area, is still lacking (Holgado, Morgan & Evans, 2016).

Problem Statement 3: In terms of CE and industrial symbiosis, supply chain systems are not introduced in real-world problems concerning recycling and cooperation among companies is lacking.

Based on the above-referred aspects, the main problem in the CS is CDW treatment. Aiming to address it, novel technologies that leverage EoL concrete are of great interest. Their implementation and introduction to the market close the loop of concrete production and contribute to the achievement of a circular vision. Since concrete is an artificial material, it is highly dependent on its raw materials. Proper SCM is required for the reduction of wastes along the value chain and supply chain mapping is a tool of engaging companies and suppliers to document the exact source of every material, every process and every shipment involved in bringing goods to market.

Hence, the focus of this work is on the material of concrete owing to its potentials in terms of recycling. One step ahead, the used case is the Dutch environment since technological improvements have been identified in this geographic area.

1.3 Research Objective

The objective of this work is the design of a closed-loop supply chain for concrete production with the focus on the geographic area of the Netherlands. The research highlights three developing technologies, which target to bring changes in conventional concrete production. Crusher, ADR and HAS technologies are currently developing in the 'Resource & Recycling Laboratory' of the faculty of Civil Engineering in the TU Delft and are part of three funded EU-projects. Based on existing market conditions, a 'Concrete-to-concrete Recycling Plant' composed by the three mentioned technologies is proposed as a solution to the identified research problems through organizing circular concrete. Possible cases for concrete production and concrete recycling are developed with the final target to assess and evaluate the feasible ones. On the basis of the theory and practice of SCM, the proposed cases are illustrated with supply chain mapping. Trade-offs in transportation and logistics between the conventional and closed-loop supply chains are also presented.

Following the definition of the aim of this research and short research background, the design objective can be summarized as follows:

The design of a closed-loop supply chain concerning the integration of novel technologies in conventional concrete production in the Netherlands.

The thesis report consists of 6 Chapters, which are developing in accordance with the research objective. The design activities that assist the process of reaching the research objective with the relevant chapters are following presented:

Design activity 1 – Identification of feasible options for circular concrete management: The location of a 'Concrete-to-Concrete Recycling Plant' leads to the examination of two extreme cases (Chapter 3).

Design activity 2 – Identification of the current and future feasible options for concrete production: The categories of concrete production combined with the feasible options for circular concrete management lead to the examination of six extreme cases (Chapter 4).

Design activity 3 – Supply chain mapping for each feasible case for concrete production: The cases formulated in the previously mentioned design activity are mapped with supply chain tools (Chapter 4).

Design activity 4 – Identification of the most efficient solution for a sustainable way of concrete production: The points of difference among the cases are identified and the most efficient cases are discussed (Chapter 5).

1.4 Research Methodology

Throughout this thesis report, a design approach is developed. Aiming to identify the stages and formulate the research methodology, different models were examined. Worth-referring examples are the 'Model of Dym and Little', the 'Engineering Design' as well as the 'Design Science Research Methodology (DSRM) Process Model'. The design approach that applied to this research, is based on the common phases of these models and the stages are selected in order to meet the research objective's requirements:

- Stage 1. Problem definition: The research problem is clarified. Furthermore, design activities are formulated and the project is scoped.
- Stage 2. Conceptual design: The design objectives and concepts are examined. The current state performance is assessed and a solution to the main problem is proposed.
- Stage 3. Detailed design: The design for the current and future situation is developed.
- Stage 4. Evaluation: The feasibility of the designed solution is assessed.
- Stage 5. Communication: The specifications and their justifications are documented. The conclusions provide answers to the main research question.

1.5 Thesis Outline

The five already referred stages are conducted in a subsequent way. Chapter 1 constitutes the first stage of the design approach. The problem of EoL concrete treatment in the Netherlands, as well as the insufficient communication concerning the novel technologies for concrete recycling, are identified.

Additionally, research objectives and design activities are formulated. The next two chapters compose the second stage of the design approach. More specifically, in Chapter 2, the current industry situation is described and the concepts concerning the production of concrete and its transportation along the supply chain are identified. In Chapter 3, technologies for concrete recycling are described and a ‘Concrete-to-concrete Recycling Plant’ is proposed as a solution to the main research problem. In Chapter 4, the third stage is taking place. Cases regarding the current and future concrete production in accordance with the recommended solution are identified. The SCOR model and a Business Process Management approach set the guidelines for the detailed design of this thesis. The stage of evaluation follows. In Chapter 5, a feasibility assessment is conducted and two different approaches regarding the detailed design are examined in order to clarify the proposed solution. A calculation model for concrete recycling gathers valuable information about processes that are designed in stage 3 and an organizational perspective examines the feasibility of introducing a ‘Concrete-to-concrete Recycling Plant’ in the CS. In the final stage in Chapter 6, the results are communicated and the conclusions of the design approach are presented. Furthermore, the limitations of the research and recommendations are displayed.

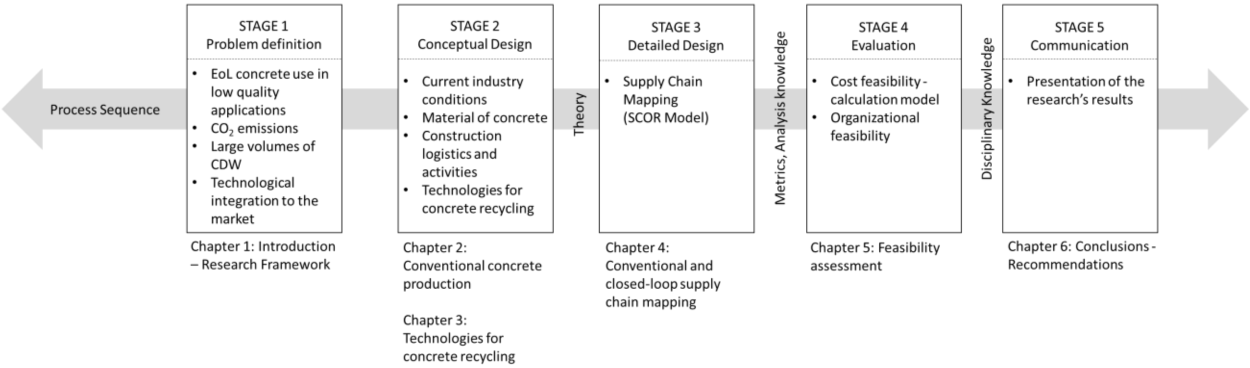

Figure 1.2 Report outline

1.6 Research Deliverable

The result of this research is a feasibility assessment of concrete recycling based on a design approach. A calculation model regarding the processes in concrete production and concrete recycling, as well as an organizational perspective of integrating the developed technologies in the CS, set the guidelines for the evaluation of a ‘Concrete-to-concrete Recycling Plant’. A comparative analysis between the conventional and closed-loop production of concrete presents the way novel technologies change the transportation of materials and the logistic concepts in terms of an urban environment. This project creates an overview regarding the potentials of concrete recycling in accordance with the feasible logistics trade-offs as well as the current market situation. Over and above, it composes supplementary research for the ‘Resource & Recycling Laboratory’ in the faculty of Civil Engineering in TU Delft, through targeting to complete the picture of circular concrete and finally introduce RA to concrete production. Therefore, specific parts of this research are developed in accordance with the laboratory requirements since they will be used in handbooks that cover every aspect of the technologies and they will be communicated in companies in the constructor sector.

1.7 Research Relevance; Scientific, Social, and MoT

Scientific Relevance & Societal Relevance

The conducted research targets to solve the identified research problems and enhance the development of a theoretical as well as a practical body of knowledge. The concept of CE aims to diminish greenhouse gas emissions as well as wastes and attain material's highest value (Korhonen et al., 2017; Haas et al., 2015, European Commission, 2015). Nevertheless, more research is required in the CS in order to achieve its environmental and financial sustainability. This work targets to connect industries related to concrete production in a specific area through the exchange of by-products and materials as well as the proper management of the EoL concrete stream. Additionally, it contributes to the Dutch ambition of reaching a CE vision, which is considered a sustainable alternative to the linear 'take-make-waste' paradigm since it decouples economic growth from environmental degradation (Linder et al., 2017).

Besides, the quality of RA and financial issues regarding the recycling processes raise great concerns in the industries related to concrete production. The design approach of this work aims to overcome this barrier as well as communicate and increase awareness concerning the quality of recycled materials. It takes advantage of construction material's value, introduces them into the economy, decreases the percentage of CO_2 emissions and leads to societal changes through creating healthy urban living spaces. Finally, it composes supplementary research for the 'Resource & Recycling Laboratory' in the faculty of Civil Engineering in TU Delft concerning the novel technologies for concrete recycling.

Relevance to Management of Technology (MoT)

With regard to the MSc Management of Technology, the following three indicators have been defined as suitable for a thesis project:

i. *'The work reports on a scientific study in a technological context'*

This thesis has a scientific direction by analyzing new technologies applied in the construction industry. To be more precise, it compromises novel solutions for the treatment of waste streams in the concrete industry through increasing cooperation among the involved actors. Therefore, this research has a technological context since it targets to evaluate the current level of development of the proposed technologies by analyzing applications of an industrial as well as laboratory scale and weight its environmental and financial benefits. The scientific relevance has been explained earlier in this section.

ii. *'The work shows an understanding of technology as a corporate resource or is done to form a corporate perspective'*

This work shows an understanding of the technologies for concrete recycling as a corporate resource. Owing to this reason results from industrial-scale experiments, a market analysis of the evolved industries as well as a comparative analysis between the conventional and closed-loop supply chain of concrete are developed. This thesis facilitates companies related to concrete production, to successfully integrate novel technologies into their businesses and cooperate with stakeholders proceeding finally to sustainable innovation implementation.

iii. *‘Students used scientific methods and techniques to analyze a problem as put forward in the MoT curriculum’*

The courses of the MoT curriculum and the related concepts used in this thesis are presented:

- Business Process Management and Technology – MOT1531: Examination of workflows and supply chains, activities for creating values for customers
- Emerging and Breakthrough Technologies – MOT2421: Exploration and analysis of innovation opportunities and problems
- Technology Dynamics - MOT1412: Incorporation of values to steer innovation into a societally responsible direction
- High-tech Marketing – MOT1533: Market analysis and marketing techniques
- Research Methods – MOT2312: Design and execution of research, design approach
- Logistics and Supply Chain Innovation – SEN9720 (Specialization Course): Product and information exchange among companies, the role of transport between logistic systems

This topic is highly relevant to the field of MoT program since it is described by an interdisciplinary nature and requires a combination of engineering innovation with societal support to develop a successful approach.

CHAPTER 2. CONVENTIONAL CONCRETE PRODUCTION

'Concrete is a stonelike material obtained by permitting a carefully proportioned mixture of cement, sand, and gravel or other coarse aggregate, and water to harden in forms of the shape and dimensions of the desired structure'.

In this Chapter, the current situation and the related aspects concerning the production of conventional concrete are described. It comprises the second stage (Figure 2.1) of the design approach that is applied throughout the thesis. More specifically the objectives of the formulated problem are identified and theoretical findings of the design phase are explored. A systematic literature review (SLR) concerning the industry conditions, the material of concrete as well as the construction logistics concepts and activities in concrete production are presented.

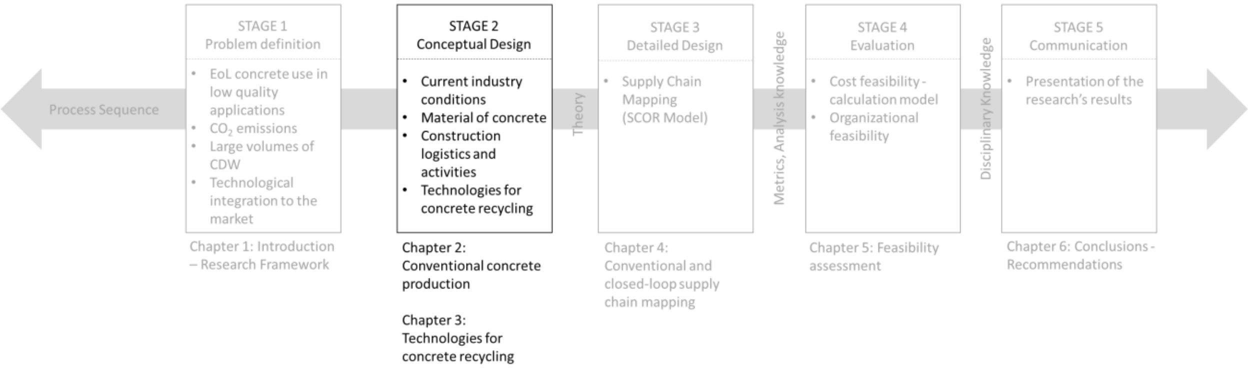

Figure 2.1 Stage of the design approach of Chapter 2

Initially, the market situation in each industry relevant to concrete production is described. The current conditions in the concrete industry, cement industry as well as the extraction of aggregates are analyzed since they will influence the future potentials in concrete recycling.

Afterward, the focus strives on the manufacturing of cement and the material of concrete. More specifically, the examination of types of cement is achieved in order to correlate the grades of the concrete with its forthcoming use. Dutch companies' reports in the demolition and CS were valuable tools since the emphasis is on specific types that are commonly used in the Dutch CS. The different categories of concrete production are explored; i) prefabricated and ii) site-cast/ ready-mixed concrete establish the backbone for the mapping of the conventional and closed-loop supply chain in Chapter 4.

Finally, transportation and logistics concepts put the guidelines for the aspects that should be considered in a closed-loop approach of the concrete's production. The presented logistics concepts and activities are in accordance with the production of concrete, and they are adjusted to the requirements of the construction industry.

2.1 Current industry conditions

Aiming to analyze the future potentials of the market and the enablers and stoppers of introducing new methods in the CS, the current situation in the industry of concrete, cement, and aggregates is examined. The rivalry among competitors, the power of suppliers and buyers as well as the threat of new entrants and the pressure from substitutes in each sector are described.

This part will be the core of the Porter's Five Forces schematic approach and the examination of potentials of integrating RA in the conventional concrete production, which are extensively described in 'Chapter 5: Feasibility Assessment'.

Concrete industry

The concrete production is related to companies, which are highly automated and have the distinguishing feature of major quality standards. The volumes of produced building materials are related to each company's size and capacity. Research centers and construction companies are currently trying to decommoditize concrete with product innovation (e.g. 3D printing), branding and packaging initiatives.

Concerning the material's composition, concrete is not a virgin material, whereas it consists of cement, fine and coarse aggregates as well as water. Accordingly, its suppliers play a significant role in its production since it cannot be produced without the source of its main components. Concrete companies require the establishment of a network formed of raw material suppliers, distributors as well as contractors.

Nevertheless, the industry of concrete can manage its inputs by selecting recycled materials or reducing the use of fossil fuels. Raw materials and energy are commodities that are not distinctively differentiated and the switching cost from one supplier to another is low. Currently, a high percentage of aggregates is virgin materials and not RA. However, in the upcoming years, the recycled materials will constitute a large percentage of concrete's composition and in accordance with the Dutch legislation, they will not be just an alternative (Michel Baars, 2019). Concrete's substitutes are other building materials, such as wood, clay bricks, gypsum, stone, asphalt, glass, steel. Regarding large building and infrastructure projects, the above-referred materials do not represent a major challenge owing to their different mechanical and chemical properties.

Concrete industries are either integrated with transportation and logistics infrastructure or they are the distribution channel that is normally controlled by cement companies. New entrants usually need to secure transportation for their products or strong cooperation with transportation companies before entering the market. They are not responsible for many processes in the industry and as a consequence, the barrier of entry is very low.

The production of concrete is categorized into the site-cast/ ready-mixed and the prefabricated one. In the geographic region of the Netherlands, there is a high number of ready-mixed concrete companies that offer low prices in close proximity to the construction site. Nonetheless, regarding the prefabricated concrete companies, there are just a few of them. In terms of profitability and concerning an efficient operation, the geographic coverage of each company is limited. Diverse competitors exist in the market from large to small companies and the level of rivalry is high. The stakes are mostly related to capital investment to open a new concrete company and thus, the ready-mixed ones are easier to expand and produce large quantities of the final product.

In 2016, the Authority for Consumers and Markets (ACM) tried to improve competition in the ready-mix concrete sector (ACM, 2016) by making concrete companies to follow commitments. These efforts aimed to eliminate unfair competition among concrete companies that are operating in the same geographic region. The Dutch vision for 2050 (Circular Economy in the Netherlands by 2050) has a great influence on the operation of concrete companies as well.

Finally, the industry growth is connected with the growth in the CS. The construction industry's growth in 2018 was in line with the overall Dutch economic performance. Construction gross added value increased to more than 5% year-on-year. In Q3 of 2018 civil and utility construction sales observed a surge of more than 11%, while infrastructure-related sales rose more than 6% (Atradius, 2019). Fixed costs in the concrete industry are rentals, utilities, personnel salaries, inventory costs (Min & Pheng, 2006). Mortar plants do not require either large geographic areas to be developed nor high-qualified personnel.

Cement industry

Cement plants are built to get economies of scale which is translated into a proportionate saving in costs gained by an increased level of production. In the Dutch geographic area, there are one integrated and three grinding plants with major quality standards. The only integrated one is the 'Eerste Nederlandse Cement Industrie' (ENCI, 2019), with a capacity of 1.1Mt/ yr ("UAE cement focus", 2012).

The cement industry is a major consumer of raw materials on top of energy for its operation. Binders (such as fly ash), gypsum and fuel are really important in the cement industry since they establish the cement's suppliers. Different compositions of binders, additives and W/C ratio are used. Despite the fact that there are a lot of types for different uses, specific compositions are the most consumed ones, with the most common, the Portland cement (European Committee For Standardization, 2000).

Additionally, cement is responsible for a percentage of 6-7% of the CO_2 emissions worldwide due to the fuel that is heated in the kiln at the temperature of 1450^o C (Shi et al., 2011). Large volumes of electricity, as well as water, are attributed to the production of cement and not to the production of mortar concrete (Shi et al, 2011). Since fuel prices and raw materials' prices increase, the bargaining power of suppliers increases as well. Besides, the cement production has decreased since great efforts are made for reducing CO_2 emissions (750kg CO_2/ton of cement produced; Claisse, 2016, "UAE cement focus", 2019).

The level of demand in the Dutch environment is achieved with imported cement from neighbor-countries (Selim & Salem, 2010). However, the imports do not constitute high levels of rivalry since the domestic cement is primarily consumed in activities in close proximity. Cement plants are characterized by moderate fixed costs since chemical processes are taking place and continuous quality control is an integral part of the factory's operations. The capital investments, as well as the exit barriers, are very important parameters for a cement plant. The stakes are mostly related to capital investment, which is exceptionally excessive. Additionally, cement plants have long term government licenses and thus, the rivalry, as well as the barrier of entry, are high. The large cement companies have already been established in the market. According to Cemex, *'the cost of stopping a cement plant is significant due to lost sales. The inventories in the distribution* *channel do not exceed the duration of the 2 days; hence there is no buffer to cover supply shortages'* (Agudelo, 2009).

Large capacity augmentations cannot be easily controlled by a cement plant since the levels of production cannot fluctuate extremely. Proper precautions for the storage of cement, such as the duration and the location as well as the atmospheric moisture content are necessary after the process of manufacturing and before cement's use in the construction site.

Industry of aggregates

In the Netherlands, there are few mineral resources and most of the sediments are originated from the rivers Rhine and Meuse (De Mulder at al., 2003). Coarse-grained is realized in the southeast and east while fine-grained in the west and north part of the country as well as the North Sea (Ike, 2007). Firms in the sector do not produce in very large volumes and aggregates are materials extracted from nature since there is a restrictive policy for issuing extraction permits (Van der Meulen, Van Gessel, & Veldkamp, 2005).

The products are differentiated slightly based on their size. More specifically, three main categories of aggregates (fine sand, coarse sand, and gravel) are divided into classes according to their grain size distribution (extremely, very and moderately grained material) (Van der Meulen, Van Gessel, & Veldkamp, 2005).

Sand and gravel are two of the four main constituents for concrete production and their properties cannot be replaced by other materials in the building sector. The following table provides an overview of the companies that are related to aggregate extraction in the Dutch environment and the volumes of production.

Table 2.1 *Provisional Estimates of Aggregates Production Data for 2016 in the Netherlands (European Aggregates Association, 2018)*

Total number of producers (companies)	243
Total number of extraction sites (Quarries and sand & gravel sites)	288
Sand & gravel (million tons)	43.4
Crushed rock (million tons)	-
Marine aggregates (million tons)	12.5
Manufactured aggregates (million tons)	-
Recycled aggregates (million tons)	18.6
Re-used on-site (million tons)	-
Total production (million tons)	75

Incumbents in the industry of aggregates have already established their brand identities and the know-how method for extraction. The total number of companies regarding aggregate production in 2016, was 243 (European Aggregates Association, 2018).

Pre-processing storage, crushing, screening, grinding as well as product storage are part of the fixed costs concerning the aggregate production. These costs do not constitute a high percentage of the total cost of the product since most of them are automated processes (Korre & Durucan, 2009). The value of the energy and the raw material price are responsible for the highest percentage of the end price. There are quite a few differentiations in aggregates based in accordance with their way of extraction and their grained size. However, specific sizes are used based on the end-materials produced. Through specific processes, the aggregate companies offer a desirable size. This factor is highly correlated to the natural resources of the Netherlands and as a consequence, reductions or surges in capacity have slight variations. The geographic coverage of each company is specific since the aggregates are low-priced materials. Diverse competitors exist in the market from large to small companies and thus, the level of rivalry is high.

Nevertheless, the tendency has striven to the entrants which focus on the CE and materials recycling. Incentives are attributed to those who are working in accordance with a circular viewpoint and the growth in this sector is highly related to a sustainable future in the Netherlands.

2.2 The production of cement

Cement is a binder; a substance of the CS that sets hardens, and adheres to other materials in order to bind them together. It is manufactured through a closely controlled chemical combination of Al (aluminum), Ca (calcium), Fe (iron), Si (silicon) and other ingredients, as described extensively in Table 2.3. Essentially, common materials which are used for its production, include limestone, shells, and chalk or marl combined with shale, clay, slate, blast furnace slag, silica sand, and iron ore.

2.2.1 Types of cement

In this part, different types of cement, based on European standards as well as on their chemical composition, are reported. Attention has striven on Portland cement (PC), which is the most common type and it is used for the production of concrete. An analysis of the cement production in the Netherlands is conducted as well.

Portland cement – ASTM C150 standards

The most common type of cement is Portland cement (PC) or Ordinary Portland Cement (OPC). Concrete is produced the time that PC is mixed with water and creates a paste that binds with sand and rock to harden. As the chemical composition of the cement is changed, its performance is affected as well. This change in composition causes a change in cement phases, which are responsible for concrete's performance.

In the following Table 2.2, the five main types of PC with their uses are described. Additionally, in Appendix A, the chemical properties which are presented in the table are explained and their properties are analyzed. With regards to ASTM C150 and more precisely each country's specifications, the first three types of cement (Type I, II, III) change accordingly (Neville, 2012).

Table 2.2 *Compound composition (% by mass) of cement and its use based on ASTM standards (Dunuweera & Rajapakse, 2018)*

Type of cement	Use
Type I	*Common or general-purpose cement* It is appropriate for general construction, and more specifically for prefabricated concrete where there is no possibility to be in contact with soils or groundwater. Composition: C_3S = 45-55%, C_2S = 20-30%, C_3A = 8-12%, C_4AF = 6-10%
Type II	*Moderate sulfate resistance* It is used for general construction exposed to moderate sulfate attack and it is appropriate when concrete comes in contact with soils and groundwater. While during hydration, it emits less CO_2 heat than Type I, the cost is about the same. Composition: C_3S = 40-50%, C_2S = 25-35%, C_3A = 5-7%, C_4AF = 10-15% Limitation: $C_3A<8\%$ (reduce its vulnerability to sulfates)
Type III	*High early strength* It is similar but grind finer to Type I. It is commonly applicable in prefabricated concrete manufacture, where high one-day strength allows a fast turnover of molds. It is also appropriate for emergency construction and repairs, as well as for machine bases construction and gate installations. Its short-term strength (7-days compressive strength) is almost equal to 28-days one of the Types I and II. However, its long-term strength is sacrificed. Composition: C_3S = 50-65%, C_2S = 15-25%, C_3A = 8-14%, C_4AF = 6-10%
Type IV	*Low heat of hydration – (rare type)* It is used for very large concrete structures where the surface to volume ratio is significantly low. This type of cement is rarely used since Portland-pozzolan cement and ground granulated blast furnace slag, constitute low-cost and more reliable alternatives. Composition: C_3S = 25-35%, C_2S = 40-50%, C_3A = 5-7%, C_4AF = 10-15% Limitation: $C_3A<7\%$, $C_3S<35\%$ (hydration reaction is developed at a slower rate and consequently, the strength of concrete is developed slowly)
Type V	*High sulfate resistance* It is appropriate for concrete that is exposed to alkali soil and groundwater sulfates, reacts with C_3A and causes disruptive expansion. Type V has mainly been substituted by ordinary cement added with ground granulated blast furnace slag or tertiary blended cement containing slag and fly ash. Composition: C_3S = 40-50%, C_2S = 25-35%, C_3A = 0-4%, C_4AF = 10-20% Limitation: $C_3A<5\%$, $(C_4AF) + 2(C_3A)<20\%$

Cement types – EN 179-1 standards

In Appendix B, 27 types of cement, based on EN 197-1 (European Committee For Standardization, 2000) are presented. The most important cement's components are discussed below:

Main Constituent: Clinker

The production of clinker is based on a quantified mixture of raw materials, which is composed mainly by oxides (CaO, SiO_2, Al_2O_3, Fe_2O_3) and small quantities of other materials. More specifically, Portland Cement clinker is a hydraulic material with at least 2/3 by mass of calcium silicates ($3CaO.SiO_2$ and $2CaO.SiO_2$). The remaining 1/3 part contains aluminum, iron-containing materials and other components. The ratio by mass (CaO)/(SiO_2) should be less than less than 2,0. Also, the rate of magnesium oxide (MgO) by mass should not be higher than 5,0 % (European Committee For Standardization, 2000).

Minor additional constituents

They are specially selected inorganic minerals arising during the production process of clinker or cement's main components. After proper preparation and due to granulometric distribution, the secondary components improve cement's physical properties (e.g. water retention). They may be inert or have slightly hydraulic, latent hydraulic or pozzolanic properties. However, such requirements are not imposed on them. They need to be prepared correctly; during the processes of delivery and production, they should be selected, homogenized, dried and grounded according to their form. They should not significantly increase the water demand in cement, destroy the concrete or mortar as well as reduce the protection of reinforcement from corrosion. They can be inert or have slightly hydraulic, latent hydraulic or pozzolanic properties (European Committee For Standardization, 2000).

Calcium sulfate

Regarding setting control, calcium sulfate is added to other constituents during the production of cement. It can be gypsum (calcium sulfate dihydrate, $CaSO_4.2H_2O$), anhydrite (anhydrous calcium sulfate, $CaSO_4$), hemihydrate ($CaSO_4.\frac{1}{2}H_2O$), or any mixture of them. Whereas the first two mentioned types can be found in nature, specific industrial processes can also produce calcium sulfate as a by-product. The quantity of calcium sulfate added to the clinker should be 2 to 3% by mass of the cement (European Committee For Standardization, 2000).

Additives

Concerning EN 197-1 standards, additives are constituents, which enhance the manufacturing process or the mechanical properties of the cement. The mass percentage of additives in the cement should not exceed the rate of 1% and the only exception concerns the pigments. Additionally, the organic additives volume should be less than 0,5% by mass of the cement. They do not promote corrosion of the reinforcement and mortar concrete or impair the properties of the cement (European Committee For Standardization, 2000).

2.2.2 Cement manufacturing in the Netherlands

The cement is produced in two main stages (Figure 2.2). Firstly, clinker is produced through heating limestone with other materials, such as clay, fly ash, blast furnace slag to 1450°C in a kiln. The average percentage of limestone in the clinker is around 80%. However, its exact volume is related to the type of cement that is produced. An amount of limestone that is used in the Netherlands, is imported from 'CBR's Lixhe' plant in Belgium (CBR Lixhe, 2019), which is only 12 km away to the south from the factory in Maastricht.

Secondly, the resulting hard substance, is grounded into a fine powder. The raw materials are delivered in bulk, then they are crushed and homogenized, preheated and fed into a rotary kiln which reaches flame temperatures higher than 2000°C. More precisely, before the raw materials enter the kiln, hot flue glasses are used for the preheating of the homogenized mixture. Carbonates of limestone react with the heat and they finally form CaO (burnt limestone) as well as CO_2. The high temperature melts the CaO powder and consequently, new compounds, which harden the cement are produced. The final product of this phase is called 'clinker'. The kiln's slope, as it is presented in Figure 2.2, aids the materials to reach the other end, where they are cooled in temperatures between 100 and 200°C. After cooling, these solid grains are then stored in silos (ENCI, 2010).

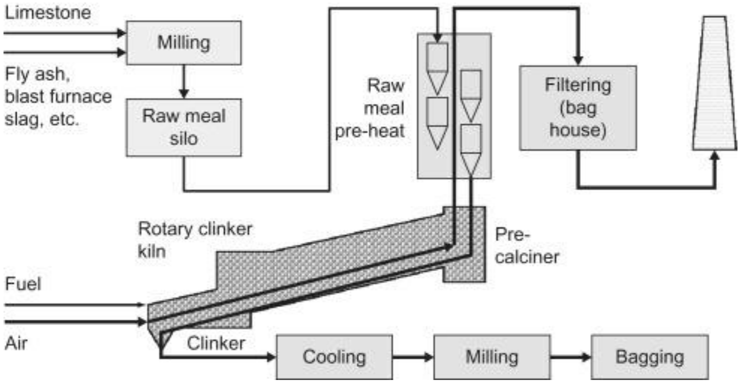

Figure 2.2 Cement production process (Habert, 2014)

Concerning the production of cement in the Netherlands, the factory of ENCI uses a mix of fossil fuels (14%), biomass fuels (44% - sewage sludge animal meal and partially PPDF pallets) and alternative fuels (42% - e.g. anode dust or glycolbottom) (ENCI, 2010). These fuels are transported to the factory from different locations. More specifically, about 35,000 tons of sewage sludge, sourced by the Waterschapsbedrijf Limburg, are transported within a vicinity of 55km from Venlo, Susteren, and Hoensbroek to Maastricht. However, aiming to reach the required quantity, the remainder is supplied by companies in Amsterdam (200km away transport distance), as well as by the two most northern regions, Friesland and Groningen (350 km transport distance). In all cases, after the delivery, natural gas dries the sewage sludge to a dry matter content of at least 90%. Sappi paper plant located nearby Maastricht (10 km transport distance) supplies paper sludge to the factory. The animal meal is transported from the Rendac plant in Brabant (100 km transport distance), and lastly, PPDF is imported from North Rhein Westphalia in Germany (100 km transport distance) (ENCI, 2010).

In Figure 2.3, an overview of the supply chain of the material of cement in the Dutch environment is presented. Additionally, Appendix C illustrates the material flows (in tons) for the different types of cement which are produced in the Netherlands. The types of cement and their composition constitute part of the calculation model, which is analyzed in feasibility assessment.

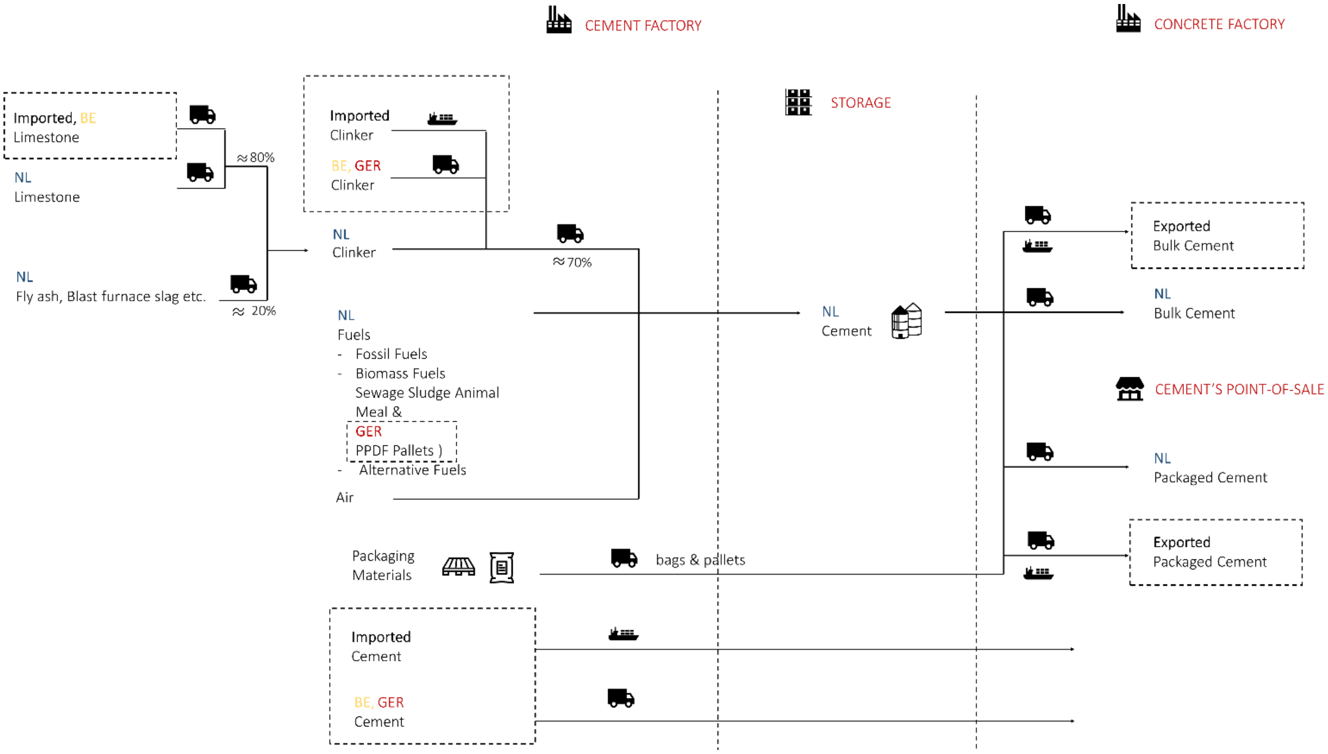

Figure 2.3 Overview of the supply chain of cement

The types of cement that are produced in the Netherlands based on EN 197-1 standards are presented in the following Table 2.3.

Table 2.3 *Types of cement produced in the Netherlands and their use (ENCI, 2019)*

Portland cement CEM I
CEM I 42.5 N[1], CEM I 52.5 N, CEM I 52.5 R It is used in the manufacturing of concrete products and in some cases in ready-mixed concrete, when it must be removed shortly after dumping. Regarding ready-mixed concrete, it can be used with or as a replacement for blast furnace cement aiming to obtain sufficient strength development. In the case of a limited alkali content, the type CEM I 52.5 R (LA) cement is suitable for use with all traditional granules without the risk of reaction between the alkalis in the cement and the granulates (ASR).
Portland composite cement CEM II
CEM II/ B-V 42.5 N

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[1] N and R are related to the strength of cement, in the function of a certain grinding fineness. A cement is produced in the strength classes 32.5, 42.5 or 52.5.

It is used for the production of blocks and stones. This cement is frequently used through the project specifications prescribed for the manufacture of concrete roads and pavements such as parking places, bus lanes, etc. In the case of using an air bubble former, it is recommended to perform a suitability test.
CEM II/ BS 42.5 N, CEM II/ BS 52.5 N It is used for structural and non-structural concrete, mortars as well as screeds.
Blast furnace cement CEM III
CEM III/ A 32.5 N It is used where no high initial strength and no fast release is required. The initial strength can be increased by supplying heat. This cement is appropriate for mass concrete and lean concrete. Due to the limited alkali content (LA), it is cement suitable for use with all traditional granules without the risk of a reaction between the alkalis of the cement and the granulates (ASR).
CEM III/ A 42.5 N It is versatile and particularly suitable for applications which require a high compressive strength at 28 days. The cement is ideal for road construction applications. By a very deliberately chosen slag content, this cement combines the favorable property of high splitting strength with very good frost and thaw salts resistance. Cement with limited alkaline content (LA) is suitable for use with all traditional granules without the risk of a reaction between the alkalis of the cement and the granules (ASR).
CEM III/ A 52.5 N It is mainly used for the manufacture of concrete products where increased durability is desired. The rapid strength development combined with the heat sensitivity makes it an ideal cement. The cement works well with all common additives and is extremely good applicable in self-compacting concrete.
CEM III/ B 42.5 N LH SR
Composite cement CEM V
CEM V/ A (SV) 42.5 N Due to the universal nature of this type, it can be used almost anywhere in the construction industry. Depending on the strength class, the cement is ideal for various applications in road construction (pavements, foundation, etc.). Due to its limited alkali content, it is suitable for use with all traditional granules without the risk of reaction between the alkalis from the cement and the granulates (ASR).
Masonry cement - MC 12.5

2.3 The production of concrete

'Concrete is a stonelike material obtained by permitting a carefully proportioned mixture of cement, sand, and gravel or other coarse aggregate, and water to harden in forms of the shape and dimensions of the desired structure' (Darwin, Dolan & Nilson, 2016).

Concrete's aggregate particles, fine and coarse, are bound into a solid mass after their chemical interaction with cement and water. Aiming to achieve the required workability of the final material, supplementary water is essential for the chemical reaction. Afterwards, the mixture is ready to fill the forms and lastly surround the embedded reinforcing steel prior to hardening (Darwin, Dolan & Nilson, 2016).

2.3.1 Categories of concrete production

In this work, the different categories of concrete production are examined; the production of prefabricated (precast) concrete and site-cast and ready-mixed concrete. A quick review regarding these categories and afterward an extensive analysis concerning the concrete production in the Netherland is presented.

Production of prefabricated concrete

Prefabricated or precast concrete is a construction product that is manufactured by casting concrete in a reusable mold or 'form'. In this category of production, a maximum quality control over the process is achieved and a consistently durable, high-quality end-product is formulated. From the prefabricated industry, it is transported to the construction project and lastly, lifted into place. The stages regarding the production of precast concrete are following described:

1. Design process

Every product is rendered by using computer added designed tools. Once design drawings are approved, they are translated into manufacturing steps in the production of concrete.

2. Manufacturing Reinforcing Cage

The steel reinforcement is cut and bended. The appropriate rebar is selected and shaken down off the storage rack. Afterward, the exact dimensions are designed in order to fit the project's requirements. The bars are assembled and tied together to develop the reinforcement cage rebar, which can be manufactured either in the cement factory or developed by another supplier.

3. Form Preparation and Pre-pour Inspection

Once the cage assembly is completed, the form is prepared. A variety of forms are used according to customers' preferences. Their maintenance regarding tolerance is more than 30 years and all openings cutouts or embedded items are secured to the form. In this respect, a form release is applied to each surface in order to confirm that the final product can be easily removed from the form. Attention is taken in order to ensure that the reinforcing cage can be transported to the construction site. The time that the setup is completed, a pre-pour inspection is conducted in order to conclusively place concrete in the construction project.

4. Concrete placement

The construction project's design requirements define the type of cement, gravel, sand, water and pozzolans that are selected to produce concrete. Raw material testing is conducted and the precise quantities of the material are identified. This is especially important in the case of high flow self-consolidating concrete. The compression strength is checked with sample cylinders and the quantity of each batch is verified. Once the materials are properly mixed, a variety of tests are accomplished; the self-consolidating concrete undertakes a spread test to verify the proper flow of the mix and the nonsegregation of the aggregate. The approved batch is transported in a bucket through an overhead crane to the production floor. Concrete is placed into the form and attention should be paid in order to allow the concrete to flow without entrapping air voids.

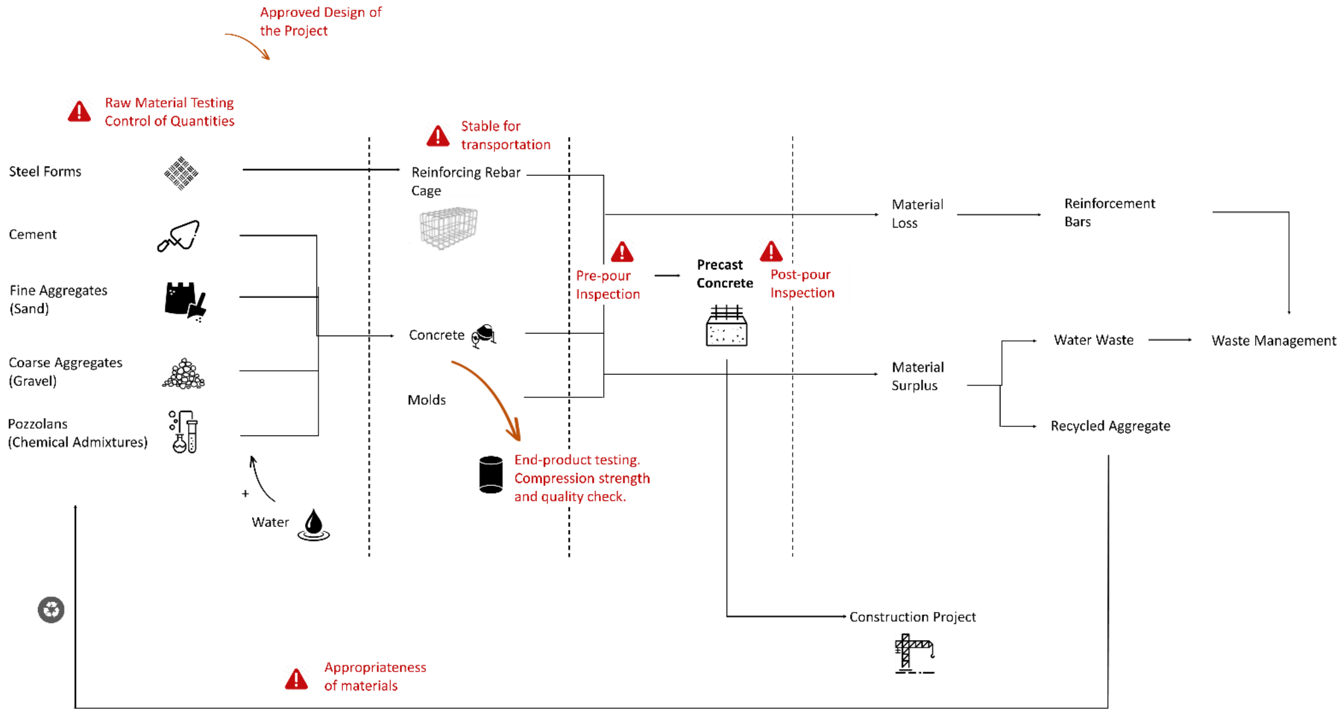

Figure 2.4 Control points in the production of prefabricated concrete

Production of site-cast and ready-mixed concrete

Cast-in-place concrete, also known as poured-in-place or site-cast concrete, is *'a concreting technique which is undertaken in situ or in the concrete component's finished position'*. This type of production is mainly selected for concrete slabs and foundations, as well as separate components, such as columns and walls. The constituents are mixed in the construction site and therefore, the workers can use the final material before it hardens.

The only difference between ready-mixed and site-cast concrete is that the first one is produced during transportation while the second one on-site. In the case of ready-mixed concrete, a ready-mixed truck is used. Several challenges arise since concrete should be used within 90 minutes after the raw materials are introduced in the mixer; therefore, transportation plays a significant role in that type of production. In terms of logistics, high coordination is required between suppliers and buyer in order to ensure the right quality at the right time at the right place. Ready-mix concrete and cement industry are normally integrated since the first one mentioned can be described as a distribution channel of the second ones.

3.3.2 Concrete manufacturing in the Netherlands

The following Table 2.4 presents the composition of conventional concrete in the Netherlands according to Krutwagen and Broekhuizen (2010) as well as Bijleveld, Bergsm, and Lieshout. (2013).

Table 2.4 *Composition of conventional concrete in the Netherlands*

Raw Materials	*Kg/ ton concrete*
Cement	150
Sand	330
Granulate (from EoL concrete)	10
Gravel	461
Concrete Iron	40

In the Dutch CS, the cement consists of 50% hoogovencement (blust furnace cement), 40% Portland cement (CEM I) and 10% portland fly ash cement. The difference between hoogovencement and PC is that the first one uses the waste product of steel production instead of the normal clinker that is used in PC. The supply chain of concrete is depicted in the following Figure 2.5. Furthermore, it is worth mentioning that the level of vertical integration is a point of differentiation among the companies in the CS. More precisely, there are firms that specialize in one activity, while firms that are active in aggregate extraction, cement mixing, and mortar production.

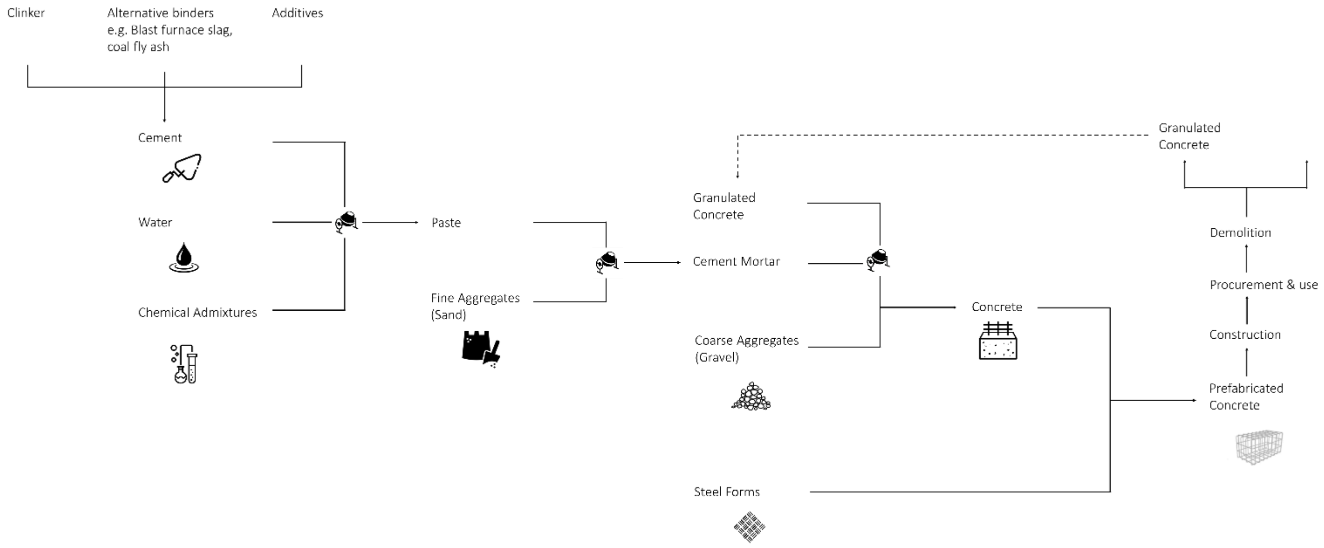

Figure 2.5 Overview of the supply chain of concrete (Bijleveld, Bergsm & Lieshout. 2013)

Concerning recycled materials, a percentage of cement can be substituted by additives with binding properties, such as blast furnace slag and coal fly ash. Additionally, fine and coarse aggregates are able to be replaced by granulated recycled concrete. Overall, Dutch concrete can be characterized exceptionally clean when locally available alternative binders and secondary fuels are used.

2.4 Construction logistics in concrete production

2.4.1 Construction logistics concepts

In terms of a city, once construction projects are completed, they contribute to sustainable and economically viable urban areas. However, in the case that transport activities are not handled properly, they have negative impacts on the surrounding community (Balm et al., 2018). It is estimated that 15-20% of heavy goods vehicles in cities are related to construction projects, and 30-40% to light commercial vans (Connekt, 2017).

Construction logistics incorporates all measures related to ensuring that equipment, material, and workers are transported, safely and at a minimum cost, to the right place at the right time (Quak et al., 2011). Construction logistics concepts that are integrated into logistics strategies can be described in a construction logistics plan; Lundesjö (2015) provides a checklist for this and the most suitable for this work is presented. Moreover, regarding van Goor, van Amstel and van Amstel (2014), Integrated Logistics Concept (ILC) consists of the following components; personal organization, supply chain strategy, Building Information Modelling (BIM), delivery pattern. ILC is frequently used in the logistics sector in the Netherlands in order to determine the layout of logistics functions in an organization. These four components do not function without a strategy and an analysis of Key Performance Indicators (KPIs).

Focus will strive on the delivery pattern, aiming to explain the supply chain of concrete in Chapter 5. According to this component, delivery pattern refers to the basic structure of the distribution across the supply chain, from production and distribution to customers. The location of production, warehousing, and transportation should be considered. The flows of raw materials, equipment as well as labor towards the construction site play a decisive role (Quak et al., 2011).

Figure 2.6 illustrates the processes of ordering, booking and delivering materials to the construction project through third-party logistics (3PL).

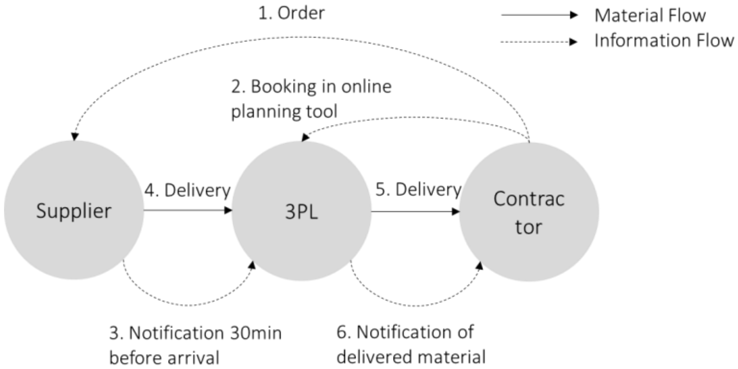

Figure 2.6 Delivery Pattern (Ekeskär & Rudberg, 2015) – the numbers indicate in which order the activities occur

According to van Goor, van Amstel and van Amstel (2003) for integrated logistics concept, the four elements that need to be accounted for, are infrastructure, planning and control, information and organization. The following analyzing components have a great impact on transportation costs in the supply chain of concrete.

A. Infrastructure

i. Logistics centers – Construction Consolidation Centers (CCC)

A CCC is described by Ludema (2015) as *'a hub place where goods can be packaged so as to increase the capacity of trucks headed to the city center and to reduce the number of transports required'*. It is a transshipment point that reduces increasingly transportation costs as well as disturbance and carbon emissions in an urban environment. Deliveries from suppliers are received and held at the CCC in order to make efficient use of inbound logistics. Typically, the warehousing does not last more than one or two weeks, while the exact duration depends on the stored product (Bogers, Weijers, Postulart, & van Amstel, 2017).

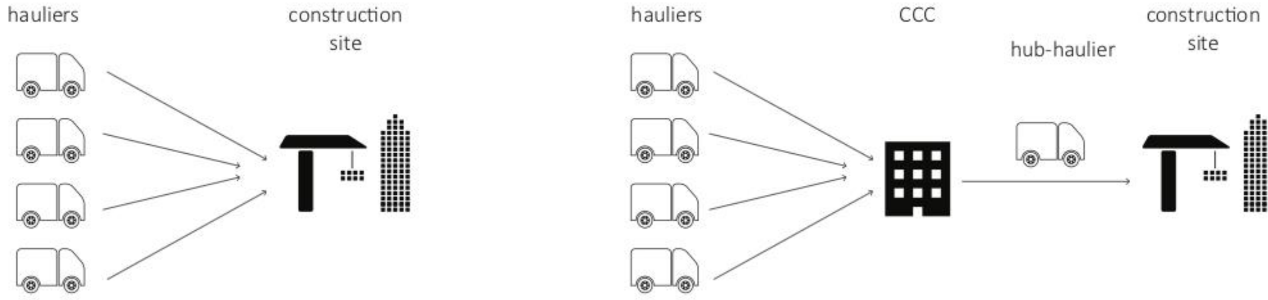

Figure 2.7 (a) Transportation to the construction site without a CCC & (b) transportation to the construction site with a CCC

ii. Prefabrication & Off-site Manufacturing

Regarding the analyzing topic, prefabrication and off-site manufacturing refer to the implementation of prefabricated elements in construction design, and more specifically prefabricated pieces of concrete for different uses. The manufacturing process is realized in a controlled environment and decreases the defective products as well as the overall wastes. Fewer transportation movements are achieved and more space on the construction site is available (Bogers et al., 2017). This method can help to accelerate the building project, gain productivity and reduce inconvenience for the city inhabitants. However, better communication and coordination along the supply chain of concrete is necessary, and transparency is of principal importance (Ufemat, 2008).

These types of low-emissions concepts can lead to new forms of combined transports. They can bring the materials to the building site by minimizing the traffic in big cities and connecting the supply with the demand (Ufemat, 2008). A noteworthy example is in London, where developing projects have achieved 70% reductions in CO_2 emissions from site traffic (TfL, 2008).

B. Planning and Control

i. Construction logistics coordinator (CLC) & construction logistics ticket

A CLC is responsible for logistics management, with or without the involvement of other actors in the value chain of concrete. More specifically, the CLC monitors and sends all required materials to the construction site in accordance with the project planning. Additionally, for a successful result, the involved stakeholders should be willing to cooperate. Based on a business case, Kolkman, Molenaar, and van Berchum (2008) outlined the benefits of the use of a CLC through pinpointed that the total costs reduced more than 2.5%. The construction logistics ticket or 'building ticket' targets to control the onsite logistical processes by providing clarity for suppliers and developing a safe work environment (Segeren, 2010). More specifically, it is a tool that controls which suppliers will have access to the construction site and based on that, a CLC can organize timely the deliveries to the construction site.

ii. Consideration of logistics issues in the design

The project's structural design can influence its long term efficiency. Throughout the design phase, architects and designers make decisions that have a great impact on logistics (Papaprokopiou, 2010). Therefore, an analysis of the risks while examining the preliminary design of the construction site is necessary. Construction materials with the biggest volume, such as concrete, are able to cause the main logistics problems in the construction site. Consequently, their exact quantities should be identified.

iii. Just-in-time (JIT) delivery to the building site

JIT is a concept developed by the Japanese who created the Toyota Production System and later translated it as the lean production system. This type of delivery ensures that the materials are transported immediately to the construction site and there are no intermediate processes that can delay or interrupt the final installation, such as storage in a laydown or staging area. In the first phase of the construction project, a JIT service is essential where there is supply the large construction elements.

iv. Delivery management system and other IT support

ICT systems can tag and track materials through manufacture, distribution, assembly, and installation or construction. In the Recycling Laboratory in the Faculty of Civil Engineering at TU Delft University, experiments are conducted for the placement of radio frequency identification systems (Di Maio, Berkhout, 2019) in prefabricated concrete. The tag system allows the tracking of materials to the construction site and it is able to provide considerable detail about the on-site situation. Appropriate IT systems for the construction sites are low-cost devices that are becoming more widespread (TLB, 2010).

C. Information – Building Information Modelling (BIM)

A Building Information Model, or BIM, is *'a digital representation of physical and functional characteristics of a facility. It serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its lifecycle from inception onward. A basic premise of BIM is a collaboration among different stakeholders at different phases of the lifecycle of a facility to insert, extract, update, or modify information in the BIM, to support and reflect the roles of stakeholder'* (National BIM standard 2007).

BIM enables the involved actors of concrete's value chain to share information through open standards, thus improving coordination and preventing errors. Moreover, it offers the ability to predict logistical flows, monitors the construction process as well as give oversight for all stakeholders (Bogers et al., 2017).

D. Organization

i. Construction logistics cooperation

The information flow alongside the supply chain of concrete is crucial since the risks, as well as the costs, are spreading. According to Dijkmans et al. (2014), successful cooperation in construction logistics chains in Amsterdam results in fewer transport movements and greater sustainability. The expert interviews with different stakeholders in the concrete industry will contribute to the identification of the information flow and the level of cooperation that is succeeded.

ii. EMAT criteria

EMAT stands for Economically Most Advantageous Tender. During the tendering phase, clients can use EMAT criteria to score contractors' proposals on a range of different criteria, thus preventing tenders from being awarded solely on the basis of the lowest price. Van Amstel (2015) shows how the criterion 'logistical quality' can be established on the basis of Van Goor's, van Amstel's & van Amstel's (2003) integrated logistics concept.

2.4.2 Construction logistics activities

With regard to Fang & Ng's (2011) research, a diagram with the possible logistic costs in the production of concrete is presented. This puts the basis for the identification of logistic elements that are related to concrete manufacturing and are involved in the spreadsheet model that is following developed. The focus is on bulky components and the emphasis is on the determination of the flow of materials in accordance with the related costs. Three main activities are identified as illustrated in Figure 2.8; procurement, transportation, and loading. The involved stakeholders determine the processes that will be included in the production of concrete; some steps presented may not be part of the manufacturing (e.g. inventorying). It is worth referring that only the specific part of the concrete's production where logistic concepts take place is visualized.

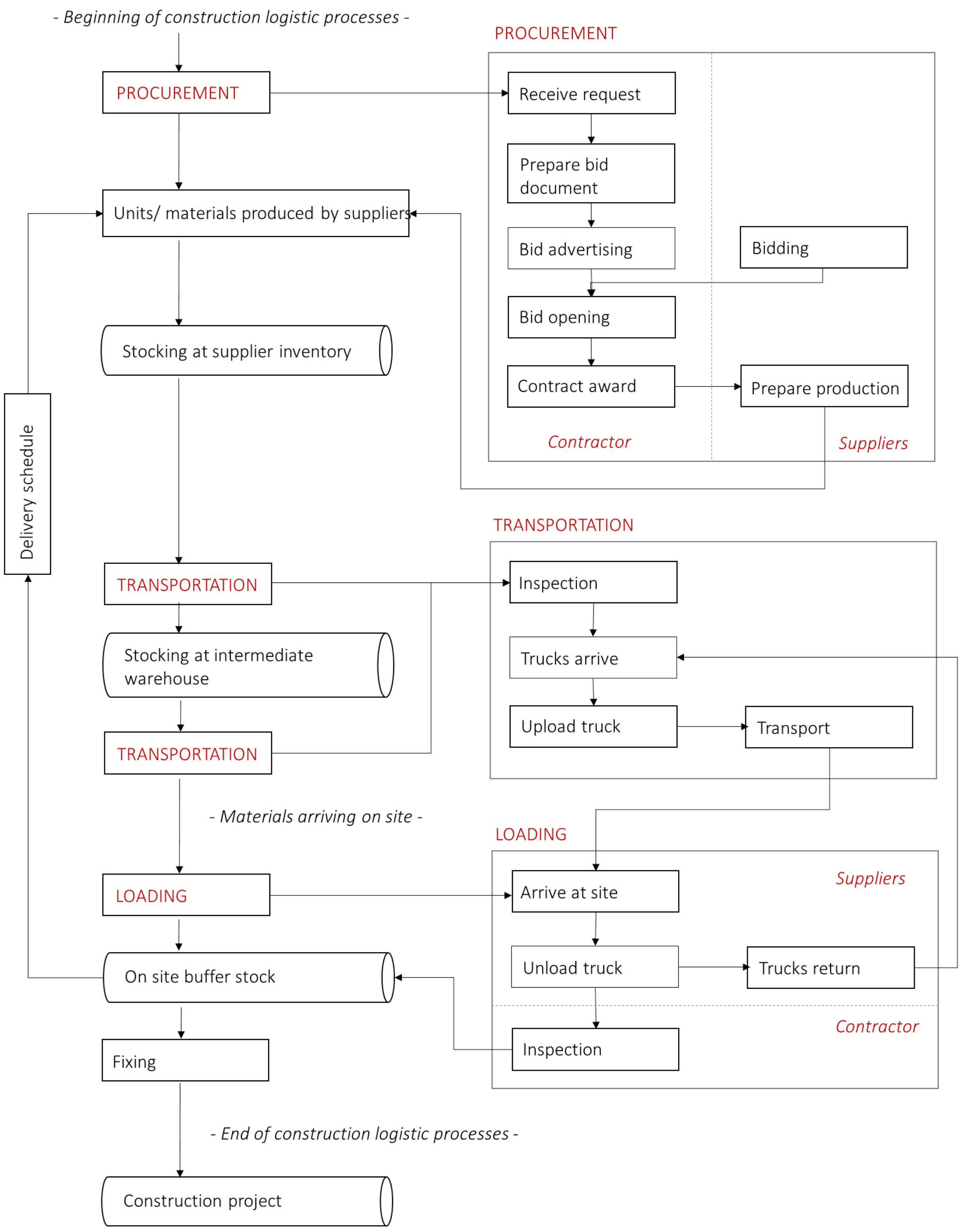

Figure 2.8 Logistic processes and activities in concrete production

2.5 Relevant work

Table 2.5 presents related work concerning the recycling of concrete and the appropriate percentages of RA in its production. It essentially connects the context of this chapter with the next one (Chapter 3: Technologies for concrete recycling). Respectively, relevant work to SCM and logistics in the CS is depicted in Table 2.6. The presented results lay the foundation of Chapter 4, where the detailed design phase of this work is developed based on mapping tools as well as logistics concepts. Useful parts of each paper's results, as well as knowledge gaps, are posed.

Table 2.5 *Relevant work for concrete recycling*

Relevant work - Reference	Useful parts for this thesis	Results related to this thesis	Knowledge gaps that this work targets to fill
Di Maio, Rem, Lofti, Serranti, Bonifazi, Hu, & Cucchietti, (2012)	Description of C2CA project. High-grade recycling for EoL exploitation.	Preliminary economic analysis shows that the C2CA approach decreases the process cost for EoL concrete into clean aggregates.	*It constitutes part of this thesis' literature research.*
Evangelista & De Brito, (2014)	Characteristics of fine recycled concrete aggregates (FRCA).	FRCA is not only a theoretical possibility.	FRCA needs further investigation to be applied in the construction industry, concerning water absorption, durability of concrete, type and amount of recycled particles.
Lotfi, Deja, Rem, Mróz, van Roekel, & van der Stelt, H. (2014)	Mechanical properties and performance of RA from EoL concrete.	Technologies in C2CA can produce high-quality RA. RA in concrete might increase the overall porosity of concrete compared to virgin aggregates.	More research for a compressive approach that delivers high-quality aggregates at economically and environmentally attractive conditions.
Lotfi, Eggimann, Wagner, Mróz, & Deja, (2015)	Examination of RA substitution, W/C ratio and type of cement to the properties of RAC.	A higher amount of mixing water (impact on W/C ratio) leads to worse mechanical and durability properties. The type of cement can have an impact on durability properties. RA can replace a high percentage of coarse aggregates in concrete.	More research on technology ADR with respect to the quality of RAC.
De Brito, & Silva, (2016)	Existing obstacles to the widespread	The replacement of NA with RA in construction projects as one of the	Quality control necessity through the

	use of RA in concrete and current standards for RA in concrete.	most effective CDW treatment approached.	construction and demolition life cycle in order to increase stakeholders' trustworthiness.
Lotfi, & Rem, (2016)	Description of HAS technology and the use of recycled fine and ultrafine particles for the production of cement and concrete.	The construction industry has a limited tendency in introducing recycled fines for high-quality applications. Recycled fines in the production of cement lead to lower CO_2 emissions due to the amount of CaO.	More research should be conducted for the exact amount of recycled fine and ultrafine particles in concrete.
Lotfi, et al. (2017)	Description of EU-developed projects regarding concrete recycling.	ADR technology can lead to higher quality coarse aggregates compared to virgin ones, only in the case that moisture has been removed. Concrete with RA hardens must faster than the compatible one. ADR technology could be adapted to light-weight concrete waste recycling.	*It constitutes part of this thesis' literature research.* The effect of recycled fractions in cement-based materials and new concrete requires more research.
Lotfi, Rem, Deja, & Mróz, (2017)	Investigation of the influence of implied factors on the quality of RA and RAC	The type of parent concrete influences the final properties of RA. Mechanical and durability of RAC is remarkably similar to those of NAC. ADR cut-size point on 2mm leads to the best performance of RAC.	More research is essential concerning the adverse effects of contaminants in ADR fines.

Table 2.6 *Relevant work for construction logistics*

Relevant work - Reference	Useful parts for this thesis	Results related to this thesis
Agapiou, Clausen, Flanagan, Norman, & Notman, (1998)	Logistics in the construction industry.	Logistics is an important management tool to ensure a strategic perspective of the material flow in the construction industry. Logistics can lead to a high-quality product and to overall savings by improving coordination and communication among stakeholders of the project.
Tommelein, & Li, (1999, July)	Just-in-time (JIT) delivery in the concrete industry.	JIT system is applied in the ready-mixed concrete industry for at least one part of the concrete supply chain

	Symbols for Value Stream Mapping to map resource flows – *useful for the development of Chapter 5.*	
Segerstedt, & Olofsson, (2010)	Supply chain management in the project-based construction industry. The common aspects of traditional manufacturing and its supply chains.	The CS is mostly local and highly volatile, which causes fragmentation of the industry. The major distinction between the construction and manufacturing sector is that the last one is project-based while the first referred engage continuous processes and relationships.
Vilasini, & Gamage, (2010)	The application of value stream mapping techniques in the production of prefabricated concrete.	*Useful for the development of Chapter 5* Value stream mapping tool can lead to a better understanding of the construction industry through cycle time reductions and quality improvements.
Vidalakis, Tookey, & Sommerville, (2011)	Logistical analysis of construction supply chains. Relationship between supply chain and logistics management. SCM in the CS.	The importance of incorporating intermediary organizations in construction supply chains. Varying demand can hinder the logistics management application in the CS. Variations in demand and logistics costs are associated with material transportation and inventory management.
Sobotka, Sagan, Baranowska, & Mazur, (2017)	Reverse logistics of construction materials during demolition projects. Planning and organizing supply chains through reverse logistics.	Effective demolishing waste management methods; reuse, resale, repair, refurbish, or other methods ending to energy recovery and disposal. The basis for the expansion of reverse supply chains is the separation of waste collection. Expanding the logistics chain through including waste recipients requires market analysis – *Useful for the development of Chapter 4.*
Dakhli, & Lafhaj, (2018).	The application of techniques from other industries in the construction sector; 'pull system', 'Just-in-Time', 'Kitting' and 'off-site fabrication. The importance of Materials Management (MM).	The establishment of well-designed materials management techniques could help to overcome storage problems. The use of efficient techniques has been well received by prefabricated companies.

	Logistics are not considered the primary concern of construction managers.	
Whitlock, Abanda, Manjia, Pettang, & Nkeng, (2018)	The barriers and benefits of Building Information Modelling (BIM) as a revolutionary technology in construction site logistics management.	Logistic management strategy is crucial to decrease wastes and secure construction site efficiency. BIM has the same principles as construction logistics management and can lead to better planning and material distribution.

2.6 Conclusions and contribution of Chapter 2

The drawn conclusions from the analysis of the third chapter are the consequent ones:

- Cement is the material with the highest complexity of concrete components and the most common type is the Portland Cement (PC).
- According to ASTM C150 standards, there are five types of PC, based on their chemical composition and their future use:
    i. Type I: Proper for general use, and more specifically for prefabricated concrete production.
    ii. Type II: Appropriate for general construction that is exposed to moderate sulfate attack.
    iii. Type III: Similar to Type I, but grind finer. Suitable for emergency construction and repairs.
    iv. Type IV: Cement for high-volume concrete structures (rare type).
    v. Type V: Applicable in concrete that is exposed to alkali soil and groundwater.
- With regards to EN 179-1 standards, the cement types produced in the Netherlands and their use in concrete structures are following presented:
    i. Portland cement CEM I: concrete products and ready-mixed concrete.
    ii. Portland composite cement CEM II: structural and non-structural concrete, mortars and screeds (CEM II/ B-S), blocks, road and pavement construction (CEM II/ B-V).
    iii. Blast furnace cement CEM III: mass and lean concrete (CEM III/ A 32.5N), road construction (CEM III/ A 42.5N), concrete products with increased durability (CEM III/ A 52.5N).
    iv. Composite cement CEM V: applied anywhere in the CS.
    v. Masonry cement
- The two main categories of concrete production are the (i) prefabricated concrete and the (ii) site-cast/ ready-mixed concrete.
- The production of concrete requires multiple control testing in various stages of its manufacturing. Raw material testing, quality control, appropriateness of RA, approval of project’s design, test for reinforcing cage’s stability, end-product testing, pre-pour inspections and post-pour inspection of the final product should be conducted.
- In the Dutch CS, on average, one ton of conventional concrete consists of 150 kg cement, 330 kg sand, 461 kg gravel, 10 kg granulated concrete, 40 kg concrete iron. Water is mixing with the above components aiming to bind them together.

- Granulated concrete that is used in the CS, is originated from EoL concrete. Hence, the current percentage of recycled materials to conventional concrete is equal to 1%.
- Regarding construction logistics concepts, the four main elements with an impact on transportation costs in concrete's supply chain, are infrastructure (logistics centers – construction consolidation centers, Prefabrication and off-site manufacturing), planning and control (construction logistics coordinator and construction logistics ticket, consideration of logistics issues in the design, just-in-time (JIT) delivery to the building site, delivery management system and other IT support), Building Information Modelling (BIM) and Organization (construction logistics cooperation, EMAT criteria)
- Construction logistics in concrete production are related to three main activities; procurement, transportation and loading.
- Based on the relevant work's analysis, the importance of applying Value Stream Mapping as a logistic tool in the following chapters is identified; it can lead to a better understanding of the construction industry.

Contribution of Chapter 2

This Chapter describes the main components for the development of the design stage. It constitutes the backbone of this research since the material of concrete and its way of production are the main focus of this work. The types of cement and the categories of concrete are interrelated with the potentials of RA and, as a consequence, their analysis is necessary for further steps. Illustrations of cement and concrete supply chains are contributing to later analysis. Overall, Chapter 2 is required for the mapping of the conventional and closed-loop approach as well as the analysis of the trade-offs in transportation after the integration of RA to the supply chain of concrete.

CHAPTER 3. TECHNOLOGIES FOR CONCRETE RECYCLING

In this Chapter, the technologies regarding concrete's recycling and the potentials of integrating RA in concrete's production are examined. A closed-loop approach is presented based on technologies that can separate concrete to its raw materials by ensuring high-quality outputs. Feasible options concerning circular concrete management are proposed. It comprises the second stage (Figure 3.1) of the design approach that is developed throughout the thesis. More specifically the solution to the main problems of CDW as well as the introduction of the novel technologies to the market is formulated and design specifications are established.

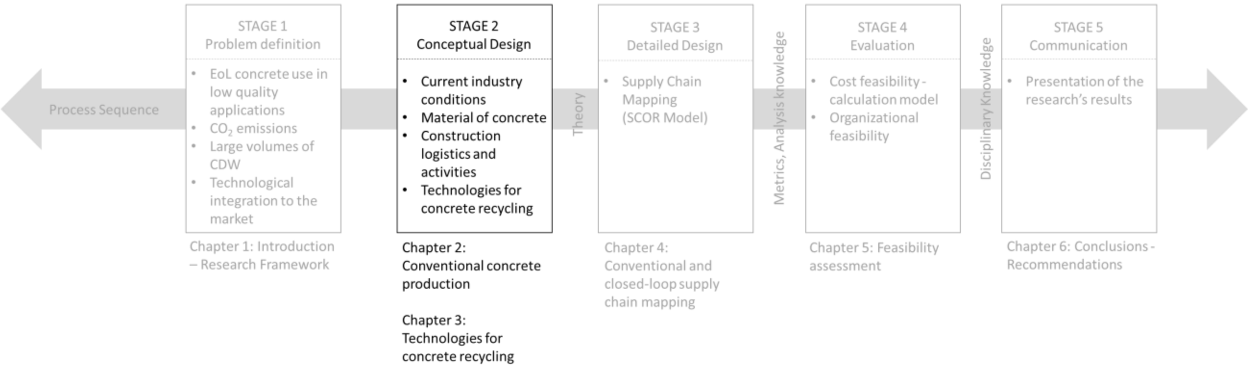

Figure 3.1 Stage of the design approach for Chapter 3

Initially, the already developed and developing technologies in accordance with on-going EU projects are described. More specifically, the main focus is on Crusher – Smart Dismantling and Demolishing, ADR technology and HAS, which crush and separate EoL concrete into high-quality raw materials. Data concerning the size of materials and volumes regarding the operational speed of the technologies have been extensively discussed with professors and researchers from the 'Resource and Recycling Laboratory' in the Faculty of Civil Engineering in TU Delft and expert interviews were conducted (Table 3.1). The approach to how these technologies close the concrete loop is graphically presented.

Table 3.1 *Experts from Resource & Recycling laboratory that I have been in contact with*

Name	Research Field – Position
Abraham Gebremariam	Postdoc Researcher
Francesco Di Maio	Research Director of Recycling Lab
Peter Berkhout	Laboratory & Field Implementation
Peter Rem	Head of Research & Recycling Section

The combination of these technologies is trying to challenge the high percentage of CO_2 emissions that are emitted during cement production and bulk transportation. A 'Concrete-to-concrete Recycling Plant' is suggested as a solution to the problem by providing recycled materials and reducing transportation movements.

To conclude, this chapter composes supplementary research for the ‘Resource and Recycling Laboratory’, targeting to a holistic approach of the novel technologies and their introduction to the market. Parts will be used in handbooks that cover every aspect of the developed technologies and they will be communicated in companies related to concrete production.

3.1 Technology Selection and Description

The analyzed technologies of this thesis are selected since they have not been applied in an industrial scale and more research is required. However, they have an experimental proof of concept and they have already been part of funded projects. Additionally, they could be combined together to formulate a concrete recycling plant and they are developing in the Dutch environment. After thorough research, the novel technologies that can close the current concrete loop and they can influence the material as well as information flow are described in this section.

More precisely, regarding the on-going EU projects, Lotfi et al. (2017) presented those that are being developed in the Dutch environment and based on the chronological order, they are the followings:

1. The C2CA Project (‘*Concrete to Cement and Aggregates*’, "Home | C2CA", 2019 - http://www.c2ca.eu/)
2. The HISER Project (‘*Holistic Innovative Solutions for an Efficient Recycling and Recovery of Valuable Raw Materials from Complex Construction and Demolition Waste*’, ("Home | HISER Project", 2019 - http://www.hiserproject.eu/) and
3. The 4-year H2020 VEEP Project (‘*Cost-effective recycling of CDW in high added value energy-efficient prefabricated concrete components for massive retrofitting of our built environment*’, (“Home | VEEP Project”, 2019 - http://www.veep-project.eu/).

The first two mentioned projects, C2CA and HISER, have mainly targeted to a new systematic approach for the production of cement and prime-grade aggregates from high-volume CDW streams (Di Maio et al., 2012). The C2CA project is a combination of innovative technologies aiming to make the products of the concrete recycling plant suitable as input materials for cement and mortar or pre-cast concrete industry. In general, materials, such as glass, metals and bricks are removed from the demolition site and afterward, the concrete is crushed and the remaining materials are sieved. The main problem with crushed concrete fines is associated with its contaminated and moisturized nature which applies for fine aggregates fraction. At that point, the third project came to realization. VEEP is a 4-year project which started in 2016 and its main objective is the development and demonstration of new cost-effective technological solutions through achieving novel closed-loop circular approaches for CDW recycling. The final goal of the project is the integration of a percentage equal to 75% by weight of CDW in the production of new concrete for the CS (Lotfi et al., 2017).

‘*Separating sand and cement makes it possible to reuse and sell both materials*’, says Dr. Francesco Di Maio (2017) from the Recycling Laboratory in the Department of Civil Engineering, ‘A*dding value to 40% of the ADR output makes recycling concrete more profitable*’.

The above-referred projects and by extension the related technologies are developed in line with the revised Waste Framework Directive (WFD). This is translated into the fact that in 2020, the minimum recycling percentage of non-hazardous CDW in concrete should exceed the rate of 70% by weight (Pacheco-Torgal, Tam, Labrincha, Ding, & de Brito, 2013). EoL concrete is one of the heaviest components of urban waste streams and therefore, its recycling process contributes to the 2020 WFD goal (Corinaldesi & Moriconi, 2009).

The technologies that are based on the EU-projects and will lay the groundwork of this research are defined.

A. Crusher – Smart Dismantling and Demolishing

The first analyzing technology is called Crusher – Smart Dismantling and Demolishing. Its importance is derived from the fact that the last years, great efforts are done concerning the purity of EoL concrete. A better planning of dismantling and demolition is managed to lead to high-quality RA since the selected EoL concrete contains fewer contaminants (European Commission, 2013).

This technology crushes EoL concrete to coarse aggregates and aggregates with smaller diameter that constitute the input of ADR technology. The size of coarse parts (<16mm, <22mm or <32mm) depends on the material's future use. The smaller the size of the aggregates, the more expensive the process is. The size and volumes of crusher's inputs and outputs are presented extensively in Table 3.2. During crushing (Figure 3.2), water is sprayed for better process performance. Nevertheless, the main concern arises. Workers in the recycling process desire low levels of dust density in the air and as a consequence more water is sprayed. More water leads to higher CO_2 emissions as well as to a lower-value material. Thus, the water which will be consumed in the crushing stage will influence the percentage of moisture that is contained in the ADR input and the energy that will be consumed for the evaporation of ADR outputs (Berkhout & Rem, 2019). The exact percentage of water starts from 0% in the Netherlands and the ideal amount should be less than 3-4% of EoL concrete's volume; this is translated into 30-40 liters water/1-ton EoL concrete. The sprayed water is evaporated with HAS technology (Rem, 2019). Crusher's final target is the production of low levels of contaminants followed by mechanical upgrading of the material on-site.

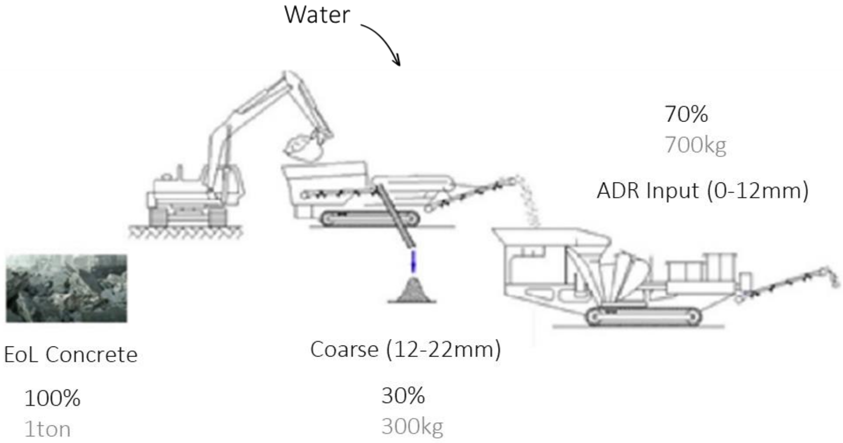

Figure 3.2 Crusher – Smart Dismantling and Demolishing technology (mass inputs and outputs for the crushing of 1 ton of EoL concrete)

Table 3.2 *Mass inputs and outputs for the crushing of 1 ton of EoL concrete (coarse part < 22mm)*

	Size		Volumes			
	min (mm)	max (mm)	%	kg	tons	tons/h
Inputs						
EoL concrete			100	1000	1	150
Water			0			
Total			100	1000	1	150
Outputs						
Coarse Part	12	22	30	300	0.3	45
ADR input	0	12	70	700	0.7	105
Total			100	1000	1	150

B. Advanced Dry Recovery (ADR) Technology

After crushing and sorting out contaminants, ADR technology is applied to remove the fines and light contaminants of the mixture. It is a new low-cost classification technology, which uses kinetic energy in order to break the bonds that are formed between moisture and fine particles. Therefore, it can classify raw materials from their moisture. After breaking up the material into a jet, the fine particles are separated from the coarse particles. As it is presented in Figure 3.3, ADR separation has the effect that the aggregate is concentrated into a coarse aggregate product (the size of coarse aggregate product depends on materials future use; either 4-12mm or 4-16mm) and a fine fraction (0-4 mm) which includes the cement paste (0-1mm) and contaminants (1-4mm) such as wood, plastics and foams (Lotfi et al, 2014; Lotfi et al., 2015). The fines from coarse separation can be abstracted with a size of 4-16mm, while the separation lights, such as wood and plastic, require a size of 4-12mm. Therefore, the technology is recommended for 4-16mm in the case that EoL concrete stems from sources which do not contain contaminants, such as bridges (Rem, 2019). This separation could facilitate the high-quality reuse of the hardened cement rich fraction in virgin cement production. The size and volumes of ADR's inputs and outputs are presented extensively in Tables 3.3 and 3.4. ADR equipment is supplied with a separation capacity ranging from 50 tons/h (1 m width) to 120 tons/h (2.4 m wide). The ADR at the region of Hoorn (pilot testing) has a capacity of 50 ton/h.

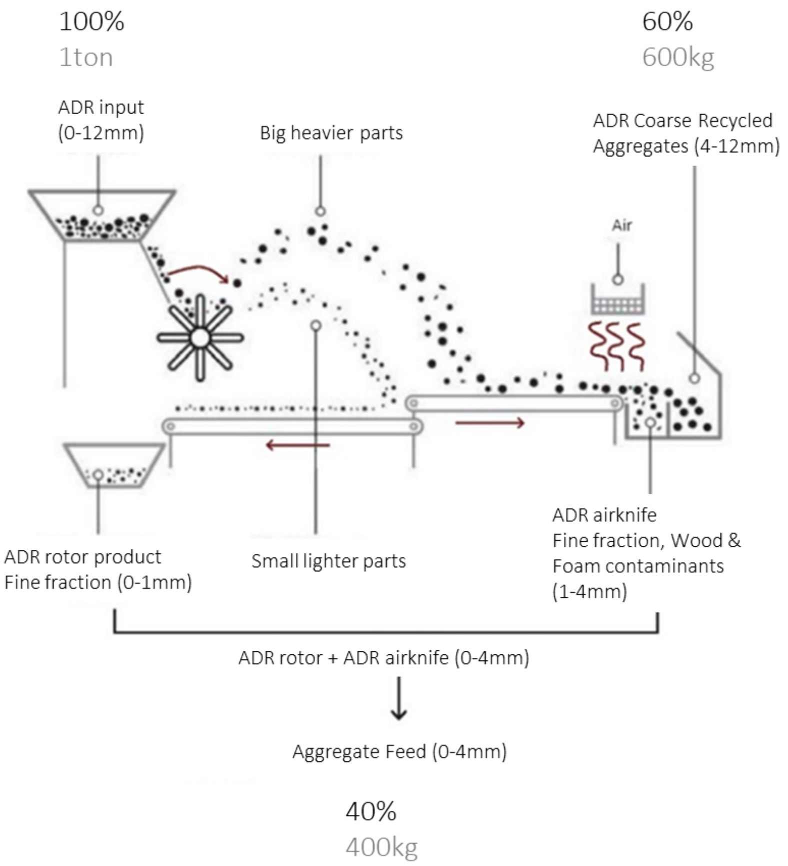

Figure 3.3 ADR Technology (mass inputs and outputs for the separation of 1 ton of ADR input)

The following Tables 3.3 and 3.4 refer to the separation of 1 ton of EoL concrete and 1 ton of ADR input respectively. In Table 3.3, the mass ADR input refers to the mass output of the crusher.

Table 3.3 *Mass inputs and outputs for the separation of 1 ton of EoL concrete with ADR technology*

	Size		**Volumes**			
	min (mm)	max (mm)	%	kg	tons	tons/h
Inputs						
ADR input	0	12	70	700	0.7	50
Total			70	700	0.7	50
Outputs						
ADR coarse recycled aggregates	4	12	42	420	0.42	21
ADR rotor + ADR ariknife (aggregate feed)	0	4	28	280	0.28	14
Total			70	700	0.7	35

Table 3.4 *Mass inputs and outputs for the separation of 1 ton of ADR input with ADR technology*

	Size		Volumes			
	min (mm)	max (mm)	%	kg	tons	tons/h
Inputs						
ADR input	0	12	100	1000	1	50
Total			100	1000	1	50
Outputs						
ADR coarse recycled aggregates	4	12	60	600	0.6	30
ADR rotor + ADR ariknife (aggregate feed)	0	4	40	400	0.4	20
Total			100	1000	1	50

At that point, the main query which arises is why it is not taken advantage of all available tons of ADR input (output of crusher: 105 tons/h) and why the technology is operating in lower volumes. Nevertheless, researchers from TU Delft are exploiting the available equipment in Hoorn, which operates with a separation speed of 50 tons/h.

To sum up, ADR is one of the technologies which are closing the loop of concrete and exploit EoL concrete for high-quality uses. In the following Figure 3.4 is presented schematically how C2CA concrete recycling technology (ADR constitutes the biggest part of the C2CA project) targets to a cost-effective system approach. A number of innovative technologies as presented in scheme 3.4 (b) close the conventional concrete production, which is figure in scheme 3.4 (a).

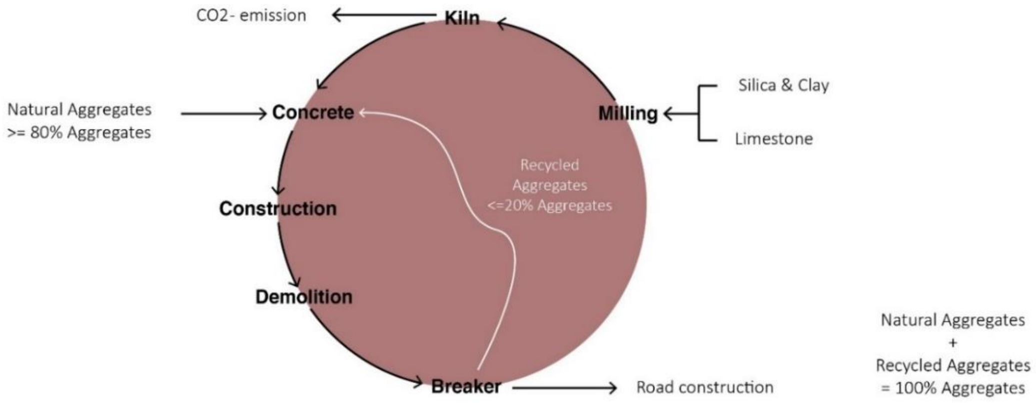

Figure 3.4 (a) Conventional concrete production

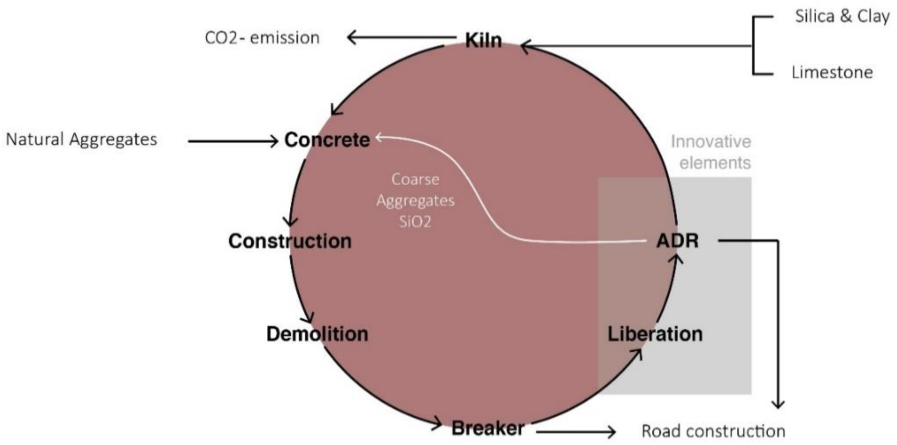

Figure 3.4 (b) Closed-loop concrete production based on the C2CA project

C. Heating Air Classification System (HAS)

Based on Lotfi's research (2016), the main concern refers to the finer fraction of crushed EoL concrete (ADR output) owing to the moist mixture of silica aggregates, cement paste as well as water (10-15%), contaminated with 0.5-1% of foreign materials. The highest percentage of water included in the fraction, is attributed to the crushing process, as described in the technology of crusher.

The crushed concrete fines (0-4mm – ADR output), constitute one of the massive by-products of concrete recycling and due to their moisturized and contaminated nature, no high-quality applications are achieved. In view of this problem, Heating Air Classification System (HAS) offers an effective recycling process. This technology separates the cementitious powder (0-0.250mm) from the sandy part (0.250-4mm) in the crushed concrete fines and delivers attractive products with the minimum possible amount of contaminants (Figure 3.5), through a combination of heat and air classification (Lotfi & Rem, 2016). The latest insights through research in the laboratory, indicate that the cement paste spalls of the sand grain if it is heated rapidly in short period of time (Berkhout, 2019).

Overall, concerning the three mentioned technological advancement, the highest interest is attributed to the ultrafine part, which can be used in the following two different ways (Berkhout & Rem, 2019).

1. It can replace additives (e.g. fly ash) but without impacting on the cement production. The result will be lower CO_2 emissions since the concrete binder will contain less cement from the kiln.
2. It can replace a percentage of limestone. The result will be lower CO_2 emissions since the old cement does not produce any amounts of CO_2.

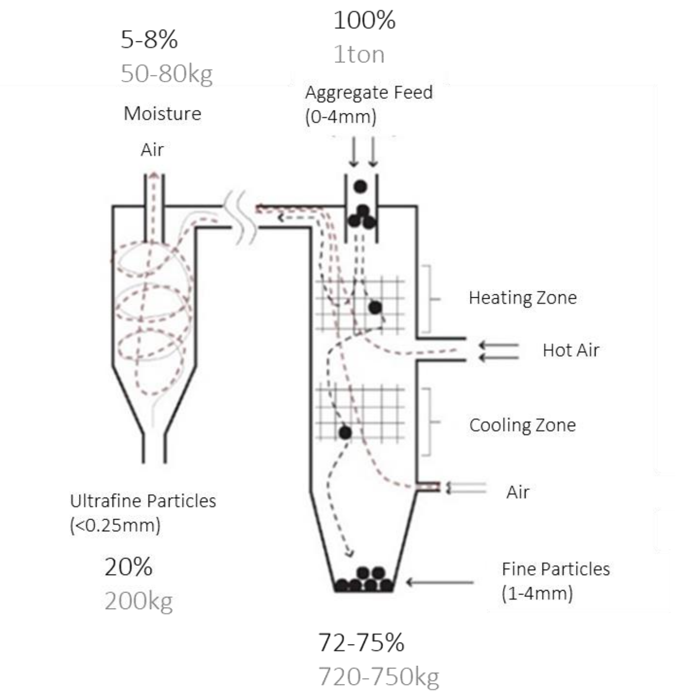

Figure 3.5 HAS (mass inputs and outputs for the separation of 1 ton of ADR input

The following Tables 3.5, 3.6 refer to the separation of 1 ton of EoL concrete and 1 ton of HAS input respectively. In Table 3.5, the mass HAS input refers to the mass ADR output.

Table 3.5 *Mass inputs and outputs for the separation of 1 ton of EoL concrete with HAS technology*

	Size		**Volumes**							
	min (mm)	max (mm)	min (%)	max (%)	min (kg)	max (kg)	min (tons)	max (tons)	min (tons/h)	max (tons/h)
Inputs										
ADR rotor + ADR ariknife (aggregate feed)	0	4	28		280		0.28		3	
Total			28		280		0.28		3	
Outputs										
Moisture			1.4	2.24	14	22.4	0.014	0.0224	0.042	0.0672
Ultrafine particles	0	0.25	5.6	5.6	56	56	0.056	0.056	0.168	0.168
Fine particles	1	4	20.16	21	201.6	210	0.2016	0.21	0.6048	0.63
Total			28		280		0.28		0.42	

Table 3.6 *Mass inputs and outputs for the separation of 1 ton of EoL concrete with HAS technology*

	Size		Volumes							
	min (mm)	max (mm)	min (%)	max (%)	min (kg)	max (kg)	min (tons)	max (tons)	min (tons/h)	max (tons/h)
Inputs										
ADR rotor + ADR ariknife (aggregate feed)	0	4	100		1000		1		3	
Total			100		1000		1		3	
Outputs										
Moisture			5	8	50	80	0.05	0.08	0.15	0.24
Ultrafine particles	0	0.25	20	20	200	200	0.2	0.2	0.6	0.6
Fine particles	1	4	72	75	720	750	0.72	0.75	2.16	2.25
Total			100		1000		1		3	

Additionally, a graphical representation of the closed-loop approach for concrete's production through applying the technologies ADR and HAS is presented in Figure 3.6 (b). This figure is subsequent to Figure 3.4 (b) and illustrates the exploitation of RA as high-quality materials in the CS.

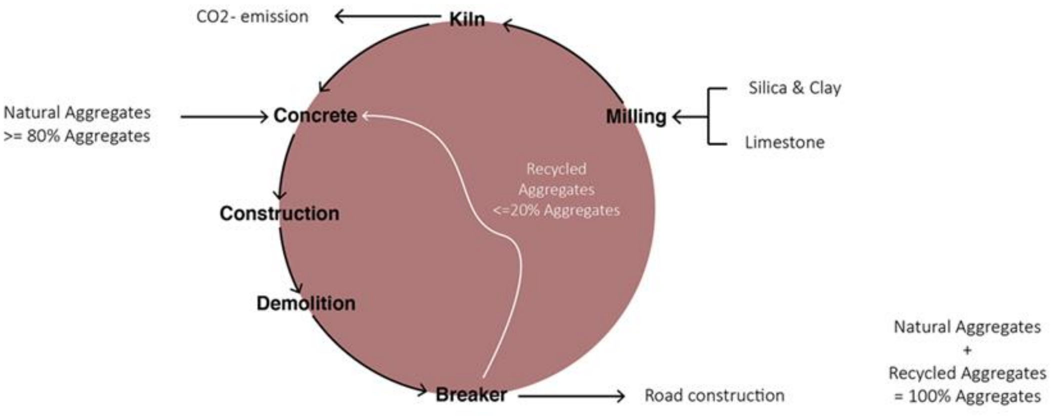

Figure 3.6 (a) Conventional concrete production

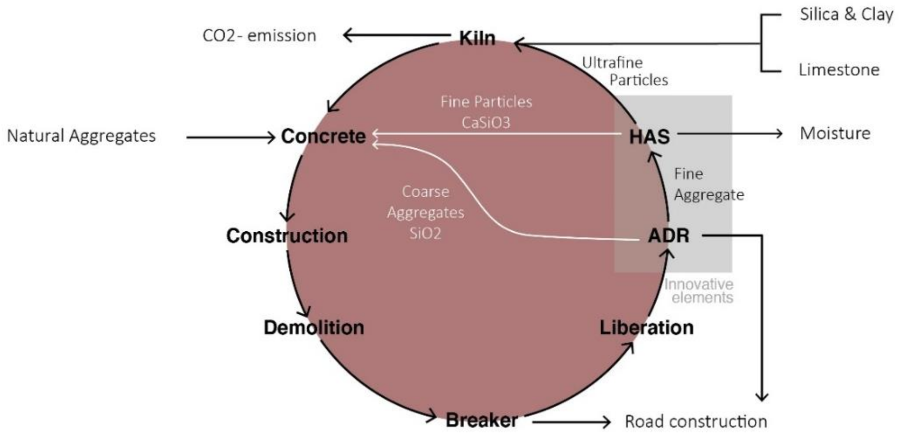

Figure 3.6 (b) Closed-loop concrete production based on HAS

In a nutshell, the following flowcharts represent the steps of the recycling process through applying the technologies ADR and HAS (Figure 3.8), as well as the mass flow distribution expressed by mass percentage (Figure 3.7).

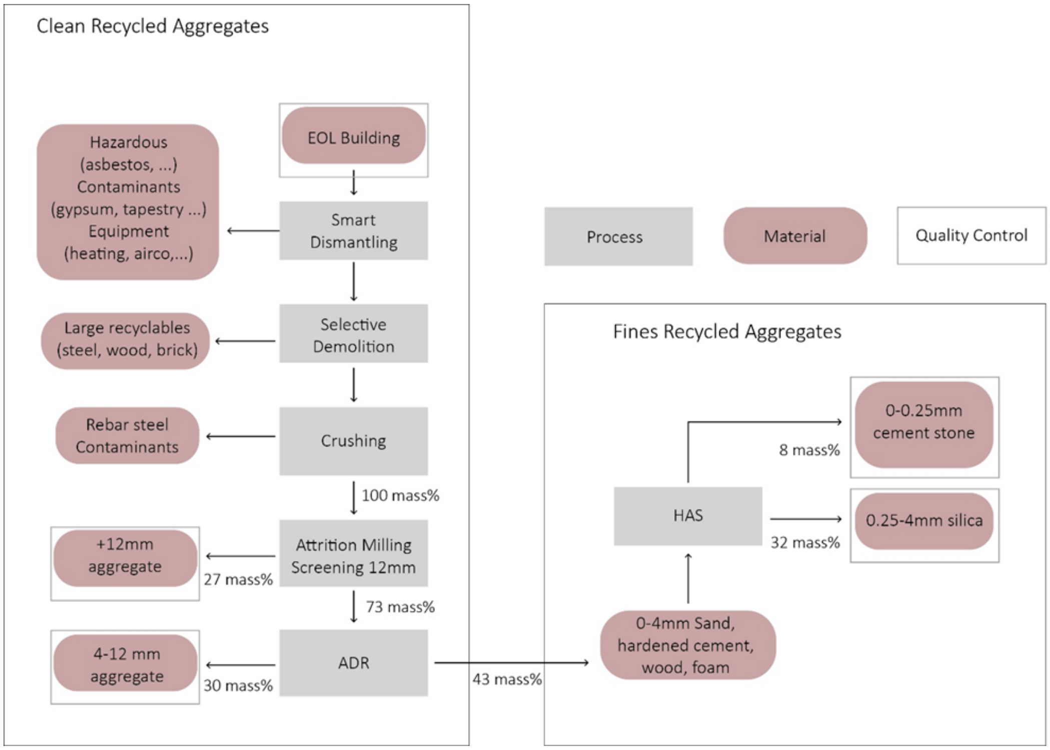

Figure 3.7 Mass flow distribution: Separation of concrete's raw materials expressed by mass %

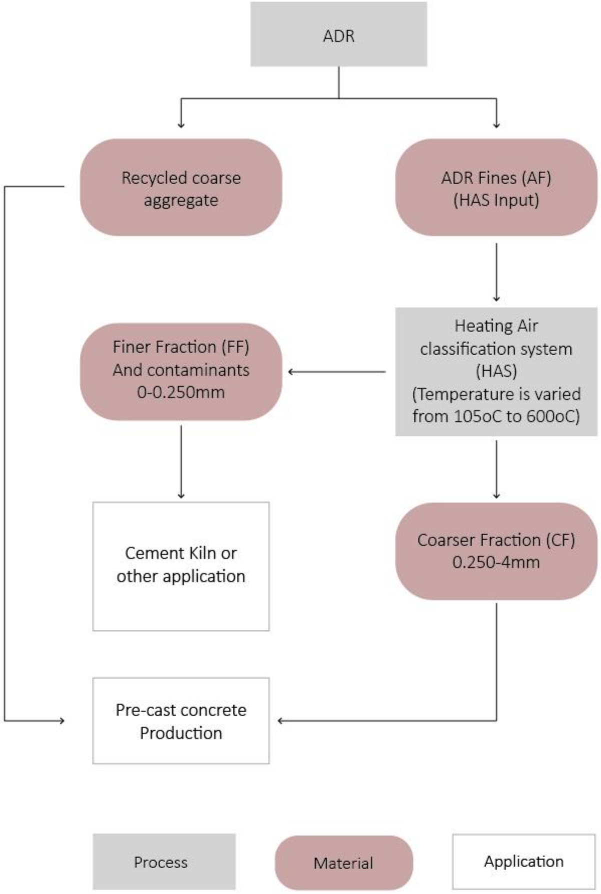

Figure 3.8 Recycling process through applying ADR and HAS technologies

3.2 Concrete-to-concrete Recycling Plant

3.2.1 Project's requirements

Regarding the integration of RA to concrete production and their application in construction projects, the analyzing technologies should be combined properly to produce a cost-efficient and sustainable outcome. In parallel with the developed projects, a 'Concrete-to-concrete Recycling Plant' is proposed as the solution to the main problem (Rem, 2019). A recycling plant consists of mobile technologies that will separate and control concrete's RA.

The financial constraints of the recycling process, as well as the high aggregate product quality, constitute the EoL concrete recycling a challenging prospect for the construction and demolition sector. Furthermore, another aspect that should be considered, is the strong societal pressure to reduce bulk transport of building raw materials in urban areas, and therefore, apply more in situ recycling technologies for CDW (Lotfi et al., 2013).

The proposed solution is developed in accordance with recycling concrete's requirements and in line with the realization of a circular vision in the Dutch CS. The application of RA in the construction industry should fulfill the specifications of conventional concrete since it is aimed to be used in high-quality applications. More specifically, the processing of good quality RA begins before the process of demolition. The Dutch National Building Decree and Soil quality decree require that during demolition and recycling substances present should not cause negative effect on health or environment. RA for concrete have to satisfy specification for cleanliness and strength. Therefore, recycling companies should invest in equipment and knowledge to achieve these conditions. (Federation Internationale du Recyclage, 2017). Additionally, concerning the composition, RA concrete requires a lower Water to Cement (W/C) ratio and higher cement content to obtain strength comparable to conventional concrete (Limbachiya et al., 2012).

A recycling concrete plant targets to accomplish the above requirements and retrieve concrete's main components (sand, gravel, and cement) from relatively clean old concrete which is originated from demolished buildings. Steel rebars and light contaminants, such as wood and plastics, should be removed from the concrete in order to take advantage of its main components. After crushing and extracting the steel rebar; the input material for the plant consists of particles from 0 to 22 mm. However, this material does not have the ideal grain size distribution for new concrete, it contains light contaminants, it has high levels of moisture absorption and contains fragile particles made up of sand-cement structures connected to gravel. Aiming to address the above-referred difficulties, four technologies need to be applied:

1. Advanced Dry Recovery (ADR)
2. Heating Air Classification System (HAS)
3. Laser-Induced Breakdown Spectroscopy (LIBS)
4. IR sensor sorter - RFID

These technologies can either be used consecutively or separately. However, for perfect separation and a quality assessment, the following process scheme describes the complete concept of mobile concrete recycling (Figure 3.10). In the following pictures (Figure 3.9), parts of the recycling plants are presented. More details are examined in the design stage of this thesis.

*Figure 3.9 (*a) Separation of fines and lights from moist crushed concrete on-site (W. de Vries, PhD-thesis TU Delft) & (b) HAS - Heat treatment of fines and lights (industrial prototype at 3 tons/h at the TU Delft lab).

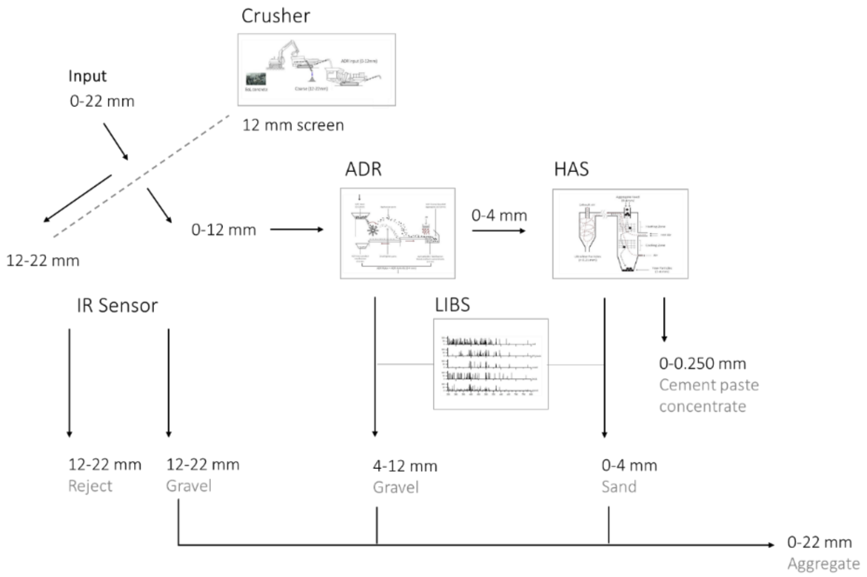

Figure 3.10 Concrete-to-concrete recycling plant and applied technologies

3.2.2 Description of Possible Cases for a 'Concrete-to-Concrete Recycling Plant'

With regards to the location, two possible cases are developed concerning a 'Concrete-to-Concrete Recycling Plant'. The cases are selected after extensive discussions with professors from the 'Resource and Recycling' laboratory in the faculty of Civil Engineering in TU Delft as the two extreme scenarios. They are assessed extensively in the design phase, combined with the categories of concrete production.

i. Recycling plant is operating near mortar supplier or near prefabricated concrete industry

Selectively demolished concrete is transported in the recycling plant and processed with the novel technologies. Afterward, the outputs (ADR and HAS outputs) are immediately ready for use in order to produce new mortar or concrete. In this case, the involved stakeholders in the production of concrete remain the same as in the present day. The major changes in the value chain of concrete are attributed to the suppliers of concrete's raw materials.

ii. Recycling plant is operating at the demolition site

Concerning this case, trucks carry the aggregate towards mobile mortar plants at nearby construction sites in the town. The management and control of the concrete quality become the responsibility of the owner of the mobile mortar facility, and the quality of the RA is required to be documented and guaranteed before shipment. This case has greater transportation costs compared to the first one, whereas it decreases the cost of investment.

3. 3 Conclusions and contribution of Chapter 3

Aiming to derive solid answers to the problem of concrete recycling, cooperation with the 'Resource and Recycling' laboratory in TU Delft proved of vital importance.

More explicitly, this chapter poses the solution to the main problem of this thesis' design approach. A recycling plant is suggested as a proposal to the exploitation of CDW as well as the integration of the novel technologies to the market. Three EU-funded-projects (C2CA, HISER, and VEEP) are working on EoL concrete separation into its raw materials through using the technologies 'Crusher', 'ADR' and 'HAS', which are currently developing in the faculty of Civil engineering. Table 3.7 presents the main characteristics of the analyzed technologies. The conventional supply chain of concrete exhibits noticeable conversions through leveraging ADR and HAS and leading to a closed-loop concrete production, which is depicted in Figure 3.11. Additionally, the following conclusions are drawn through this chapter's exploratory research:

- The crushing and separating diameter of technologies' inputs is related to the material's future use.
- The present installations of ADR and HAS have different operating speeds and they separate different volumes of materials per operating hour. Concerning that issue, Abraham Gebremariam, a postdoc researcher from the 'Resource and Recycling Laboratory', pinpointed that the ADR technology is presently available from the equipment supplier at capacities from 50 tons of concrete/h to 120 tons/h. Regarding the HAS technology, it currently separates 3 tons of fine materials/h and the main objective for the near future is its upgrade to 10 tons/h and afterward to 30 tons/h.
- Concerning the novel technologies, the highest interest is attributed to HAS, since it can replace additives (e.g. fly ash) as well as a percentage of limestone in cement, and can result in lower CO_2 emissions.
- A 'Concrete-to-concrete Recycling Plant' is proposed as a solution to concrete recycling and it consists of mobile technologies that separate and control concrete's RA. The two extreme cases based on the plant's location contribute to circular concrete management:

    i) Recycling plant is operating near mortar supplier or near prefabricated concrete industry
    ii) Recycling plant is operating at the demolition site.

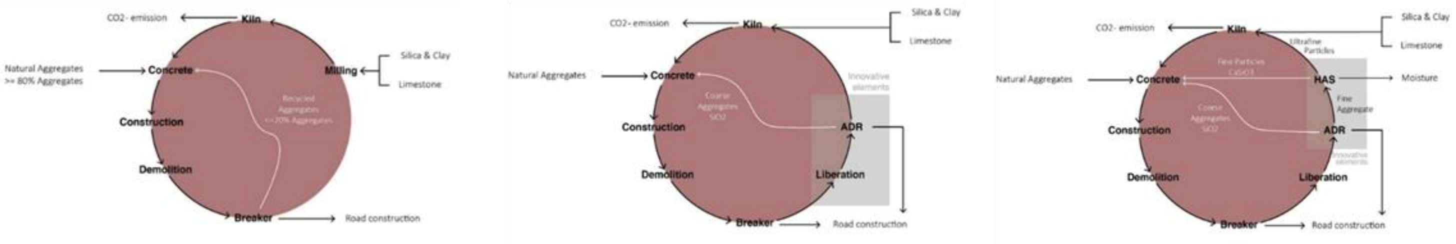

Figure 3.11 Levels of converting a conventional supply chain of concrete to a closed-loop one

Table 3.7 *Inputs and outputs of technologies for concrete recycling*

Technologies	Operating speed	Inputs	Outputs
Crusher	150 tons/h	EoL concrete	• Coarse aggregates = 30% EoL concrete • ADR input (smaller diameter) = 70% EoL concrete
Advanced Dry Recovery (ADR)	50-120 tons/h	ADR input	• ADR coarse recycled aggregates = 60% ADR input • ADR rotor + ADR ariknife = 40% ADR input
Heating Air Classification System (HAS)	3 tons/h	ADR rotor + ADR ariknife (Aggregate feed)	• Moisture = 5-8% HAS input • Fine particles = 72-75% HAS input • Ultrafine particles = 20% HAS input

Contribution of Chapter 3

In this chapter, an approach of converting a conventional concrete production into a closed-loop one through utilizing the highest possible percentage of recycled materials is presented. The examined technologies constitute the backbone of this research. The developed closed-loop approach which results in fewer CO_2 emissions lays the foundations for the subsequent chapter's analysis. Additionally, a 'Concrete-to-concrete Recycling Plant' and two extreme cases regarding the plant's location, give the solution to the current problem of transportation and direct utilization of concrete's recycled materials.

CHAPTER 4. CONVENTIONAL AND CLOSED-LOOP SUPPLY CHAIN MAPPING

Chapter 4 constitutes the design and development phase of this thesis (Figure 4.1). The detailed design takes advantage of the conceptual design, which is defined in Chapters 2 and 3. The components of the concrete production and the solution to the main research problem are illustrated through a mapping process.

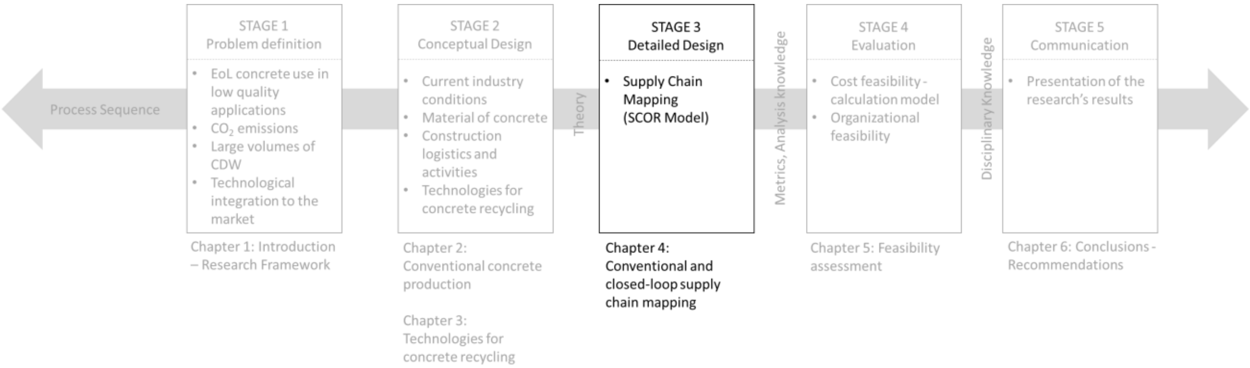

Figure 4.1 Stage of the design approach for Chapter 4

At the beginning of this chapter, business scope diagram and performance positioning for the current and future attributes in the concrete industry is developed in terms of the SCOR Framework and Level 1 – strategic metrics. In addition, the main part of the chapter is divided into six sections based on the categories of concrete production as well as the integration of RA to this process. The current and future feasible cases for concrete production are following presented:

1. Prefabricated concrete
2. Prefabricated concrete with a 'Concrete-to-concrete Recycling Plant' operating near the prefabricated concrete industry.
3. Prefabricated concrete with a 'Concrete-to-concrete Recycling Plant' operating at the demolition site.
4. Site cast/ Ready-mixed concrete
5. Site-cast/ Ready-mixed concrete with a 'Concrete-to-concrete Recycling Plant' operating near the mortar plant.
6. Site-cast/ Ready-mixed concrete with a 'Concrete-to-concrete Recycling Plant' operating at the demolition site.

The SCOR Model formulated by Supply-Chain Council (SCC, 2010) is used as a supply chain mapping tool to understand the complexity of concrete production and its modifications with the integration of technologies for concrete recycling to the market. It is created in levels 2 and 3 for the accomplishment of the design approach which is developed along the thesis report. Tables and maps with the involved processes to the concrete production and a detailed analysis of them are presented.

The visualization of the conventional and closed-loop supply chain of concrete is an essential step for the examination of the trade-offs in logistic concepts and transportation of raw materials. A comparative analysis between the conventional and closed-loop production of concrete is presented based on the supply chain mapping of this chapter.

4.1 Business Scope Diagram

Under the supply chain operations reference (SCOR) model, the business scope diagram, which sets the industry's targets, is implemented (APICS, 2018). Figure 4.2 depicts the conventional and closed-loop concrete production. The three columns in the diagrams consist of the suppliers, concrete industry and customers. Each column's parts are presented in different key nodes that stand for a geographic entity of concrete's supply chain. The point of differentiation among the two approaches is the supply of RA, which is deficient in the conventional supply chain of concrete. Whereas the concrete industry's Head Quarter (Concrete HQ) is a part of the factory, its position and distinctive functionality are emphasized by being presented in a different node from the factory. Key nodes' connections highlight the information and material flow among the involved stakeholders. 'Commercial customer' is referred to the packaged concrete, which is supplied to the '*bouw*' sector and can be purchased by every customer.

Assumption: The prefabricated concrete is not inventoried before its transportation to the construction project.

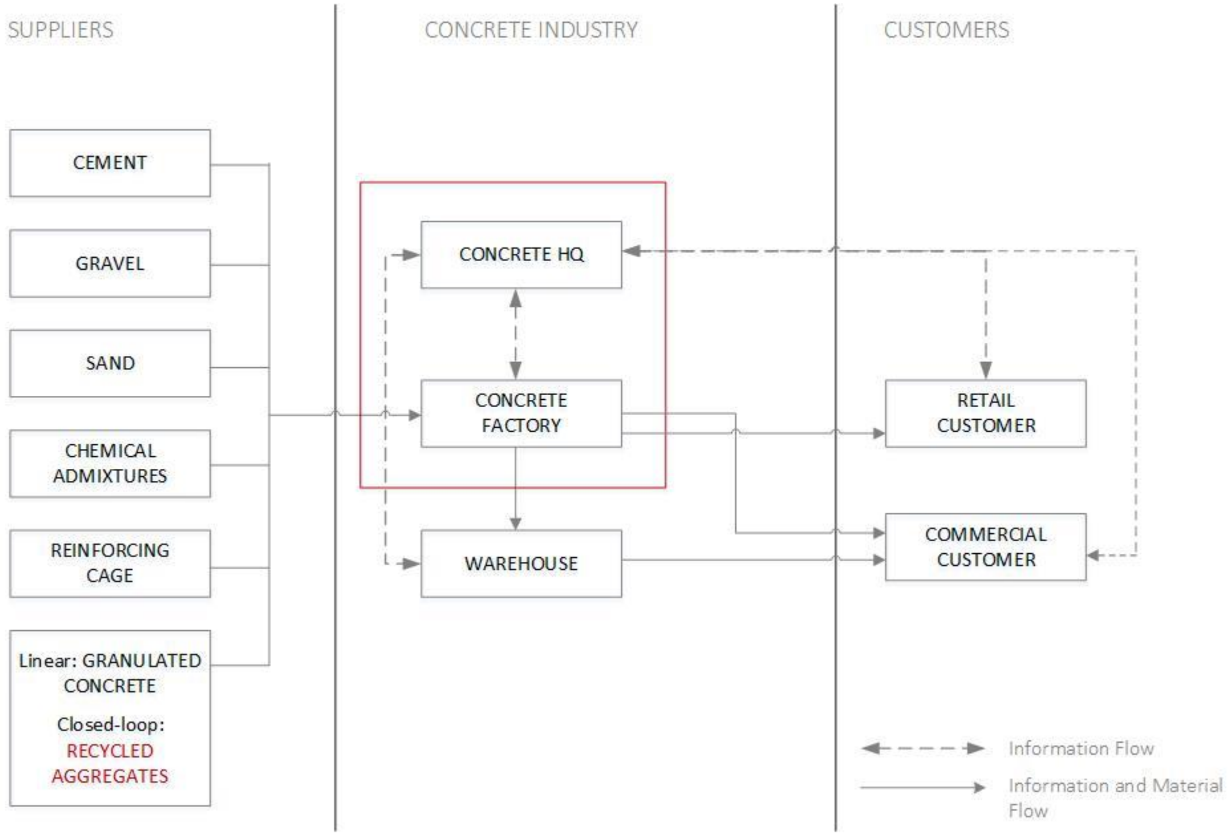

Figure 4.2 Business Scope Diagram for the conventional and closed-loop approach

4.2 Performance Positioning

Concerning the performance measurement, predefined metrics, which are hierarchically structured on three levels, are proposed by the SCOR Framework. The most aggregated level is Level 1 metrics[2], which are commonly identified as KPIs. In the following Table 4.1, the 11 KPI measurements are listed based on five strategic attributes (APICS, 2018). They set the guidelines for the assessment of current and future performance as subsequently described.

Table 4.1 *Level 1 metrics and corresponding attribute (APICS, 2017)*

Attribute	**Strategic metric – Level 1**	
Customer		
Reliability	RL.1.1 Perfect order fulfillment	
Responsiveness	RS.1.1 Order fulfilment cycle time	
Agility	AG.1.1 Upside supply chain flexibility AG.1.2 Upside supply chain adaptability	AG.1.3 Downside supply chain adaptability AG.1.4 Overall value at risk (VaR)
Internal		
Cost	CO.1.1 Total supply chain management cost	CO.1.2 Cost of goods sold
Assets	AM.1.1 Cash-to-cash cycle time AM.1.2 Return on supply chain fixed assets	AM.1.3 Return on working capital

The most essential point for the measurement of the current and future performance is the metrics' identification based on their relevance for the analyzing concrete chain. Concerning the performance of the conventional supply chain (Current performance – Table 4.2), as well as the closed-loop supply chain with the use of novel technologies (Future performance – Table 4.3), it is accessed when the industry is 'Superior', has an 'Advantage' or has 'Parity'.

Table 4.2 *Concrete's industry current performance*

Performance attribute	**Performance vs. competition in supply chain**
SC Reliability	Superior The production of concrete requires on-time delivery in accordance with the right quantity and the right quality. The analyzing sector and more specifically, construction logistics incorporates all measures in order to ensure that equipment, material, and workers are transported, safely and at a minimum cost, to the right place at the right time (Quak et al., 2011). Reliability is of superior importance since the outcome of the construction process should be the customer's anticipated one.

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[2] There is no logical connection between the levels in the process mapping and the performance metrics and should not be confused with level 1 processes.

SC Responsiveness	Advantage It cannot be excluded from the conventional supply chain of concrete. Responsiveness is determined by the cumulative cycle time for all activities. Tasks are performed immediately since concrete is a material that requires specific treatment.
SC Costs	Parity Concrete is not a virgin material, whereas it consists of many raw materials. Each concrete component requires labor costs, material costs, transportation and management costs. The highest percentage of the total costs is attributed to raw materials' transportation and consequently, the cost of operating the supply chain processes is of significant importance.

Table 4.3 *Concrete's industry future performance*

Performance attribute	**Performance vs. competition in supply chain**
SC Reliability	Superior As already described in the current performance (Table 4.2), reliability constitutes the most important attribute in the CS. Even if, the novel technologies will change the method of concrete production, the main outcome will remain the same.
SC Agility	Parity With respect to the integration of the technologies to the market, the industry targets to respond to market changes, external influences as well as gain a competitive advantage. The recycling plant contributes to the vision of sustainability in the Netherlands by introducing the concrete processes into a circular way of production.
SC Assets Efficiency	Advantage Proper asset management is the main purpose of future performance. Recycling technologies target to inventory reduction and capacity utilization through the immediate use of materials (demolition → recycling plant → construction). A JIT management system is one more reason that sets 'assets efficiency' of advantage importance.

4.3 Developed cases for the prospects of concrete production

Aiming to run effectively and efficiently a construction project, logistics is one aspect that has to be planned out in detail at the beginning. In a logistics plan, a strategy on how to approach the construction work at each stage of its development is required. Planning of the project, as well as cooperation among the involved actors, is essential for the construction tasks' realization (Balm, Berden, Morel & van Amstel, 2018).

The two former chapters portray the components of the design phase. In particular, the two main categories of concrete as well as the 'Concrete-to-concrete Recycling Plant', constitute the backbone for the development of six different cases, which represent the prospects of concrete production (Table 4.4). The aim is the interpretation of the nature and impact of the most uncertain and important driving factors affecting the CS. Additionally, they set the guidelines for the SCOR Mapping design.

It is worth referring that the cases presented in Table 4.4 are based on the already referred cases (Recycling plant is operating near mortar supplier or near prefabricated concrete industry, Recycling plant is operating at the demolition site) with regards to the recycling plant's location. Aiming to achieve a clear picture, a quick review regarding transportation movements in the closed-loop approach is presented through a business process management approach.

Table 4.4 *Developed cases for the possible options of concrete production*

Category of concrete production	**Supply Chain approach**	**Analysis**
Prefabricated	Conventional	Case 1: Prefabricated concrete production
	Closed-loop	Case 2: Prefabricated concrete production with a 'Concrete-to-concrete Recycling Plant' operating near prefabricated concrete industry
	Closed-loop	Case 3: Prefabricated concrete production with a 'Concrete-to-concrete Recycling Plant' operating at the demolition site
Site-case/ Ready-mixed	Conventional	Case 4: Site-cast/ Ready-mixed concrete production
	Closed-loop	Case 5: Site-cast/ Ready-mixed concrete production with a 'Concrete-to-concrete Recycling Plant' operating near mortar supplier
	Closed-loop	Case 6: Site-cast/ Ready-mixed concrete production with a 'Concrete-to-concrete Recycling Plant' operating at the demolition site

In the following design phase, the cases are analyzed based on points of similarity among their supply chains and with regards to the selected method of concrete production as well as the supply chain approach.

4.4 Detailed Design

4.4.1 Recycling plant is operating near mortar supplier or near prefabricated concrete industry

Concerning the integration of technologies to concrete production, a mobile recycling plant which is operating near a mortar supplier or a prefabricated concrete industry is proposed. In this aspect, communication among stakeholders constitutes an important parameter for material recycling and the completion of the project. Mortar and prefabricated concrete industries should cooperate since a 'Concrete-to-Concrete Recycling Plant' can be transported to the mortar industry. Therefore, companies in close proximity can use the same equipment with one investment (Figure 4.3).

Relevant cases of Table 4.4:

- Case 2: Prefabricated concrete production with a ‘Concrete-to-concrete Recycling Plant’ operating near prefabricated concrete industry
- Case 5: Site-cast/ Ready-mixed concrete production with a ‘Concrete-to-concrete Recycling Plant’ operating near mortar supplier.

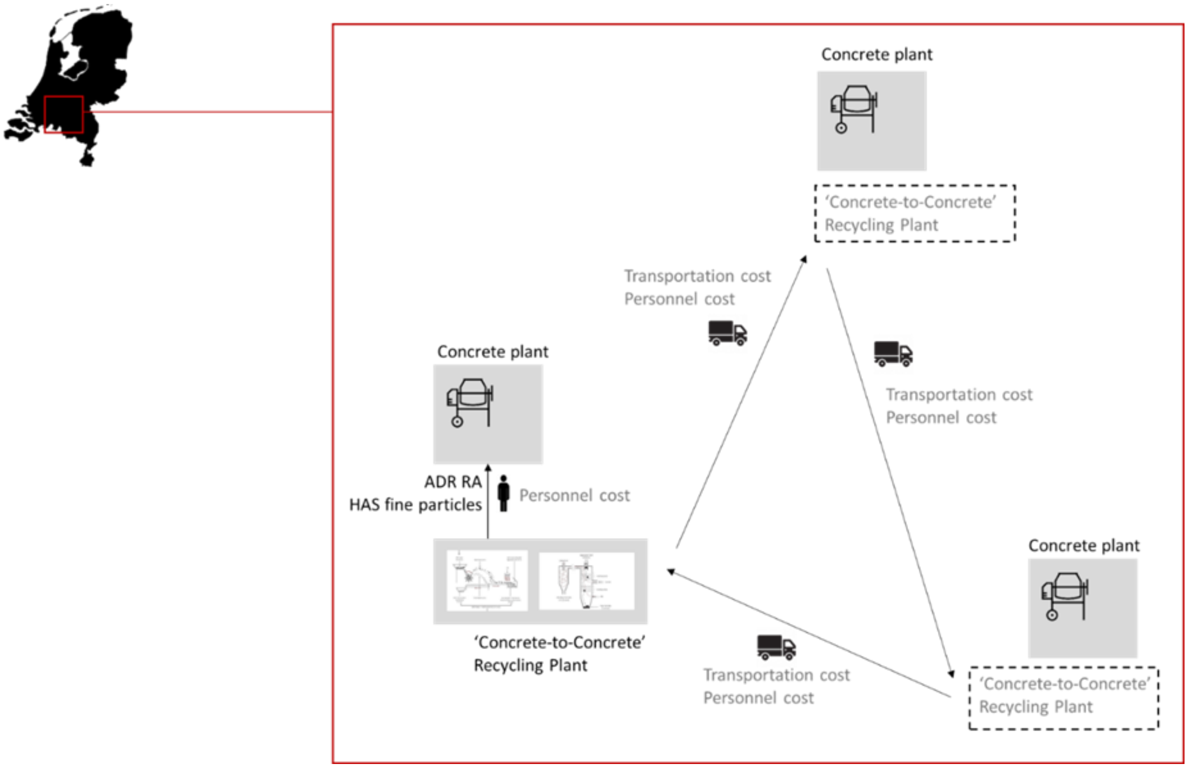


Figure 4.3 Transportation of recycling plant in Cases 2 and 5

The following two Figures 4.4 and 4.5 represent a schematic approach of the transportation movements in the vicinity of the recycling plant and are developed in line with the ‘Resource and Recycling Laboratory’. Noteworthy points ate the followings:

- There are only personnel costs and no transportation costs between the recycling plant and the prefabricated concrete industry/ mortar plant.
- Owing to limited truck capacity and restricted transportation movements, a percentage of CDW does not reach the recycling plant and is reused as a low-quality material (low-quality application – landfill).
- The truck which supplies cement to the concrete plant returns back to the factory with the HAS output. Consequently, no extra transportation movements are conducted for the supply of recycled materials to the cement factory (Rem, 2019). The transferred ultrafine particles can be used in cement production and replace a percentage of raw materials.

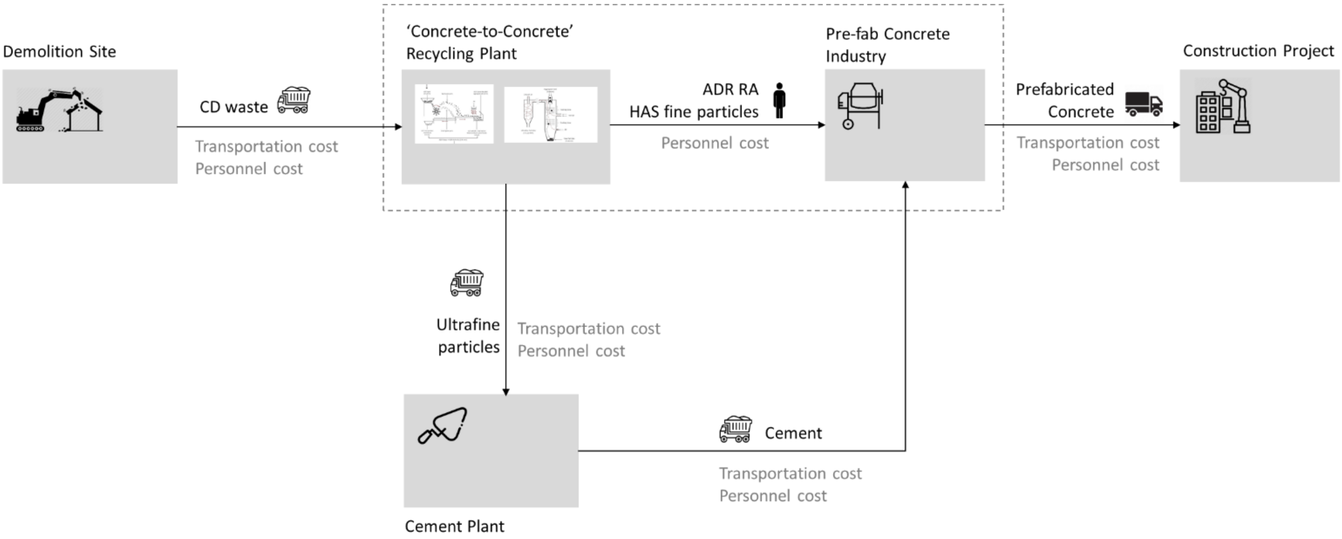


Figure 4.4 Transportation in Case 2

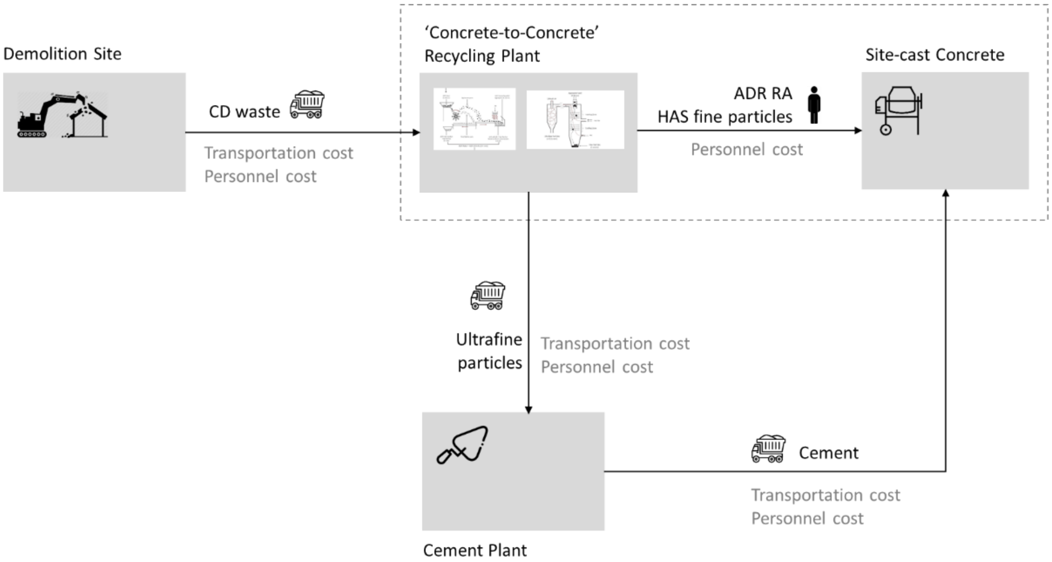


Figure 4.5 Transportation in Case 5

4.4.2 Recycling plant is transported at the demolition site

Regarding the integration of novel technologies to concrete production, the second developed case concerns a mobile recycling plant that is transported at the demolition site. Mortar and prefabricated concrete industries, as well as demolition companies in close proximity, should cooperate in order to use the same equipment with one investment (Figure 4.6). A remarkable difference from the previous case is that the concrete plant is transported in different demolition sites for each project and various stakeholders can be involved.

Relevant cases of Table 4.4:

- Case 3: Prefabricated concrete production with a ‘Concrete-to-concrete Recycling Plant’ operating at the demolition site
- Case 6: Site-cast/ Ready-mixed concrete production with a ‘Concrete-to-concrete Recycling Plant’ operating at the demolition site.

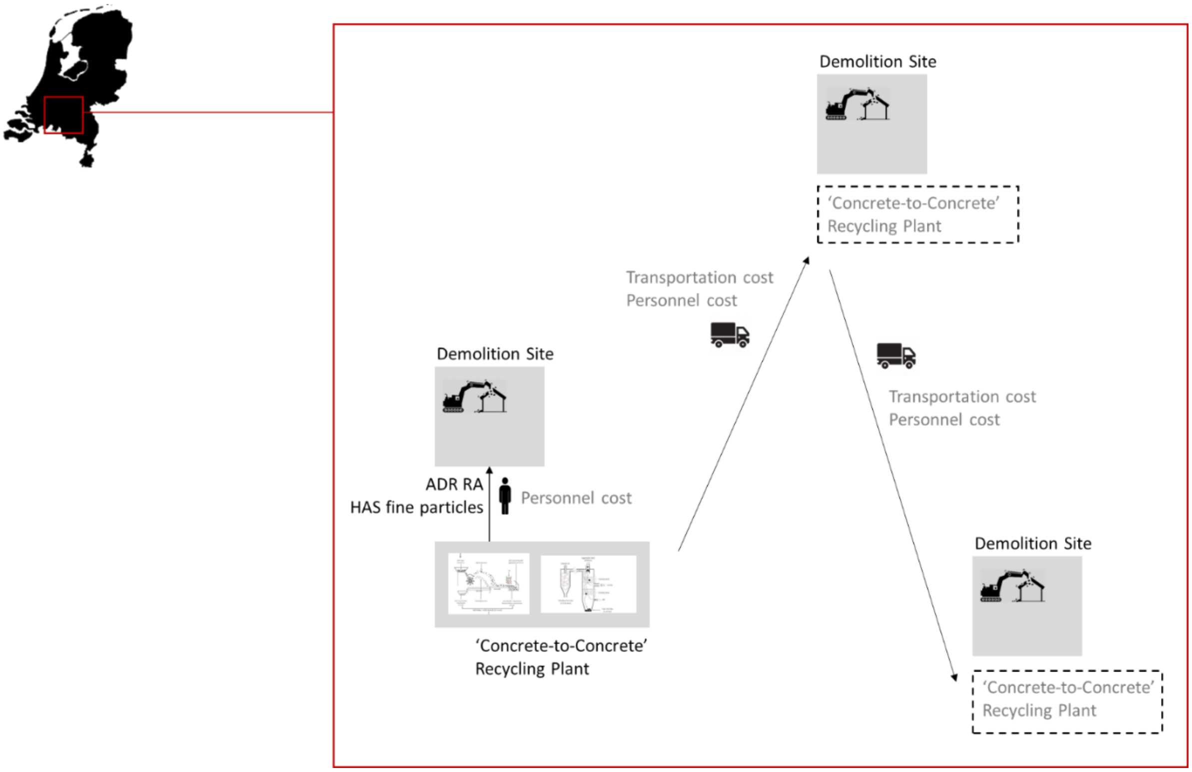


Figure 4.6 Transportation of recycling plant in Cases 3 and 6

The following two Figures 4.7 and 4.8 represent a schematic approach of the transportation movements in the vicinity of the recycling plant. Noteworthy points ate the followings:

- There are only personnel costs and no transportation costs between the recycling plant and the demolition site.
- All the provided CDW can be directly separated into high-quality recycled materials.
- Compared to Cases 2 and 5, extra transportation movements are conducted for the supply of recycled materials to the cement factory. The recycling plant is in a different location from the concrete plant.

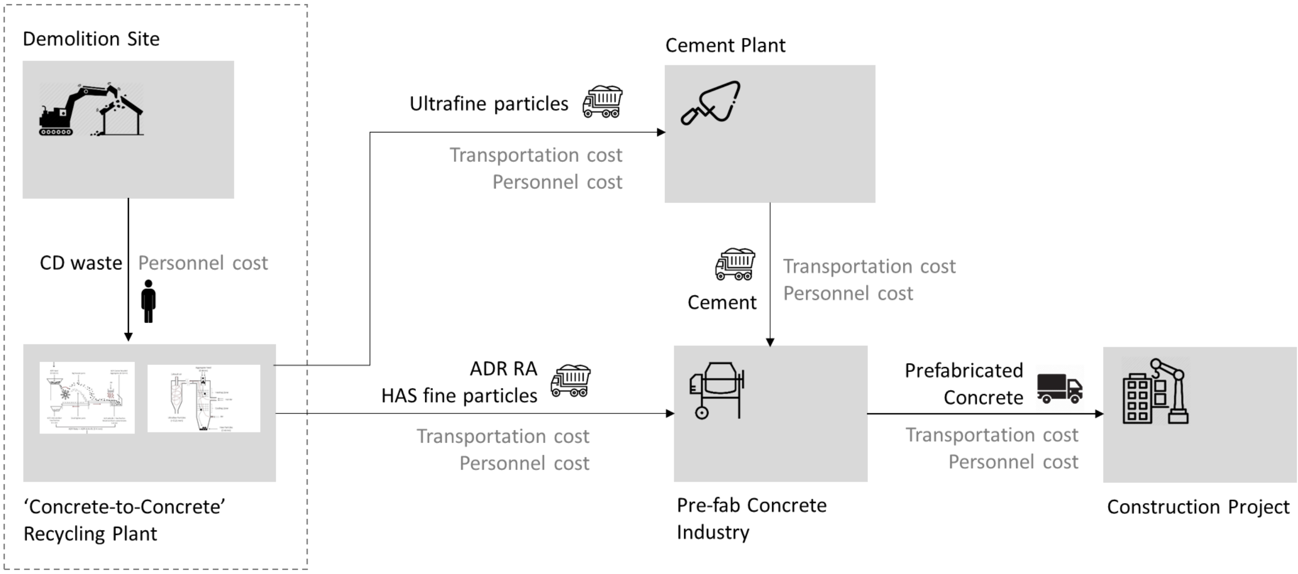


Figure 4.7 Transportation in case 3

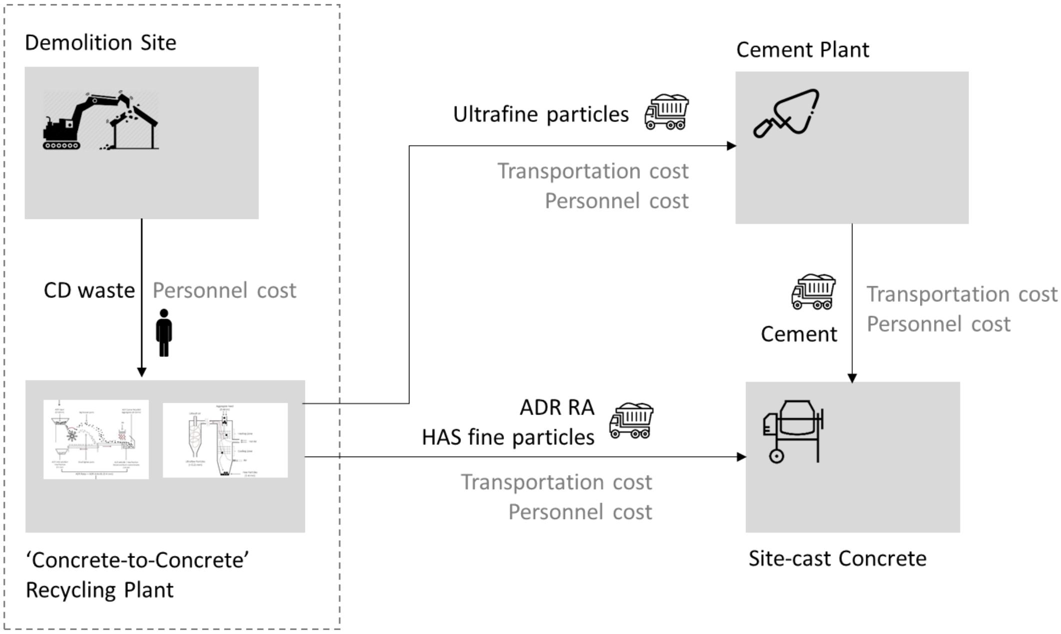


Figure 4.8 Transportation in Case 6

Supply Chain Operations Reference (SCOR) Model

Supply Chain Operations Reference (SCOR) model is one of the most commonly used frameworks in the supply chain industry.

The SCOR Model provides methodology, diagnostic and benchmarking tools that help organizations make dramatic and rapid improvements in the supply chain. ‘*Plan*, *Source*, *Make*, *Deliver* and *Return’* processes define the business activities associated with customer’s demand satisfaction. The current state analysis of a company’s processes as well as the quantification of operational performance through using a set of standard metrics are also included in the model. SCOR framework enhances communication among supply chain partners and improves the effectiveness of SCM, technology, and related supply chain improvement activities.

Regarding the material analysis of concrete’s production, the thread diagram for prefabricated and site-cast/ ready-mixed concrete is designed in the version 10.0 from APICS (APICS, “*Supply Chain Operations Reference Model SCOR V10.0*”, 2010). A mapping of the material flow describes the complexity of concrete’s industry in order to visualize and identify possible problems. Aiming to identify further problems in the supply chain processes at the construction site, a mapping at SCOR Level 3 is illustrated for each category of concrete. The processes of the SCOR model in Levels 2 and 3 are listed in appendices F and G respectively.

In the following sections, the SCOR mapping is developed for each category of concrete separately. Initially, the prefabricated concrete production is examined for the conventional (Case 1 for prefabricated concrete) and the closed-loop approach with the integration of recycled materials and a ‘Concrete-to-concrete Recycling Plant’ operating in accordance with the construction project (Cases 2 and 3 for prefabricated concrete). Afterward, the site-cast/ ready-mixed concrete production is examined for the conventional (Case 4 for site-cast/ ready-mixed concrete) and closed-loop approach for concrete production as well (Cases 5 and 6 for site-cast/ ready-mixed concrete).

4.4.3 Prefabricated concrete production

Prefabricated concrete in SCOR Level 2

The material flow for prefabricated concrete from the suppliers’ suppliers to the construction site (Case 1) is mapped in the SCOR methodology in level 2 (Figure 4.9). Level 2 metrics are associated with a narrower subset of processes (Appendix F). In this section, the worth-referring parts of the mapping are following described, whereas more details are analyzed extensively in level 3 assessment.

The complexity of cement as a material is noticeable in the mapping process. The mapping begins with suppliers’ suppliers. More specifically, for the production of clinker, which is a make-to-order product, limestone and binders are required. A delivery and source of stocked limestone (sD1 and sS1), as well as delivery and source of make-to-order binders (sD2 and sS2), are completed. The first one referred follows the traditional strategy that is used to match the inventory with anticipated customer demand, while the second one is modified to the customer’s specifications. More specifically, the type of binder (e.g. fly ash, blast furnace slag) depends on the type of cement and concrete that are produced and therefore, the supplier customizes the order. Since the clinker is made, delivered and sourced-to-order (sM2, sD2, and sS2), the other raw materials for cement production are purchased as well. The chemical admixture is delivered and sourced based on concrete's future use (sD2 and sS2).

Table 4.5 *Processes of the SCOR Model in Level 2 for the production of prefabricated concrete*

Role in the supply chain	sS, sM, sD Processes	sP Processes	
Suppliers' suppliers	sD1 (limestone), sD2 (binder)	sP4	sP1
	sS1 (limestone) , sS2 (binder)	sP2	
	sM2 (clinker)	sP3	
	sD2 (clinker), sD2 (ch. admixtures), sD1 (gypsum)	sP4	
Raw materials' suppliers	sS2 (clinker + ch. admixtures), sS1 (gypsum)	sP2	sP1
	sM2 (cement), sM3 (reinforcing cage)	sP3	
	sD2 (cement), sD1 (water), sD1 (granulated concrete), sD1 (gravel), sD1 (sand), sD2 (ch. admixtures), sD3 (reinforcing cage)	sP4	
Prefabricated concrete producer	sS2 (cement), sS1 (water), sS1 (granulated concrete), sS1 (gravel), sS1 (sand), sS2 (ch. admixtures), sS3 (reinforcing cage)	sP2	sP1
	sM3 (prefabricated concrete)	sP3	
	sD3 (prefabricated concrete)	sP4	
Construction project developer	sS3 (prefabricated concrete)	sP2	sP1
	sM3 (construction project)		
Return of defective prefabricated concrete	sSR1 (prefabricated concrete)	sP5	
	sDR1 (prefabricated concrete)		

Regarding the category of prefabricated concrete and compared to the site-cast concrete production, three points should be emphasized since the included processes are only accomplished in this category. They are identified in the map and pinpointed with red squares (Figure 4.9):

- The reinforcing cage is made and delivered as an engineer-to-order product (sM3 and sD3) based on the final concrete type. It is designed, engineered and finished after the receipt of the customer's order in accordance with the construction project's specifications.
- It is the only category that includes the source and delivery of the defective product (sSR1 and sDR1). The return defective product supports any type of precast concrete which is not conforming to the project's specifications.
- More stakeholders are involved in concrete production since the precast type is not produced on-site. Nevertheless, the prefabricated concrete industry delivers (sD3) and sources (sS3) the final product to the construction site.

At this point, it is worth mentioning that in the conventional concrete production and concerning raw materials' suppliers, the granulated aggregate is equal or less to the 20% of the total amount of aggregates used in the concrete production (Paul & Van Zijl, 2012).

Assumption: For each different industry involved in the concrete production, it is assumed that the examining processes are receiving information of the sourcing plans (P2), the production plans (P3.4), the delivery plans (P4.4) and lastly, these plans are organized based on the overall supply chain plans (P1). This assumption is applied to every developed mapping in this chapter. The moment the industries are cooperating or they have multiple roles in the chain, plan processes either are missing or are conducting by the same stakeholders; in such case, not all the designed arrows are required.

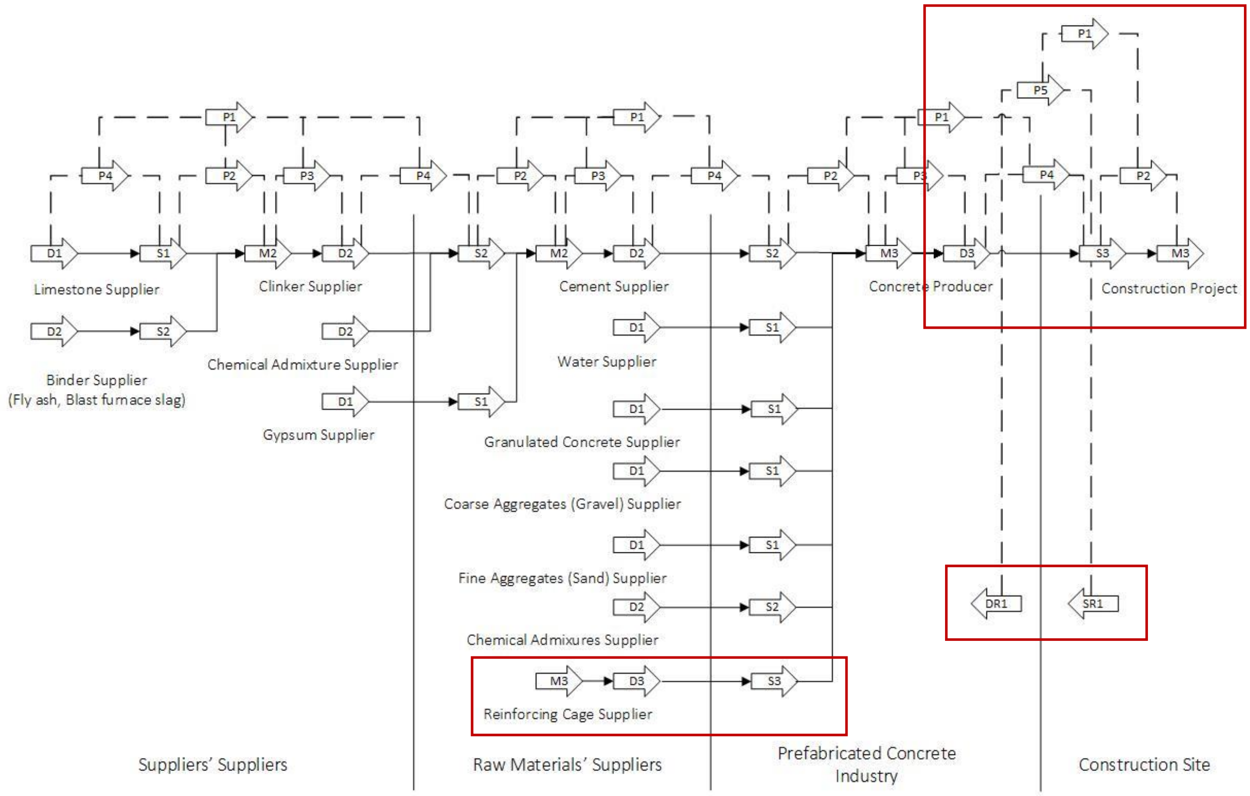


Figure 4.9 Prefabricated Concrete Production in the SCOR Model – Level 2

Prefabricated concrete in SCOR Level 3

The SCOR Level 3 model (Appendix G) specifies the business processes that are involved in the supply chain, through linking level 3 supply chain processes into a process map.

The SCOR Level 3 model for prefabricated concrete is analyzed, starting from suppliers' suppliers (limestone or another inert filler, such as silica and clay – Figure 4.10 (d)), and more specifically from the main constituents' suppliers (main constituent: clinker), where the make-to-order products are picked (sD2.9) and shipped (sD2.12). The raw materials are received (sS2.2), verified (sS2.3) and transferred (sS2.4) for making. The clinker is produced (sM2.2) and afterward, is packed (sM2.4). The last referred process is executed only in the case that the clinker is transferred to the cement factory in bags and not in bulk. The finished product and the minor additional constituents (additives) for cement's production are released (sM2.6) to deliver. The shipments are routed (sD2.6) and the cement's raw materials (clinker, binders, chemical admixtures) are shipped according to EN 197-1 specifications, and more specifically the type of cement that is manufactured.

The concrete’s raw materials suppliers (Figure 4.10 (c)) constitute the next analyzing step in the SCOR model. The product deliveries of cement’s compounds are scheduled (sS2.1) based on the construction period of the project. The source of make-to-order products contains also the receipt of the products (sS2.2), a raw material testing (sS2.3) and the transfer of the products (sS2.4) for the cement’s production. What is following is the issue of the engineer-to-make reinforcing cage, based on the project’s specification (sM3.3). The cage and the cement are produced and tested (sM3.4) as well as packed (sM3.5 – this process is omitted for bulk cement) for delivery (sM3.7). The process of delivery consists of the package of the products (sD3.10), the shipment (sD3.12) as well as the receipt and verification by the concrete producer (sD3.13).

The raw materials for prefabricated concrete manufacturing (Figure 4.10 (b)) are received (sS3.4) and pre-pour inspected (sS3.2). The precast concrete’s compounds are the cement, fine and coarse aggregates, water, additives as well as the reinforcing cage. Example of additives includes pozzolanic materials, such as fly ash and silica fume. The concrete’s production is the subsequent step and the post-pour inspection follows (sM3.4). The installation of the precast material is scheduled (sD3.4) and the product is shipped (D3.12).

In the construction site (Figure 4.10 (a)), the precast concrete is received (sS3.4), verified (sS3.5) and then, the construction process is starting. In the case that the precast concrete does not fulfill the project’s specifications, its delivery as a defective product is scheduled (sSR1.4), then it is returned (sSR1.5) and finally is authorized (sDR1.1) by the prefabricated concrete producers.

The above-analyzing processes related to their objective are receiving information of the sourcing plans (sP2.4), the production plans (sP3.4), the delivery plans (sP4.4) and lastly these plans are organized based on the overall supply chain plans (sP1.4 - establishment and communication of supply chain plans). The connections among the processes are presented with information as well as material arrows.

In the following Table 4.6, the included processes in the SCOR model in level 3, for the production of prefabricated concrete are listed.

Table 4.6 *Processes of the SCOR Model in Level 3 for the production of prefabricated concrete*

Role in the supply chain	sS, sM, sD Processes	sP Processes	
Suppliers’ suppliers	sD2.6, sD2.9, sD2.12	sP4.4	sP1.4
	sS2.2, sS2.3, sS2.4	sP2.4	
	sM2.2, sM2.4, sM2.6	sP3.4	
	sD2.6, sD2.7, sD2.12	sP4.4	
Raw materials’ suppliers	sS2.1, sS2.2, sS2.3, sS2.4	sP2.4	sP1.4
	sM3.3, sM3.4, sM3.5, sM3.7	sP3.4	
	sD3.6, sD3.7, sD3.10, sD3.12, sD3.12	sP4.4	
Prefabricated concrete producer	sS3.4, sS3.2	sP2.4	sP1.4
	sM3.4, sM3.7	sP3.4	
	sD3.4, sD3.12	sP4.4	
	sS3.4, sS3.5	sP2.4	sP1.4

Construction project developer	sM3.3	
Return of defective prefabricated concrete	sSR1.4, sSR1.5	sP5.4
	sDR1.1	

Concerning the visualization of the SCOR mapping in Level 3, owing to its large size, it is divided into the following parts on the basis of each stakeholder's role in the supply chain:

- Figure 4.10 (a): Construction project developer
- Figure 4.10 (b): Prefabricated concrete producer
- Figure 4.10 (c): Raw materials' suppliers
- Figure 4.10 (d): Suppliers' suppliers

The continuous line in the figures represents the material flow, while the discontinuous one the information flow.

Activities concerning the transportation of materials

The process elements of the SCOR model related to the selection of the appropriate transportation system of the product for delivering to the customer are analyzed extensively (red squares in Figure 4.10):

- sD2.6, sD3.6 – *Route Shipments*
- sD2.12, sD3.12 – *Ship Products*

Loads are consolidated and routed by modes and locations. Factors that influence distribution are (a) market demand, (b) seasonal surges, (c) government policies, (d) political lobbies - connectivity, (e) infrastructure – technology, as well as (f) country geography (Tripathy, 2015). More specifically, the customers' needs and the quantities for the planned projects have an impact on transportation since the suppliers plan their route in accordance with the projects that are located in close proximity in the same chronological period of time. Sand, grave as well as cement trades are arranged regionally or nationally based on the demand. Distribution channels, the capacity of trucks as well as the order quantities play a decisive role in the transportation route of concrete's raw materials.

- sD2.7, sD3.7 – *Select Carriers and Rate Shipments*

Specific carriers are selected for the lowest cost per route, and shipments are rated and tendered. They are assigned to operate optimally, taking into account their capacities, as well as the waiting time of the trucks (Zuñiga, Wuest, & Thoben, 2015).

In Figures 4.10 (a-d) are depicted the processes related to each category of involved stakeholders.

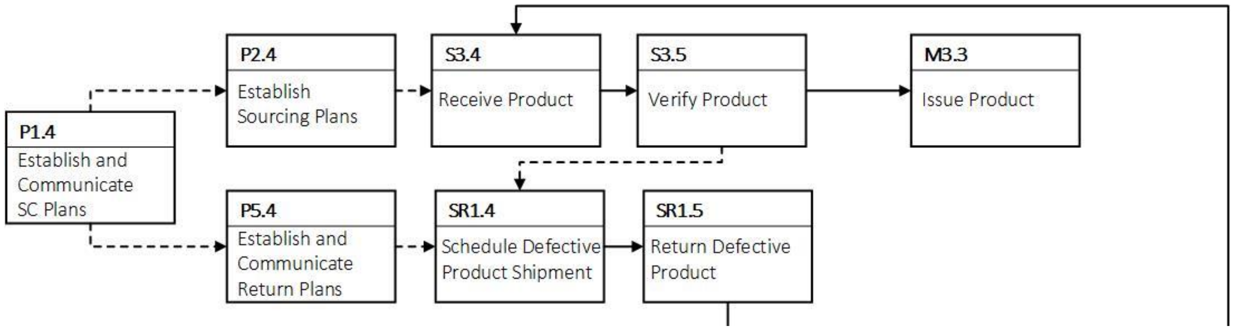


Figure 4.10 (a) Processes on the construction site for prefabricated concrete production in the SCOR Model –Level 3

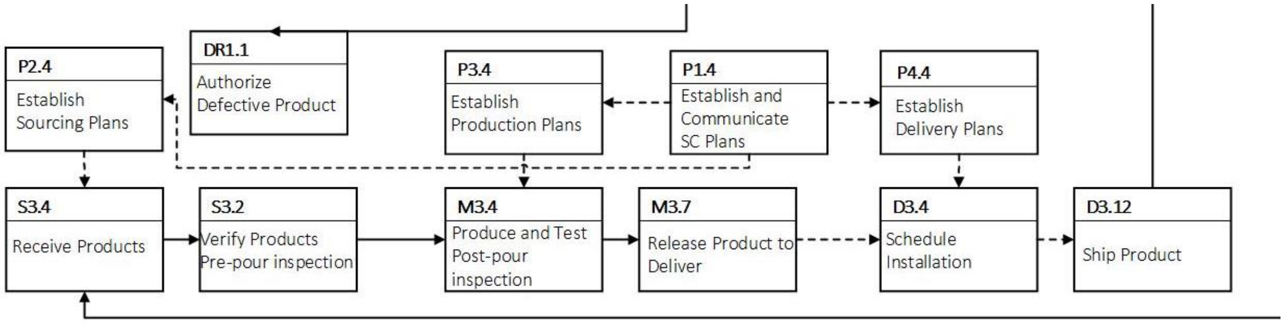


Figure 4.10 (b) Processes in the prefabricated concrete industry in the SCOR Model – Level 3

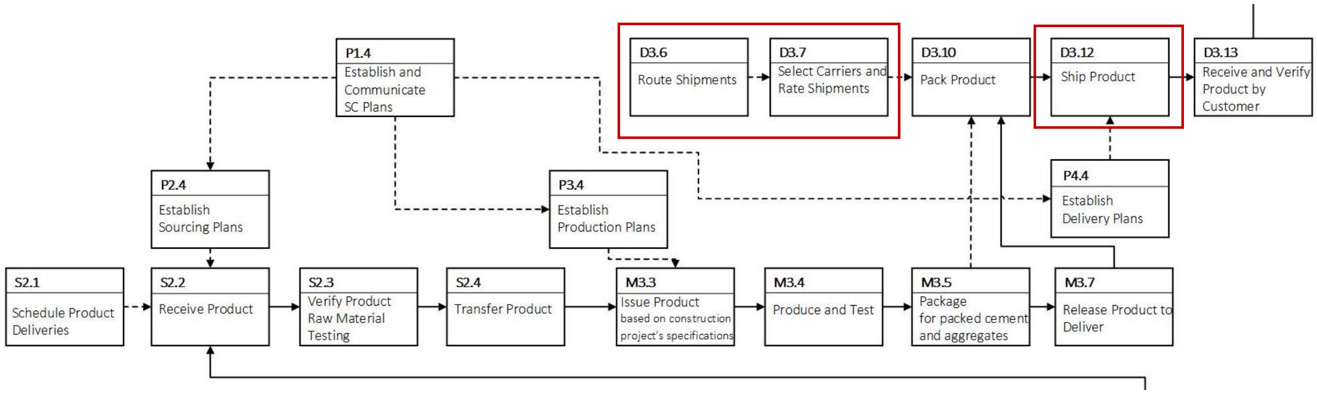


Figure 4.10 (c) Processes of raw materials' suppliers for prefabricated concrete production in the SCOR Model – Level 3

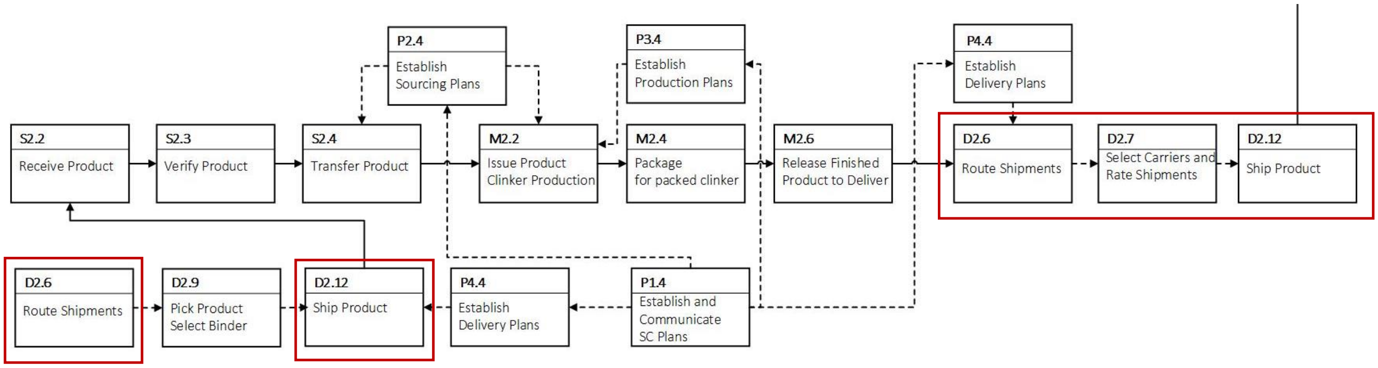


Figure 4.10 (d) Processes of suppliers' suppliers for prefabricated concrete production in the SCOR model – Level 3

4.4.4 Prefabricated concrete with a ‘Concrete-to-concrete Recycling Plant’

Prefabricated concrete with a ‘Concrete-to-Concrete Recycling Plant’ in SCOR Level 2

A ‘Concrete-to-concrete Recycling Plant’ is a proposal for the integration of the technologies for concrete recycling to the market. Two extreme cases are developed; the first one concerns the operation of the plant next to the prefabricated industry (Case 2), while the second one supports a mobile version that is transported to the demolition site (Case 3). In Level 2, these cases are represented with the same graph and the same metrics. Nevertheless, the different points are distinct in Level 3 of the SCOR model.

The supply chain concerning the raw materials in the prefabricated industry has been previously examined in this chapter. Dissimilarities are connected with the use of RA which are originated from the technologies ADR and HAS. In Table 4.7, these areas are posed with red font color and in Figure 4.11 with grey arrows. More explicitly, the new entrant materials in concrete production are the following:

- Ultrafine particles (HAS output, d<0.25mm), which can replace:
    i. Additives; such as fly ash
    ii. A percentage of limestone.
- Fine particles (HAS output, 1mm<d<4mm), which can replace fine aggregate.
- Coarse recycled aggregate (ADR output, 4mm<d<12mm or 4mm<d<16mm); the diameter depends on the type of concrete that is produced. For the referred reason ADR output constitutes a make-to-order product.

Table 4.7 *Processes of the SCOR Model in Level 2 for the production of prefabricated concrete with a ‘Concrete-to-Concrete Recycling Plant’*

Role in the supply chain	**sS, sM, sD Processes**	**sP Processes**	
Suppliers’ suppliers	sD1 (limestone), sD2 (binder) sD1 (ultrafine particles –HAS output)	sP4	sP1
	sS1 (limestone), sS2 (binder) sS1 (ultrafine particles –HAS output)	sP2	
	sM2 (clinker)	sP3	
	sD2 (clinker), sD2 (ch. admixtures), sD1 (gypsum)	sP4	
Raw materials’ suppliers	sS2 (clinker + ch. admixtures), sS1 (gypsum)	sP2	sP1
	sM2 (cement), sM3 (reinforcing cage)	sP3	
	sD2 (cement), sD1 (water), sD1 (gravel), sD1 (sand), sD2 (ch. admixtures), sD3 (reinforcing cage) sD2 (ADR coarse RA), sD1 (fine particles – HAS output)	sP4	
Prefabricated concrete producer	sS2 (cement), sS1 (water), sS1 (gravel), sS1 (sand), sS2 (ch. admixtures). sS3 (reinforcing cage) ss2 (ADR coarse RA), sS1 (fine particles – HAS output)	sP2	sP1
	sM3 (prefabricated concrete)	sP3	
	sD3 (prefabricated concrete)	sP4	
	sS3 (prefabricated concrete)	sP2	sP1

Construction project developer	sM3 (construction project)	
Return of defective prefabricated concrete	sSR1 (prefabricated concrete) sDR1 (prefabricated concrete)	sP5

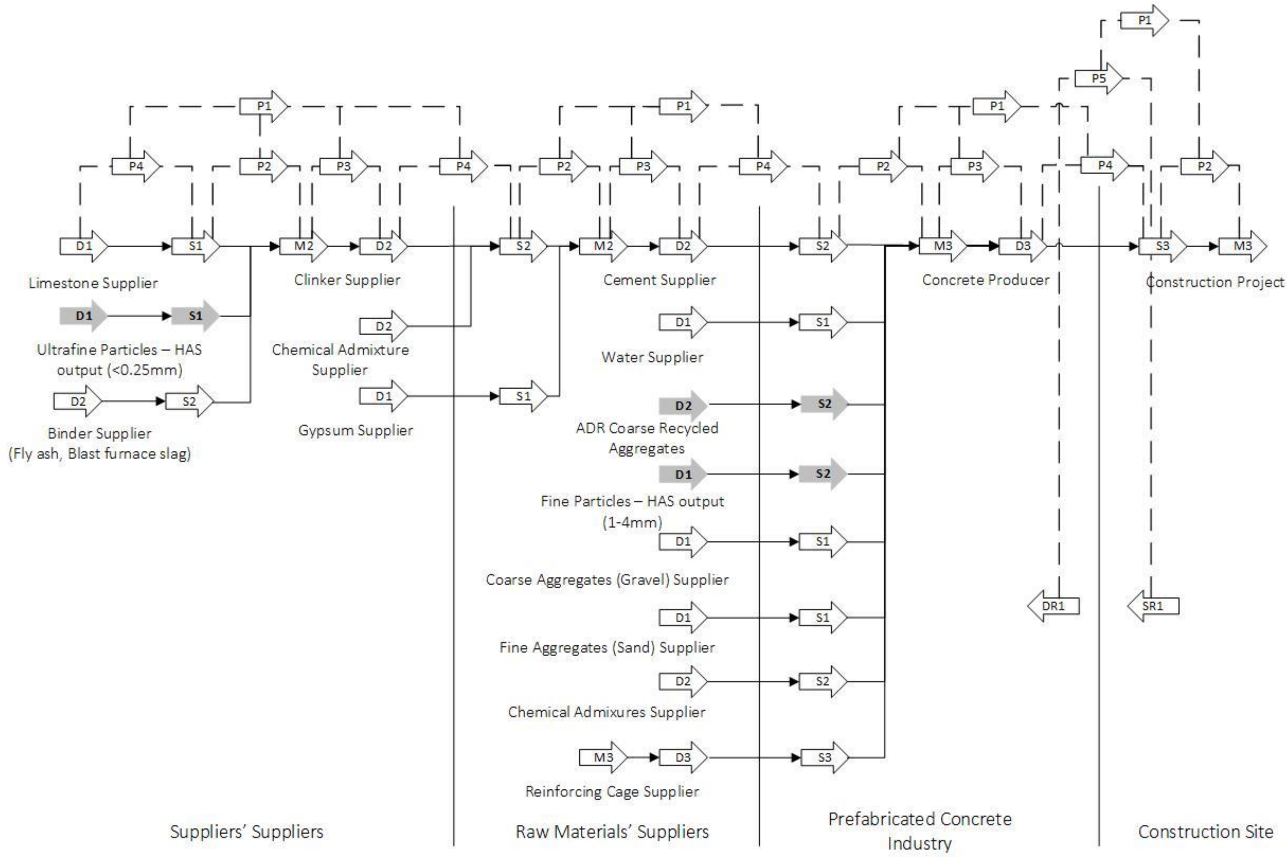


Figure 4.11 Prefabricated concrete production with a 'Concrete-to-Concrete Recycling Plant' in the SCOR Model – Level 2

Prefabricated concrete with a 'Concrete-to-Concrete Recycling Plant' in SCOR Level 3

In the subsequent Table 4.8, the way of transformation, in the indicated areas I and II of Figure 4.12, is assessed in accordance with the integration of the Recycling Plant. Figure 4.12 illustrates the two points of difference compared to the conventional prefabricated concrete production. There is a distinction between the two proposed cases since it is observable that the recycled materials change completely the way of transportation. The used quantities of virgin materials are entirely different and the routes are shipped based on concrete's composition and the % of RA in the final product.

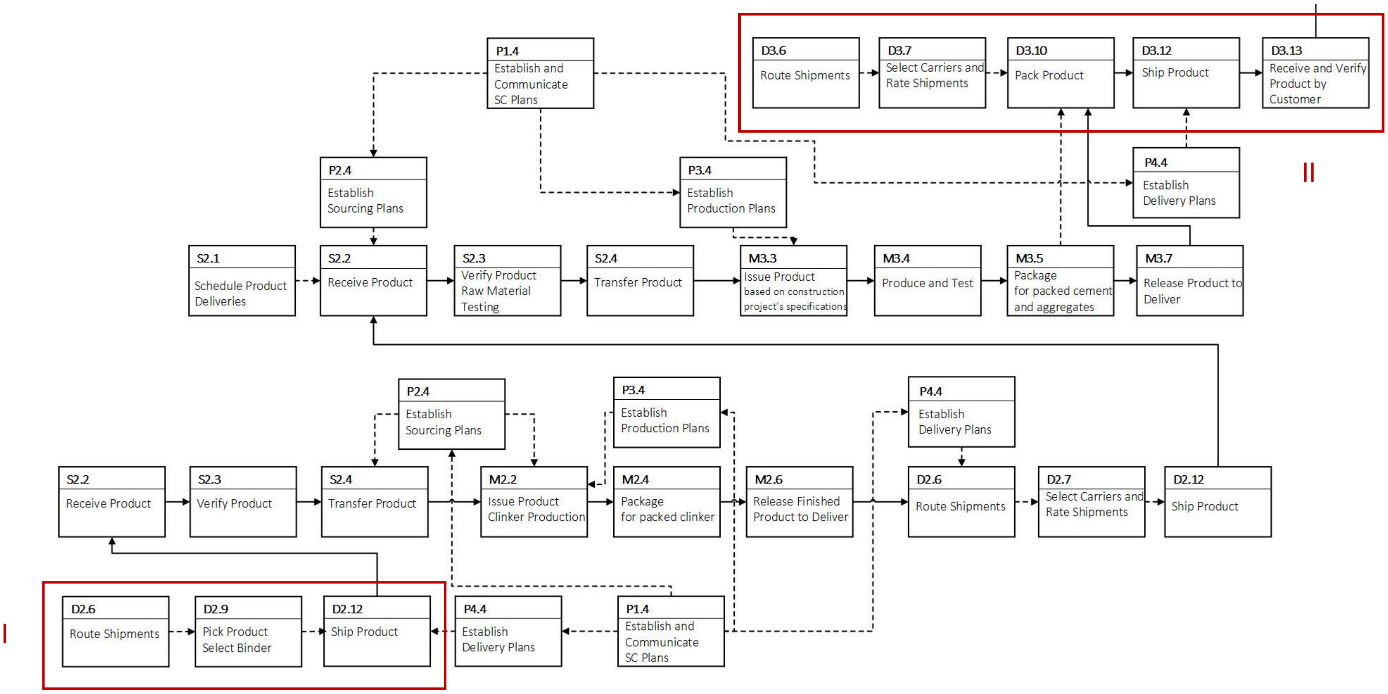


Figure 4.12 Areas of difference in the prefabricated concrete industry with a 'Concrete-to-Concrete Recycling Plant' in the SCOR model – level 3

The above-presented parts in Figure 4.12 are the parts depicted in 4.10 (c) and 4.10 (d). The way they differentiate with the novel technologies is discussed in the following Table 4.8.

Table 4.8 *Areas of difference for the prefabricated concrete industry with a 'Concrete-to-Concrete Recycling Plant' in the SCOR model – level 3*

Area in Figure 4.12	Case 2 Prefabricated concrete production with a 'Concrete-to-concrete Recycling Plant' operating near prefabricated concrete industry	Case 3 Prefabricated concrete production with a 'Concrete-to-concrete Recycling Plant' operating at the demolition site
Area I (Suppliers' suppliers)	*There is no difference between the two cases*. Regardless of the recycling plant's location, the ultrafine particle (HAS output) is required to be transported from the plant to the cement factory. The metric that is added is 'sD2.7 – *Select carriers and shipments*': the cement producers select the % of RA and the plant that will supply its materials.	
	sD Processes sD2.6, sD2.7, sD2.9, sD2.12	
Area II (Raw materials' suppliers)	Area B should remain the same since the RA (HAS and ADR outputs) are not the only required raw materials. However, if the metrics were developed only for the RA, only sD.13 is essential. In Case 2, the plant is next to the prefabricated concrete plant. Thus, there are no route	Area B remains the same owing to the fact that the RA are transported from the closest demolition project to the prefabricated concrete industry.

	shipments, no carriers' selection, no packaging as well as no product shipment.	
	sD Processes	
	sD2.13	sD3.6, sD3.7, sD3.10, sD3.12, sD3.13

4.4.5 Site-cast/ Ready-mixed concrete production

Site-cast/ Ready-mixed concrete in SCOR Level 2

In this section, the activities (Table 4.9) in the SCOR model in level 2 for the production of site-cast or ready-mixed concrete (Case 4) as well as the mapping (Figure 4.13) are displayed. The points of difference with prefabricated concrete production are noticeable in Figure 4.9 (red squares) and are explained in section 4.4.3. The additionally referred processes remain the same.

It is worth mentioning that the categories of site-cast and ready-mixed concrete are presented together since the concrete is produced through following the same processes whereas in different locations. Site-cast is produced on the construction site, while the ready-mixed is sometimes mixed during its transportation to the site.

Table 4.9 *Processes of the SCOR Model in Level 2 for the production of site-cast/ ready-mixed concrete*

Role in the supply chain	sS, sM, sD Processes	sP Processes	
Suppliers' suppliers	sD1 (limestone), sD2 (binder)	sP4	sP1
	sS1 (limestone) , sS2 (binder)	sP2	
	sM2 (clinker)	sP3	
	sD2 (clinker), sD2 (ch. admixtures), sD1 (gypsum)	sP4	
Raw materials' suppliers	sS2 (clinker + ch. admixtures), sS1 (gypsum)	sP2	sP1
	sM2 (cement)	sP3	
	sD2 (cement), sD1 (water), sD1 (granulated concrete), sD1 (gravel), sD1 (sand), sD2 (ch. admixtures)	sP4	
Site-cast/ Ready-mixed concrete producer	sS2 (cement), sS1 (water), sS1 (granulated concrete), sS1 (gravel), sS1 (sand), sS2 (ch. admixtures)	sP2	sP1
	sM3 (concrete)	sP3	

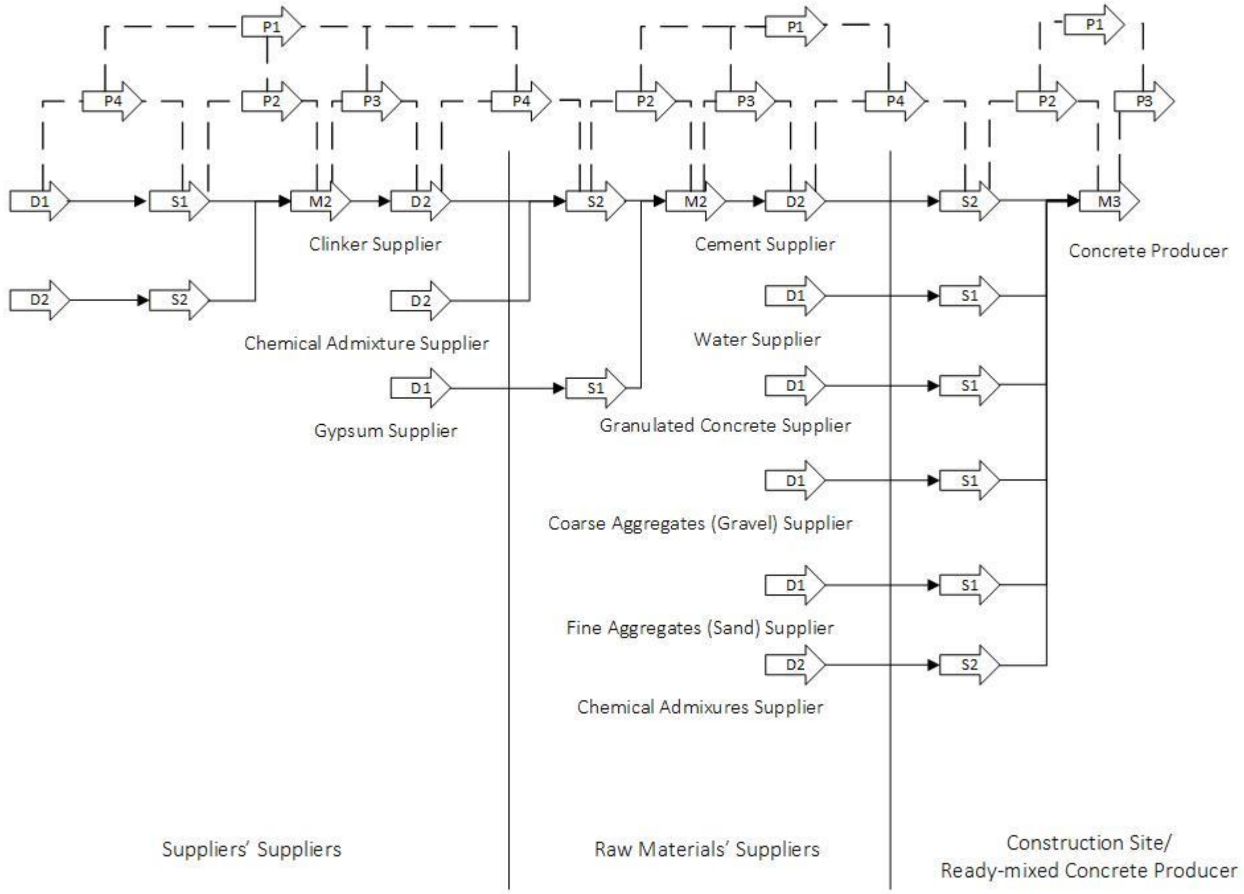


Figure 4.13 Site-case/ Ready-mixed Concrete Production in the SCOR Model – Level 2

Site-cast/ Ready-mixed concrete in SCOR Level 3

The SCOR model in level 3 differs from the corresponding one in section 4.4.3 in the processes which are relevant to raw material suppliers and site-cast/ ready-mixed concrete producers. The dissimilar metrics are presented with a red font color.

With regards to raw material suppliers (Figure 4.14 (b)), the cement constitutes a make-to-order product that is issued (sM2.2) based on the demand in the construction market. The type of cement is produced and tested (sM2.3) as well as packed (sM2.4 – this process is omitted only for bulk cement) for delivery (sM2.6). The cement producers and the aggregate extractors route the shipments (sD2.6) and select carriers (sD2.7) in accordance with the geographic proximity of the construction projects and the demand. The process of delivery consists of the package of the products (sD2.10), the shipment (sD2.12) as well as the receipt and verification by the concrete producer (sD2.13). Lastly, the concrete's compounds (Figure 4.14 (a)) are received (sS2.2) and verified (sS2.3). The production is finalized (sM3.1) and the concrete is issued (sM3.3).

Table 4.10 *Processes of the SCOR Model in Level 3 for the production of site-cast/ ready-mixed concrete*

Role in the supply chain	sS, sM, sD Processes	sP Processes	
Suppliers' suppliers	sD2.6, sD2.9, sD2.12	sP4.4	sP1.4

	sS2.2, sS2.3, sS2.4	sP2.4	
	sM2.2, sM2.4, sM2.6	sP3.4	
	sD2.6, sD2.7, sD2.12	sP4.4	
Raw materials' suppliers	sS2.1, sS2.2, sS2.3, sS2.4	sP2.4	sP1.4
	sM2.2, sM2.3, sM2.4, sM2.6	sP3.4	
	sD2.6, sD2.7, sD2.10, sD2.12, sD2.12	sP4.4	
Site-cast/ Ready-mixed concrete producer	sS2.2, sS2.3	sP2.4	sP1.4
	sM3.1, sM3.3	sP3.4	

Concerning the visualization of the SCOR mapping in Level 3, owing to its large size, it is divided into the following parts on the basis of each stakeholder's role in the supply chain:

- Figure 4.14 (a): Site-cast/ Ready-mixed concrete producer
- Figure 4.14 (b): Raw materials' suppliers

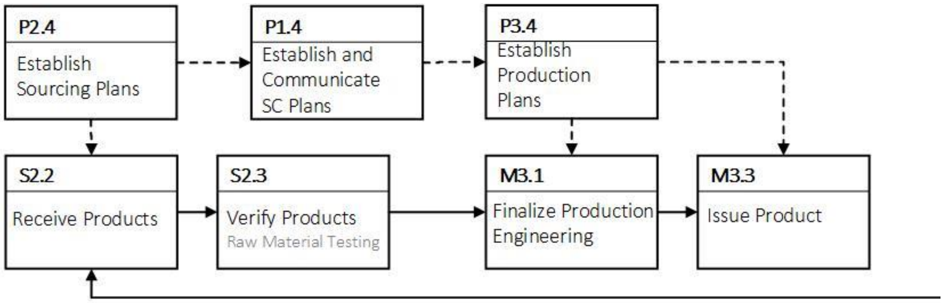


Figure 4.14 (a) Processes by site-cast/ ready-mixed concrete producer in the SCOR Model – Level 3

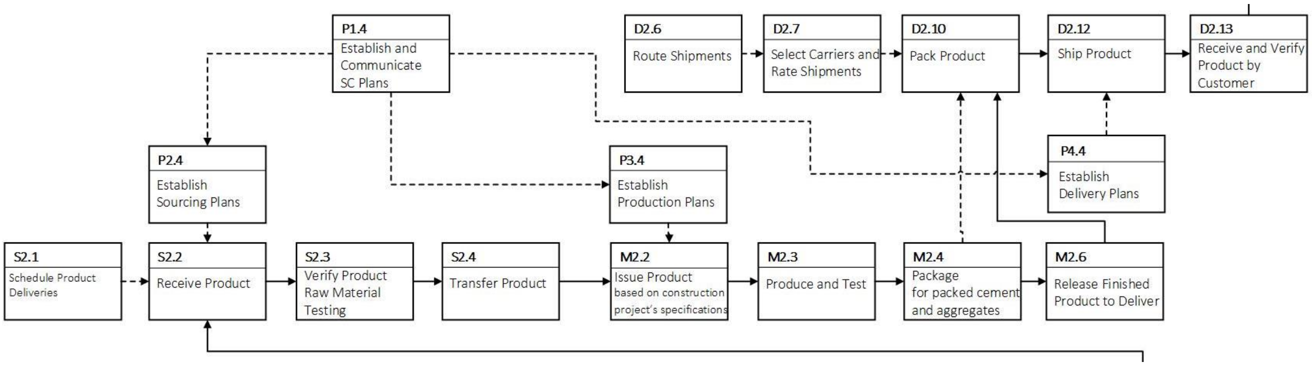


Figure 4.14 (b) Processes of raw materials' suppliers for prefabricated concrete production in the SCOR Model – Level 3

4.4.6 Site-cast/ Ready-mixed concrete with a 'Concrete-to-concrete Recycling Plant'

The modifications that have been analyzed in section 4.4.4 are applied to this part as well. The tables and figures for the production of site-cast/ ready-mixed concrete with the use of RA (Case 5 and Case 6) are listed below.

Site-cast/ Ready-mixed concrete with a 'Concrete-to-Concrete Recycling Plant' in SCOR Level 2

Table 4.11 *Processes of the SCOR Model in Level 2 for the production of site-cast/ ready-mixed concrete with a 'Concrete-to-Concrete Recycling Plant'*

Role in the supply chain	sS, sM, sD Processes	sP Processes	
Suppliers' suppliers	sD1 (limestone), sD2 (binder) sD1 (ultrafine particles –HAS output)	sP4	sP1
	sS1 (limestone), sS2 (binder) sS1 (ultrafine particles –HAS output)	sP2	
	sM2 (clinker)	sP3	
	sD2 (clinker), sD2 (ch. admixtures), sD1 (gypsum)	sP4	
Raw materials' suppliers	sS2 (clinker + ch. admixtures), sS1 (gypsum)	sP2	sP1
	sM2 (cement)	sP3	
	sD2 (cement), sD1 (water), sD1 (granulated concrete), sD1 (gravel), sD1 (sand), sD2 (ch. admixtures) sD2 (ADR coarse RA), sD1 (fine particles – HAS output)	sP4	
Site-cast/ Ready-mixed concrete producer	sS2 (cement), sS1 (water), sS1 (granulated concrete), sS1 (gravel), sS1 (sand), sS2 (ch. admixtures) sS2 (ADR coarse RA), sS1 (fine particles – HAS output)	sP2	sP1
	sM3 (concrete)	sP3	

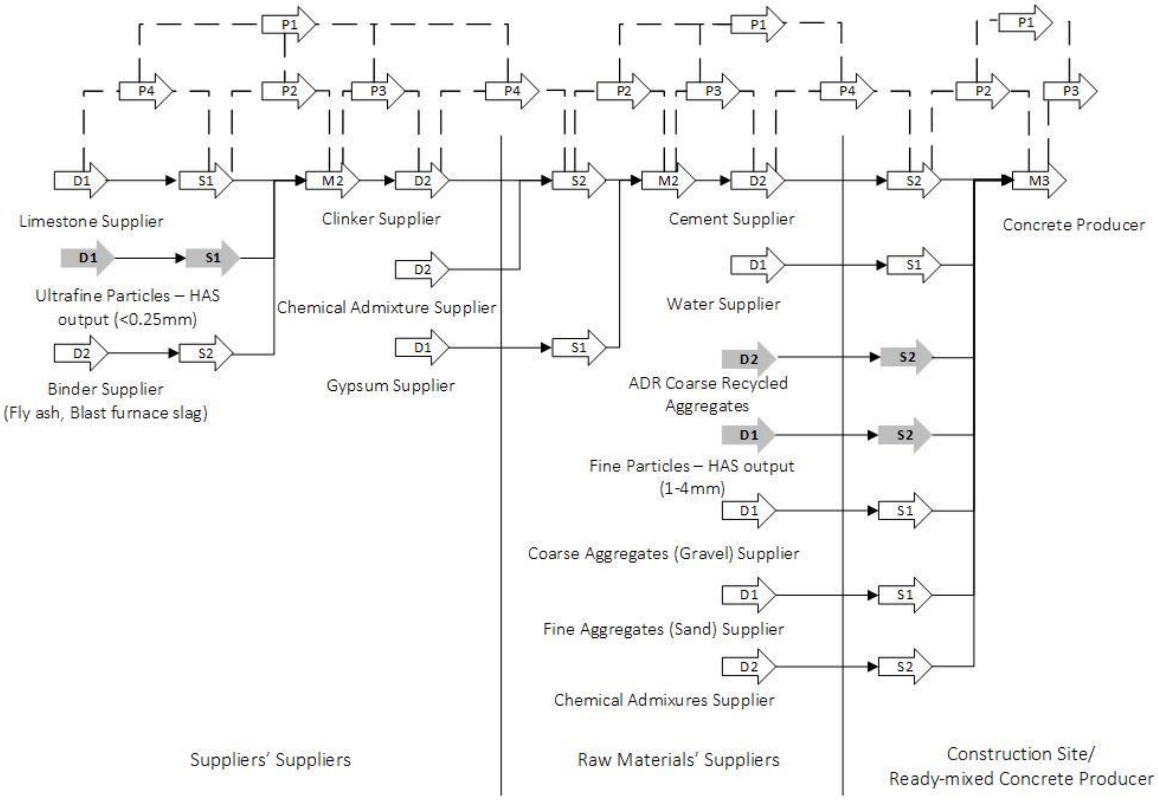


Figure 4.15 Site-case/ Ready-mixed Concrete Production with a 'Concrete-to-Concrete Recycling Plant' in the SCOR Model – Level 2

Site-cast/ Ready-mixed concrete with a 'Concrete-to-Concrete Recycling Plant' in SCOR Level 3

Figure 4.16 (a), refers to level 3 of the SCOR model where only RA are used. It is presented in order to visualize how a recycling plant next to a concrete industry influences the transportation of materials and diminishes the necessitated processes. Between Cases 3 and 6, there are no changes in this part of the supply chain.

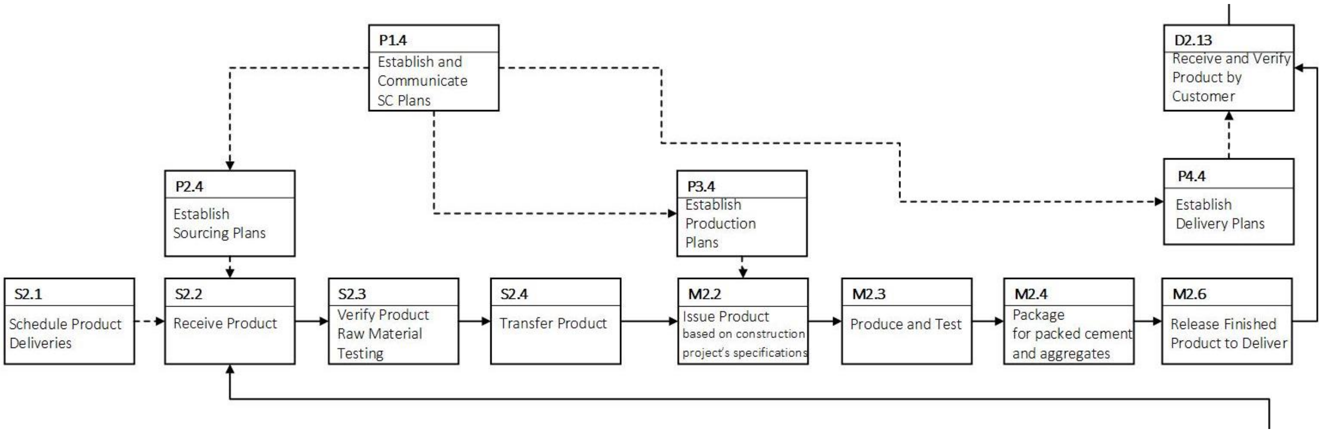


Figure 4.16 (a) Processes of raw materials' suppliers for site-cast/ready-mixed concrete production with a 'concrete-to-Concrete Recycling Plant' in the SCOR Model – Level 3 (Case 5)

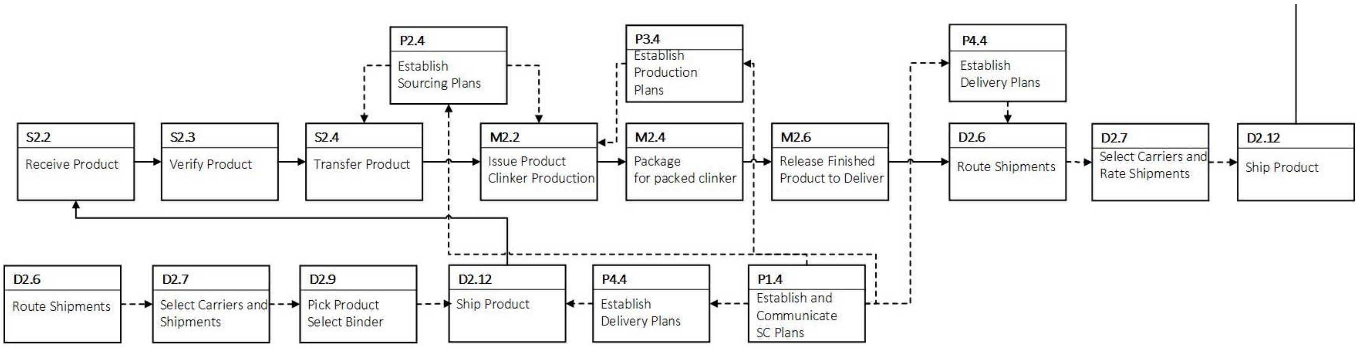


Figure 4.16 (b) Processes of suppliers' suppliers for site-cast/ready-mixed concrete production with a 'concrete-to-Concrete Recycling Plant' in the SCOR Model – Level 3 (Cases 5 and 6)

4.5 Conclusions and contribution of Chapter 4

The SCOR mapping has been developed after an extensive literature regarding the processes that are involved in the concrete production. The points of difference among the cases are presented in the following Tables 4.12 and 4.13, and are explained in line with the SCOR Model in Level 3.

Table 4.12 *Conclusions for the conventional supply chain of concrete production based on the SCOR Model*

	Conventional supply chain	
	Case 1 Prefabricated concrete production	**Case 4** Site-cast/ Ready-mixed concrete production
Engineer-to-order products: sM3, sD3, sS3 *The product is designed, engineered and finished after an order has been received*	- Production of reinforcing cage based on project's specifications and transportation to the concrete industry. - Production of prefabricated concrete - Development of the construction project	The only Engineer-to-order product is the final product: site-cast or ready-mixed concrete
Make-to-order products: sM2, sD2, sS2 *Consumers purchase products that are customized to their specifications*	The products which are differentiated based on the final product's specifications are the followings: - Binders for clinker production (e.g. fly ash, blast furnace slag) - Chemical admixtures for cement and concrete production	
Return Process: sSR1, sDR1	Return of defective product in case that the precast concrete is not conforming to the project's specifications.	*No return process*
Transportation	More industries-stakeholders are involved in the production process. Transportation from the prefabricated industry to the construction site constitutes an additional movement.	
	Concerning transportation, in both categories of concrete and either for engineer-to-order or make-to-order products, the following processes are followed: - sD2.6, sD3.6 – *Route Shipments* - sD2.7, sD3.7 – *Select Carriers and Rate Shipments* - sD2.12, sD3.12 – *Ship Products*	

The above-referred remarks and differences between the categories of concrete can be applied to the closed-loop approach as well.

In the following Table 4.13, the points of difference are identified based on the location of the 'Concrete-to-concrete Recycling Plant'.

Table 4.13 *Conclusions for the closed-loop supply chain of concrete production based on SCOR Model*

	Closed-loop supply chain	
	Case 2 and Case 5 Recycling plant is operating near concrete industries	**Case 3 and Case 6** Mobile versions of the recycling plant are transported at the demolition site
Integration of recycled materials to the concrete production	**Stocked products**: sD1, sS1 - Ultrafine particles (HAS output, d<0.25mm), which can replace: i. Additives; such as fly ash ii. A percentage of limestone. - Fine particles (HAS output, 1mm<d<4mm), which can replace fine aggregate. **Make-to-order products**: sD2, sS2 - Coarse recycled aggregate (ADR output, 4mm<d<12mm or 4mm<d<16mm); the diameter depends on the type of concrete that is produced.	
Transportation	- The integration of recycled materials changes the shipping routes of virgin materials' suppliers since the demanded quantities do not remain the same. - Cement and clinker producers select the % of raw materials and the plant that will supply its materials (sD2.7).	
	Regarding raw materials, a high % is substituted by RA, which is supplied without the need for route shipment, carrier's selection, packaging, and product shipment	Differences are observed in the quantities and the route shipments but not in the total transportation movements.

More specifically, in the case that the recycling plant is operating near the concrete industry, fewer transportation shipments between the mortar plant and the cement factory are realized. Ultrafine particles can be transported directly to the cement plant since there is an available truck; the one that has transported cement for concrete production. Additionally, the use of the plant is achieved by specific stakeholders and trustworthiness among the actors constitutes easier the process of recycling. On the contrary, when the recycling plant is operating at the demolition site, various stakeholders could be involved in each recycling process, according to the available projects and their location. With regards to warehousing, one more benefit of Cases 2 and 5 is that there is no inventorying after material separation. Technologies are operating at different speeds and the materials can be used directly after the technological activities. The main advantage of Cases 3 and 6 in comparison 2 and 5 is that due to the fact that CDW does not need warehousing, there is a higher chance of leveraging wastes for the production of high-value materials.

Contribution of Chapter 4

In this chapter, the design phase of the thesis is developed. The points of difference between the conventional and closed-loop approaches are presented through a model-based service-oriented framework that leverages the SCOR model for performance monitoring of construction supply chains. Chapter 4 takes advantage of the conceptual design of Chapters 2 and 3 and lays the groundwork for the following one, which formulates the evaluation phase. It constitutes an attempt to create a basis for further research, through mapping the SCOR model in Level 1, 2 and 3. An extensive analysis of the processes that take place in the supply chain of concrete is conducted, with a special focus on transportation in concrete manufacturing.

CHAPTER 5. FEASIBILITY ASSESSMENT

Chapter 5 formulates the evaluation stage of the design approach. The solution to the main problem is examined and more specifically, a feasibility assessment concerning a ‘Concrete-to-concrete Recycling Plant’ is elaborated.

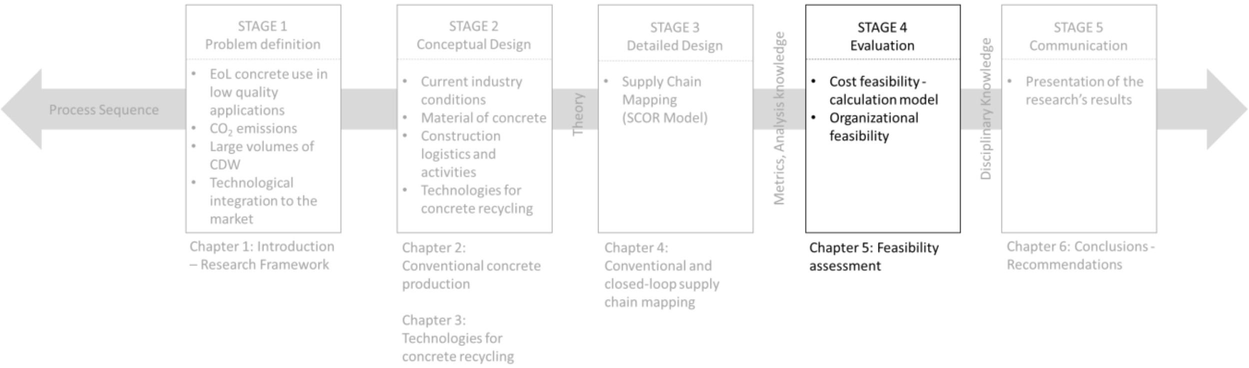


Figure 5.1 Stage of the design approach for Chapter 5

This chapter is divided into two main parts and each of them analyzes a different perspective of assessment. Initially, with regard to technological evaluation, a calculation model is developed. The design approach in Chapter 4 detected the transportation movements along the supply chain and set the guidelines for different combinations of costs, quality and time. The spreadsheet model considers the feasible cases for concrete production and assesses the logistic trade-offs. The most important dimensions of concrete recycling are compiled and the feasibility of integrating technological advancement to the market is evaluated. Value Stream Mapping (VSM) is designed and the appropriate calculations are presented. It is developed for the additional processes that take place in a ‘Concrete-to-Concrete Recycling plant’ and its aim is the examination of the flow of inventory as well as the duration of each technological process in concrete recycling. Worth-noticing point is that the calculation model constitutes additional research for the ‘Resource and Recycling’ laboratory in the faculty of Civil Engineering in TU Delft.

The second part of this chapter formulates an organizational perspective for the feasibility assessment. It completes the picture concerning sustainable construction and the recycling of demolition waste through correlating the current market conditions with the stakeholders’ viewpoints. With regards to Porter’s Five Forces Model, the role of a recycling plant in the industry of concrete, cement, and aggregates is examined. The Power-Interest grid proposed by Mendelow (1991) is designed for the actors involved in the production of concrete and survey questionnaires were sent to different stakeholders of the ‘concrete chain’ (Appendix D). Their point of view for recycling demolition waste and their level of awareness regarding the future potentials of concrete reusability is a crucial parameter for the integration of these technologies to the market and their implementation process. Lastly, the level of acceptance by the industry consists a validation process for the proposed technologies.

5.1 Calculation Model

The calculation model constitutes the evaluation stage of the design approach for this work. Spreadsheet modeling is developed by considering the possible cases for concrete production. The aim is to assess and evaluate the feasibility of implementing novel technologies to the market by considering financial and operating issues. Additionally, the most cost-efficient and sustainable case is proposed.

Components described in the conceptual design stage of this project are included in the model aiming to formulate a complete overview of concrete production and its potentials for recycling (Table 5.1).

Table 5.1 *Components of spreadsheet modeling*

Components of conceptual design	**Contribution**
Cement types (Chapter 2)	Sheet with cement types that are produced in the Netherlands, their use and their % composition.
Logistic costs (Chapter 2)	Sheet with construction logistics activities and costs that should be included in concrete production.
Technologies – Operating volumes (Chapter 3)	Sheet with production volumes and calculation of production units.
Financial aspect of a Recycling plant (Chapter 3)	Sheet with financial elements in a recycling plant.
Environmental aspect of HAS technology (Chapter 3)	Sheet with the environmental impact of HAS technology.
Components of detailed design	
Value Stream Mapping of a Recycling plant (Chapter 4)	Sheet with the activities that are taking place in a recycling plant.

According to the company's performance, the appropriate activities and materials, that are presented in the sheets, are selected.

Sheet 1: Cement Types

The information and calculations presented in sheet 1 are derived from Chapter 2, and more specifically, from the table and figures in Appendix B and C. With regards to EN-179-1 standards, the cement types produced in the Netherlands, as well as their main constituents are presented. The percentage by mass and the volumes of the cement's components (tons) are correlated with the concrete's future use according to each type of cement. Volumes regarding concrete composition are not presented since it is a material that is adapted to each project's standards and its components' volumes vary with regards to its application.

Sheet 2: Logistic costs

At this point, it is worth mentioning that the bulk transportation of the building materials in the urban environment is an issue that requires proper management (Di Maio et al., 2012). The application of in situ recycling technologies for CDW can achieve significant saving in road transportation (Lotfi, 2016). Based on EU statistics, on average concrete products or their ingredients travel for 80 km. As a consequence, 1 m^3 of concrete is equivalent to 2.5 tons of concrete, with a fuel cost of 80 x 2.5 =200 ton-km of transport, or approximately 22 kg CO_2 per m^3 of concrete (6 liters of fuel) of concrete.

For the formulation of a valid construction logistics calculation model, reliable information from actors in the construction supply chain is necessary. This cost information is a result of operational activities. To analyze the data required, it is, therefore, necessary to know and share which indicators are important to track (Balm, Berden, Morel, & van Amstel, 2018). An ELA/AT Kearny study (1993) has indicated that transport costs constitute 65% of the total logistics costs, handling costs are about 20%, and stock – administrative costs are equal to 7-8%. These resource categories form the total calculations that are presented in the second sheet. However, for inner-city logistics owing to traffic congestion, the transportation costs are increasing. In the following Figure 5.2, the cost elements with their influencing factors are presented; these factors are part of the calculation model as well.

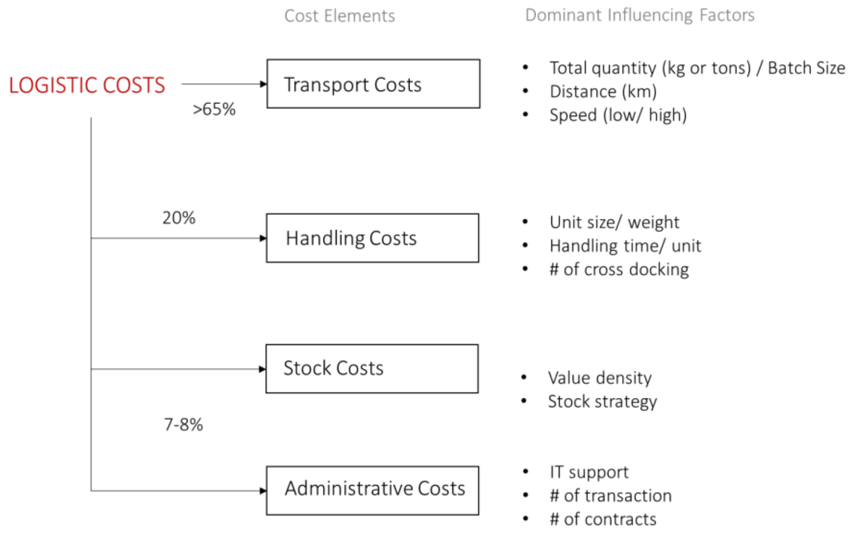


Figure 5.2 Logistic cost structure (ELA/AT Kearny, 1993)

Logistic concepts and activities have a great impact on the product’s final price and consequently, they should be examined. In this respect, it is worth noticing that stakeholders and concrete companies decide which concepts and activities should be executed. Hence, some factors are excluded in the case that the processes are not realized. The variables that are presented can be part of every case that is described in Chapter 4. The following equations analyze the logistic costs included in concrete production.

i. Storage

Storage at the supplier’s inventory

Personnel cost (handling): $C_{act} = R_{pay} * T$ (1)

Personnel cost (administrator): $C_{act} = R_{pay} * C_{unit} * Q_{stor} * T$ (2)

Storage at an intermediate warehouse (extra cost)

Capital cost (warehouse rent): $C_{act} = R_{rental} * C_{unit} * Q_{stor} * T$ (3)

ii. Transportation

Transportation to the construction site or to intermediate warehouse

Personnel cost (truck driver): $C_{act} = R_{pay} * T$ (1)

Personnel cost (inspector): $C_{act} = R_{pay} * T$ (1) – the inspector is paid based on delivery times (R_{rate} : €/ delivery)

Cost for equipment (truck): $C_{act} = R_{rental} * Q_{total} * D$ (4) – the rental rate is based on distance and quantity (R_{rental} : €/ ton/km)

iii. Procurement

Personnel cost (workers in bidding): $C_{act} = R_{pay} * T$ (1)

Contract cost: $C_{act} = R_{depr} * C_{unit}$ (5)

Travel cost: $C_{act} = R_{travel} * C_{unit}$ (6)

iv. Loading and fixing

Personnel cost (handling): $C_{act} = R_{pay} * T$ (1)

Equipment cost (crane): $C_{act} = R_{rental} * D$ (7) –The crane can be rented either based on working time (h) or on quantity (kg or tons)

Table 5.2 *Parameters for logistic costs with their description*

Parameter	Description
$\boldsymbol{C_{total}}$	Total cost of activities (€)
$\boldsymbol{C_{act}}$	Cost of activity (€)
$\boldsymbol{C_{unit}}$	Cost of unit (€/unit)
$\boldsymbol{N_{act}}$	Number of activities
T	Working hours/ Duration (h)
$\boldsymbol{R_{pay}}$	Pay rate (€/h) *the amount of money workers are paid per hour*
$\boldsymbol{R_{rental}}$	Rental rate (€/h) or (€/day) *periodic charge per unit for the use of property*
$\boldsymbol{R_{travel}}$	Travel cost rate
$\boldsymbol{R_{depr}}$	Depreciation rate *the percent rate at which asset is depreciated across the estimated productive life of the asset*
$\boldsymbol{Q_{stor}}$	Storage quantity (kg or tons)
$\boldsymbol{Q_{total}}$	Total quantity (kg or tons)
D	Distance (km)

Noting that:

- A CLC, can use the calculations that refer to storage at an intermediate warehouse with a contract requirement.
- The workers (1) can be paid either based on working times (hours) or based on handling quantities (kg or tons).
- In each activity that is repeated, the total cost is equal: $C_{total} = C_{act} * N_{act}$
- Data for each activity's price are not included in the sheet since the concrete producer can choose among a range of suppliers. However, a calculation tool for logistic costs in the construction industry is provided.

Sheet 3: Technologies – Operating volumes

In the third sheet, the appropriate computations of the novel technologies for concrete recycling are presented. Concerning the technologies that crush or separate materials, the percentage, as well as the quantities (kg or tons) of inputs and outputs, are examined. Results of crusher, ADR and HAS are extensively presented in Chapter 3 (section 3.1).

Worth-noticing points:

- The separation speed of quality control technologies is presented as well; mobile screening, IR sensoring, and LIBS. They are part of the recycling plant and they are responsible for the quality testing of the materials and not for separating EoL concrete.
- The separating speed of ADR technology depends on the length of the equipment. 1 meter separates 50 tons/h, 2 meters 100 tons/h, and so and so forth.
- The available inputs for the technologies are higher than their current performance. More extensively, the available input per hour of technologies ADR and HAS is much higher than their current separation speeds. In numbers, the crusher's output (ADR input) is equal to 105 tons/h, while ADR separates 50 tons/h; ADR output (HAS input) is equal to 14 tons/h, while HAS separates 3 tons/h.
- Calculations are presented either when technologies are operating in line, or separately.
- The crushing and separating size in crusher and ADR are modified based on the project's specifications.

Regarding the production of conventional concrete, the percentage of RA that can replace Natural Aggregates (NA) with a negligible influence is equal or less to 20% of the total amount of aggregates used for concrete production (Paul & Van Zijl, 2012).

Based on Lofti's research (2016), the raw materials composition of RAC are different from NAC, since the RA have not the same mechanical properties with NA. RA tends to absorb more water compared to NA due to the residue of the mortar adhering to the original aggregate (Rao, Jha & Misra, 2007). The high porosity and water absorption capacity of the RA are usually coupled with its low initial water content. Consequently, they render the aggregate to take up a large amount of water during the initial mixing stage and in the end decrease the initial Water/ Cement (W/C) ratio. Moreover, if the W/C ratio of the original concrete is the same or lower than that of RAC, then the strength of RAC can be as good as or higher than the strength of the original one (Tavakoli & Soroushian, 1996).

Therefore, how concrete's mechanical properties along with its chemical composition are changing related to the concrete's RA composition constitute an area of paramount importance for a topic of that dimension. The exact amount of RA and the ratio W/C in concrete requires more experiments. In 2015, Lotfi et al. conducted research concerning the performance of RA concrete by examining the different percentages of RA in concrete's composition. More specifically, they ended up to the conclusion that the concrete's production, as well as its quality control, should be done carefully in the case that the rate of RA in concrete exceeds 50% – which is translated into a number equal to 500kg of RA/ m^3 in new concrete. The higher amount of mixing water and a lower amount of strength shows in most cases worse mechanical and durability properties. The adverse effect of RA is escalated through the application of a higher amount of W/C in the system. Based on the lower W/C ratio and using superplasticizer, results in better mechanical and durability properties in RAC. To conclude, based on the already developed experiments, all durability properties are related to the type of cement and the percentage of mixing water in the mixture of concrete (Lotfi et al., 2015).

Sheet 4: Financial aspect of a Recycling plant

The fourth sheet, contains data regarding material purchase prices, operational costs as well as technologies' investments. With regards to a 'Concrete-to-concrete recycling plant', Table 5.3 presents the cost per price of inputs and outputs, as well as financial data regarding technologies. The factors of each process that should be included are listed in the sheet.

Table 5.3 *Financial data concerning purchase, operational costs, and investments*

Input	**Costs**				**Size**		**Volumes**
Material/ Equipment	Purchase (€/ton) min	max	Investment (€)	Operational (€/ton)	min (mm)	max (mm)	(tons/h)
Crushed EoL concrete (clean)	3	7			0	22	
Mobile screen			200.000				120
IR sensor sorter				1,2			40
Mobile ADR technology			350.000	1,5			50
Mobile HAS technology			450.000	8			3
Recycle aggregate	15				0	22	
Recycle cement paste	12				0	0,25	
Rejected part	-5				12	22	

The original AF fractions, with limited applicability in the production of new building materials, have a value of 1 €/ton (Lotfi & Rem, 2016). By considering, the continual fluctuation in the price of natural aggregate and crushed concrete, it is estimated that the maximum cost of the recycling process should not exceed the price of 5 €/ton.

Sheet 5: Environmental aspect of HAS technology

In the fifth sheet, data concerning the environmental aspect of applying HAS technology are presented. Based on the CSI report (2011), recycling of concrete into its aggregates does not lead to high CO_2 savings. As a consequence, technologies, that are developing in the Recycling Laboratory of the Faculty of Civil Engineering in the TU Delft University are of paramount importance for the reduction of CO_2 emissions, since they target to reuse materials. The Portland cement manufactory process is responsible for a significant part of the global CO_2 emissions (Kleijn, 2012). As already mentioned, HAS technology can separate the hardened cement paste which can replace limestone and as a result can eliminate the main source of carbon emissions in concrete production, which is the cementitious part.

The following Table 5.4 presents the amount of CO_2 emissions that are emitted from the production of a ton of cement and a cubic meter of concrete. The percentage that is attributed to energy use as well as to limestone calcining are reported as well.

Table 5.4 *CO_2 emissions from cement and concrete production (Wilson, 1993)*

Source of CO_2 emissions	Amount of CO_2 emitted in production per		% of total CO_2
	Tons of cement	m^3 of concrete (tons)	
From energy use	0.64	0.236	60
From limestone calcining	0.43	0.158	40
Total CO_2 emission	1.07	0.371	100

Regarding the technologies for raw materials concrete separation, the required heat energy for drying one ton of aggregate fraction (AF) is estimated to be 300 MJ. Based on the Ecoinvent database, if the fuel which is used is gas, 0.0716 kg CO_2 are produced for the production of 1 MJ heat (Weidema et al.,2012). As a consequence, the amount of CO_2 emission resulted from the heating of AF for the production of 1 ton of hardened cement is calculated to be 108 kg. Regarding the production of conventional concrete, the clinker emission factor is the product of the fraction of lime in the clinker multiplied by the ratio of the mass of CO_2 released per unit of lime (Gibbs, Soyka, Conneely & Kruger, 2000). Thus, for the production of one ton of clinker, almost 344 kg of chemical CO_2 will be released. A comparison between the aforesaid numbers shows that the amount of CaO in the recovered finer fraction from the recycling process is comparable with the amount of CaO in low-quality limestone. By using this fraction in the cement kiln as the replacement of limestone, the release of the chemically bound CO_2 could be reduced by a factor of three (Lotfi & Rem, 2016).

Overall, it is estimated that at least 50% by mass of the EoL concrete is suitable to process by ADR; an amount equal to 7Mt/year since the EoL concrete is around 14Mt/year. Based on a CE Delft report of 2015, in the Dutch environment, the potential for CO_2 reduction using AF in cement production is estimated equal to 60.000 tons $C0_2$/year (Van Lieshout, 2015).

The most important source of CO_2 emissions for concrete is the production of cement in the kiln. In order for clinker (the basic cement mineral) to be produced, a mix of Calcium carbonate (limestone) and other minerals are heated to 1450^oC. In the process, the combustion of fuel for heating the mix produces about 0.7 tons of CO_2 per ton of cement and the dissociation of Calcium carbonate produces another 0.5 tons of CO_2 per ton of cement. Replacing the limestone by recycled cement paste (mainly Calcium silicates) prevents the CO_2 emissions that arise with the dissociation of Calcium carbonate. Also, the kinetics of the conversion of cement paste into clinker is advantageous, and this may save even more CO_2 as a result of using less fuel for heating. In this way, a ton of recycled cement paste can save at least 500 kg of CO_2 emissions in cement production (‘Resource and Recycling Laboratory’, 2019).

Sheets 6: Value Stream Mapping for a ‘Concrete-to-concrete Recycling Plant’

In this sheet, calculations concerning the production and the value-added time of a recycling plant are presented. The initial quantity of clean concrete influences the operating hours of the examining technologies as well as the way of transportation. The value stream mapping for the concrete industry is designed aiming to visualize the necessary steps from product creation until delivery to the end-customer. It depicts and improves the flow of inventory, aiming to provide optimum value to the customer through a complete value creation process with minimum waste. The development of this lean management tool is realized for the introspection as well as process improvement through giving inputs about the information flows, material flows as well as lead time (Rother & Shook, 2003).

It is designed in accordance with the SCOR mapping and the involved processes in concrete production. The frequency of orders, scheduling and demand forecast (Figure 5.3), are determined by the production control. The volumes and duration of each technological activity in the ‘Concrete-to-Concrete Recycling Plant’ are calculated and presented in the developed mapping. An extensive analysis of the calculations is presented in the sheet since it can be applied in any quantity and volume of available clean concrete.

Targeting to examine the production lead time as well as the value-added time of the recycling process, a building comparable to the already applications in concrete recycling is selected. The dimensions of the building are following listed:

- Length: 70m
- Width: 30m
- Thickness: 0.25m
- Number of Floors: 10

The quantity of clear concrete in the 10-floor-building is calculated:

- 70 m long x 30 m wide = 2100 m^2
- 0,25 m thick x 2100 m^2 = 525 m^3 concrete per floor
- 10 floors x 525 m^3 = 5250 m^3 x 2,5 ton/m^3 = 13,000 ton.

Assumptions:

- In reference to the above-calculated number, a building that contains 13,000 tons of clean concrete is chosen to be examined
- 13,000 tons of 0-22mm clean concrete from a demolished building are recycled by one plant.
- The VSM follows the schematic approach that is presented in Figure 3.10 for the Recycling Plant.
- The rejected material of IR sensoring is shipped in order to be used in low-quality applications (this technology rejects a percentage of the material that is testing).
- Demolished buildings and mortar plants are located in an urban environment.
- Rigid tipper trucks with a capacity of 20 tons are used for material transportation in inner-city roads (Brighton, & Richards, 2010).
- The cement factory is a quarry that is not located in the borders of a city.
- Dump trucks of 50 tons are used for highway transportation (Brighton, & Richards, 2010).
- Mobile versions of the recycling plant are transported at the demolition site.
- The outputs of the technologies are directly shipped to the customers. The inventorying time refers to the moment that the last amount of quantity is shipped (days of operation).

Worth-noticing points:

A. On the recycling plant, the percentages transported from one process to the other are the followings:

- From crushing process to mobile screening: 100% of the input material
- From mobile screening to IR sensoring: 30% of the input material
- From IR sensoring to shipping: 100% of the input to IR sensoring
- From mobile screening to ADR technology: 70% of the input material
- From ADR technology to LIBS: 60% of the input to ADR
- From LIBS to shipping: 60% of the input to ADR
- From ADR to HAS technology: 40% of the input to ADR
- From HAS to LIBS: 92-98 of the input to HAS (5-8% is the abstracted moisture)
- From LIBS to shipping: 92-98 of the input to HAS

B. LIBS technology is operating on the output belt of the ADR and HAS, and no inventory exists before its usage.

C. LIBS, ADR, and HAS are examining as separate units in order to calculate the operating time of each technology. However, in the cumulative value-added time, the operating time of LIBS is not considering since it takes the same time with ADR and HAS processes.

The results of the Value Stream Mapping are summarized in the following Tables 5.5, 5.6.

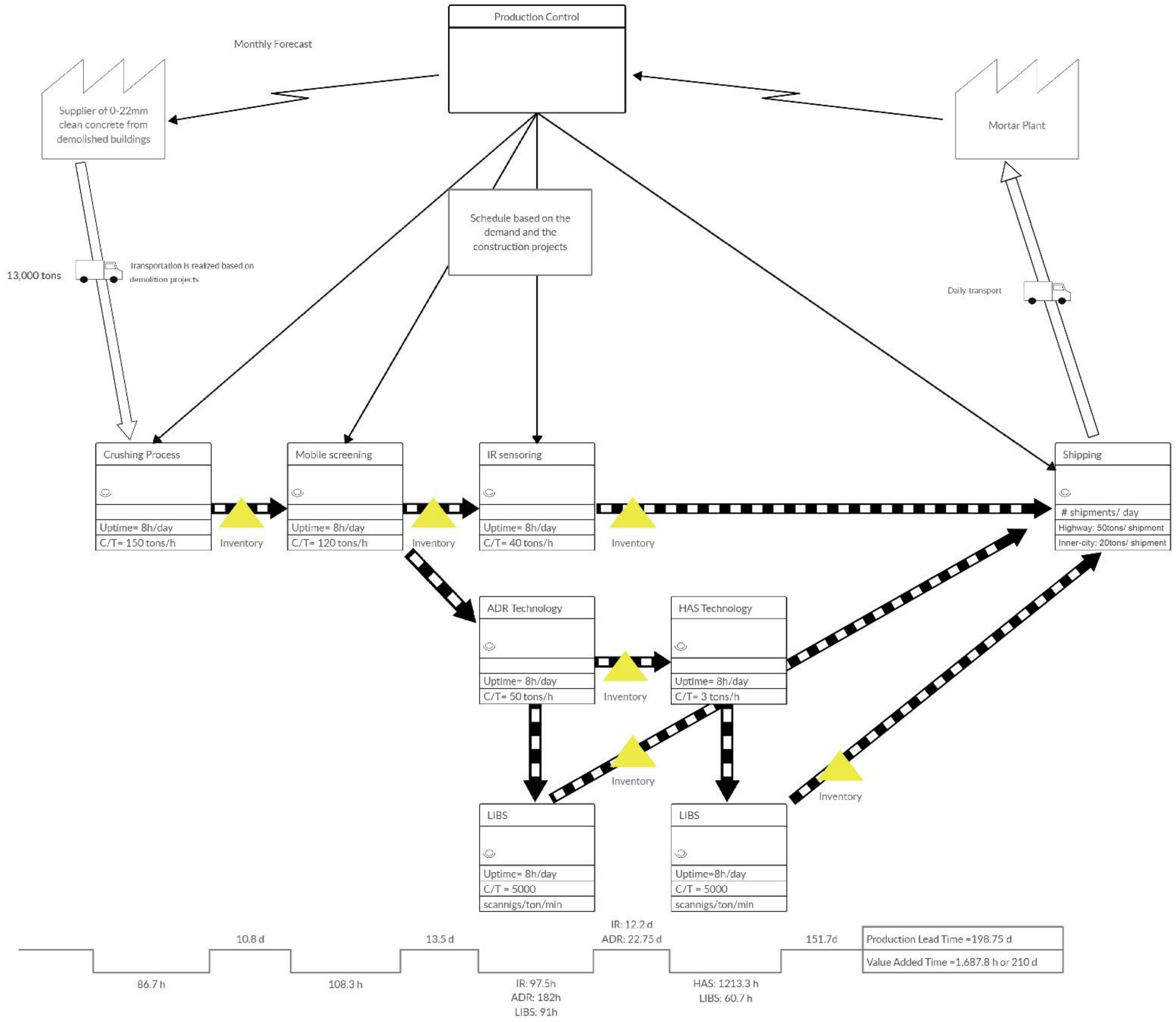


Figure 5.3 Value Stream Mapping for the 'Concrete-to-Concrete Recycling Plant'

Table 5.5 *Value Stream Mappings result s for the 'Concrete-to-Concrete Recycling Plant'*

	Hours	Uptime (hours/day)	Days
Production lead time			199
Value added time	1687,8	8	211

Table 5.6 *Percentage of each technological process to the value-added time in a 'Concrete-to-concrete Recycling Plant'*

Technological Process	Percentage (%)
Crusher – Smart Dismantling and Demolishing technology	5,13%
Mobile Screening	6,42%
IR sensoring – RFID	5,78%

Advanced Dry Recovery (ADR) Technology	10,78%
Heating Air Classification System (HAS)	71,89%
Laser-Induced Breakdown Spectroscopy (LIBS)	*Not calculated - it is working in line with ADR and HAS.*

With regards to Value Stream Mapping, the differences between Cases 2 and 5 with Cases 3 and 6 are attributed to truck shipments and inventorying:

1. **Truck Shipments**
   From the demolition site to the recycling plant, the trucks have a capacity equal to 20 tons (Cases 2 and 5). On the other hand, from the recycling plant to the cement factory (HAS output – ultrafine particles), the dumb trucks have a capacity of 50 tons (Cases 3 and 6). The second referred transportation is realized on a highway and not in inner-city transportations.
2. **Inventorying**
   In Cases 2 and 5, inventorying is realized from the demolition site to the recycling plant, while in Cases 3 and 6 from the end of technological processes to the end-customer.

The following Figures 5.4 and 5.5 explain the processes and the differences between the cases A and B concerning warehousing, transportation as well as operating speeds of the technologies. More information is presented in the calculation model.

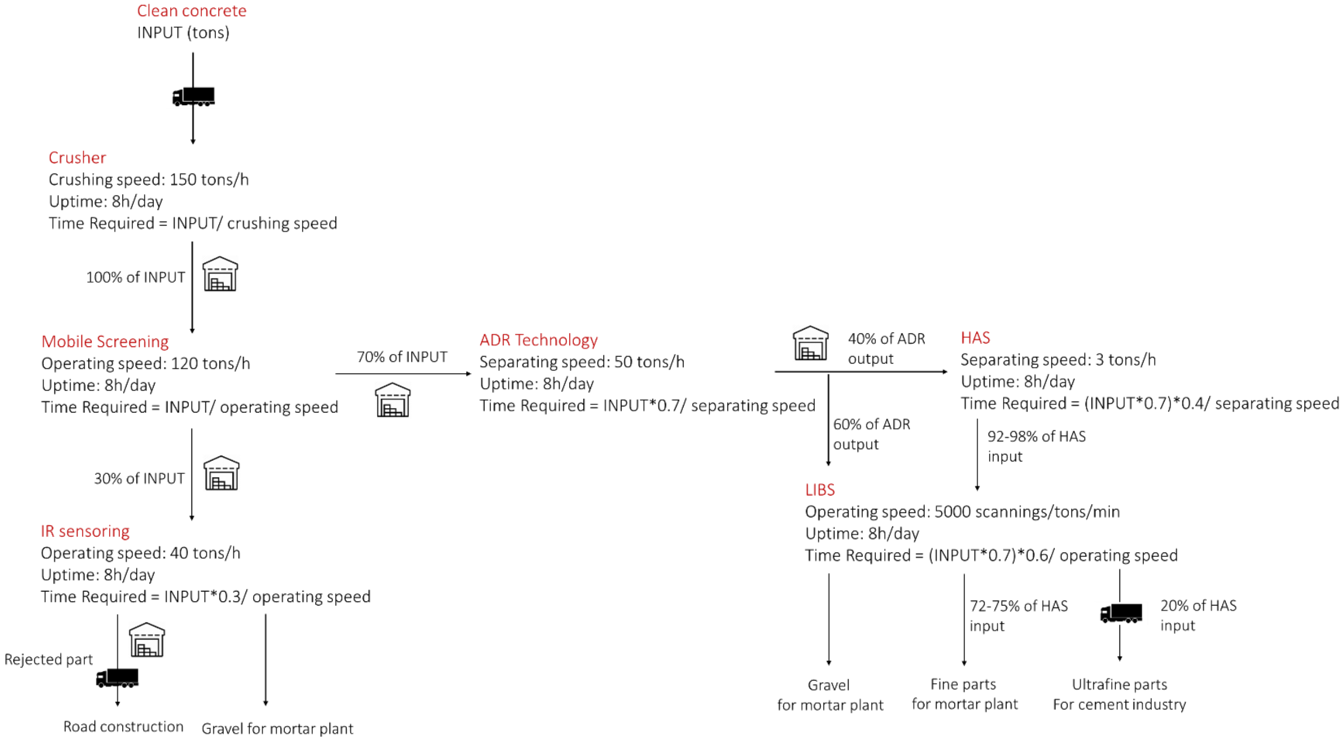


Figure 5.4 Transportation and warehousing among the processes in the 'Concrete-to-concrete Recycling Plant'

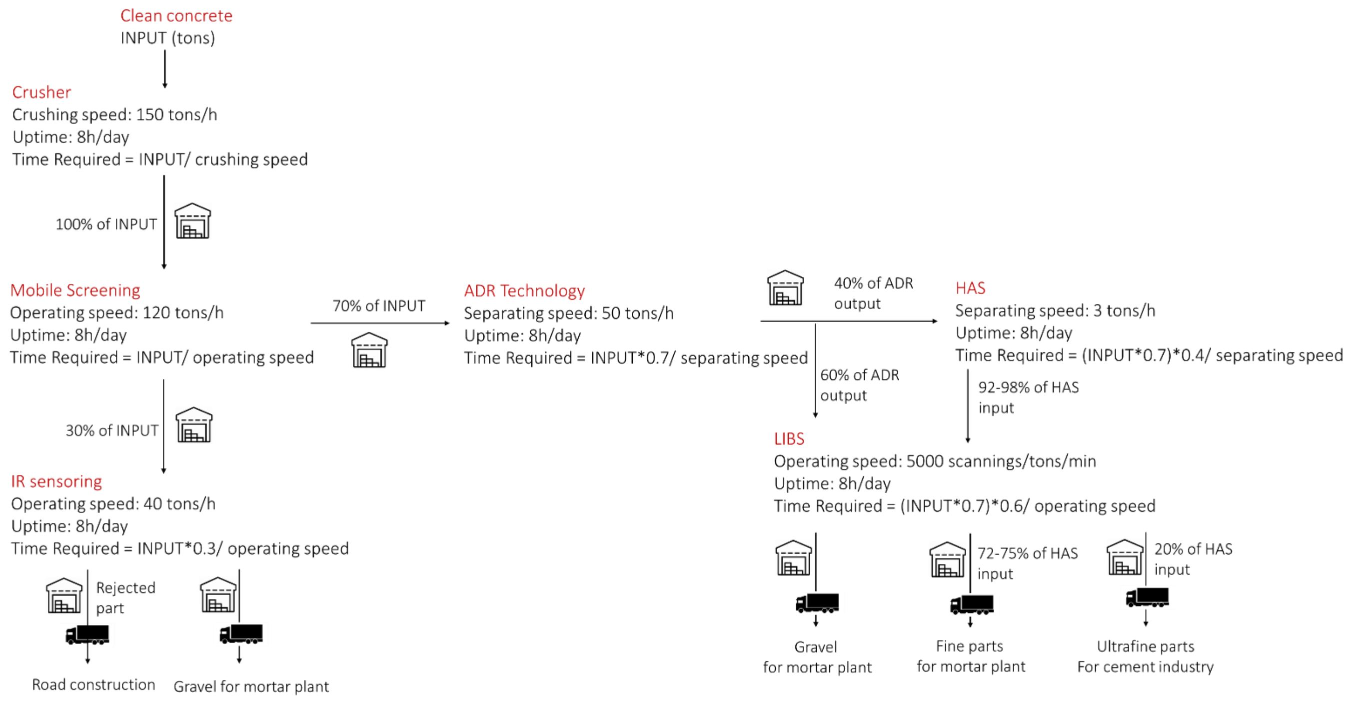


Figure 5.5 Transportation and warehousing among the processes in the 'Concrete-to-concrete Recycling Plant'

The above information and data are gathered in the last sheet of the model with the name 'Project'. The user can add the specifications and the volumes of the project and therefore calculate the relevant parameters.

5.2 Organizational Perspective

An important aspect of the introduction of the technologies for concrete recycling in the CS is the market conditions and the role of technologies in each industry related to concrete production. Consequently, aiming to attain a complete overview of the feasibility assessment, an organizational perspective seems necessary through taking into consideration the market potentials and the stakeholders' engagement in novel technologies.

5.2.1 Market potentials

Aiming to analyze the current and future potentials of the market as well as the enablers and stoppers of introducing the new technologies in the CS, the Porter's Five Forces Model is illustrated based on the current market situation, which is described in Chapter 2. The model constitutes a competitive forces framework that gives a clear image of the different dimensions that govern market competition. A better understanding, regarding the forces that critically affect the industries involved in the concrete production, are distilled. It formulates the guidelines for identifying the strengths and minimizing the wastes. Consequently, the impact of new technologies in the existing market situation is explored. The preferred framework is designed schematically for each industry involved.

It is worth mentioning that the analysis of this part refers to the Dutch producers and not to the materials that are imported or totally consumed in the Netherlands. As following illustrated, the role of novel technologies is completely different in each industry.

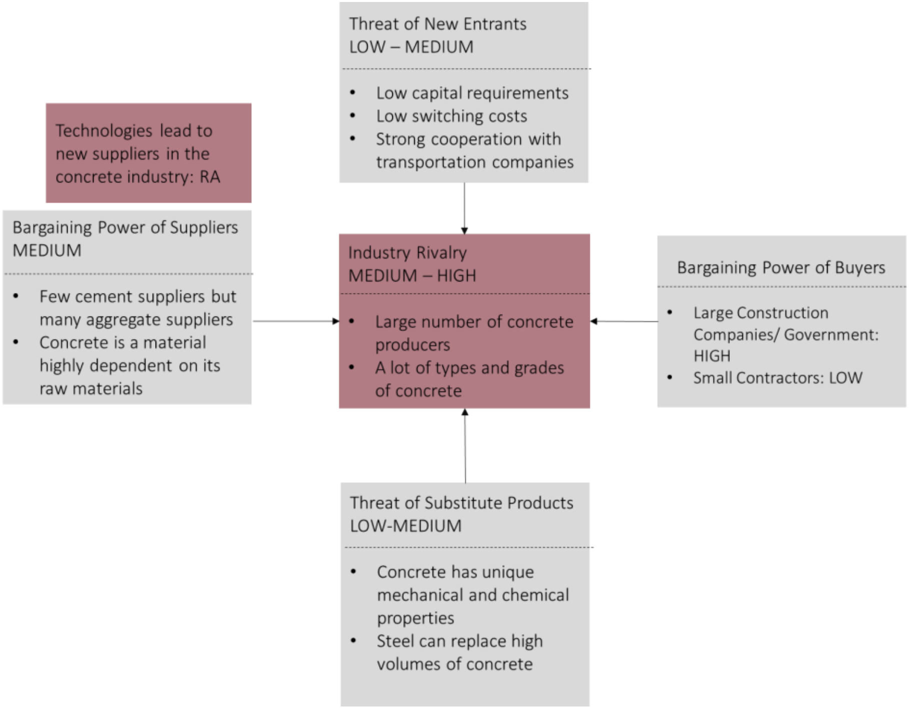
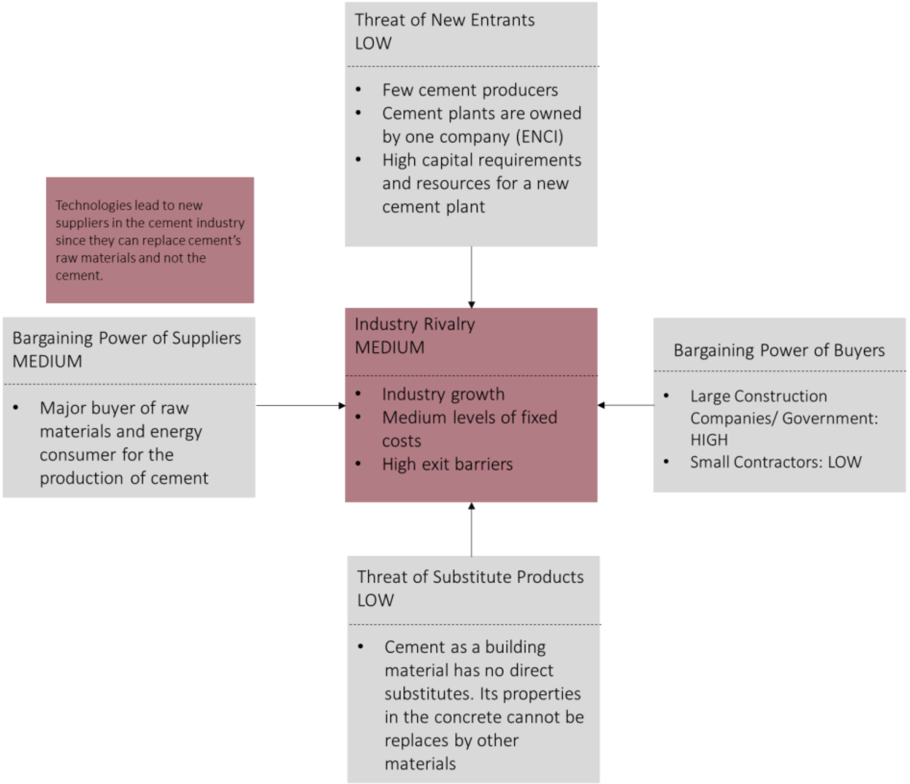


Figure 5.6 Porter’s Five Forces for the Dutch concrete industry



Threat of New Entrants
LOW

- Few cement producers
- Cement plants are owned by one company (ENCI)
- High capital requirements and resources for a new cement plant

Technologies lead to new suppliers in the cement industry since they can replace cement's raw materials and not the cement.

Bargaining Power of Suppliers
MEDIUM

- Major buyer of raw materials and energy consumer for the production of cement

Industry Rivalry
MEDIUM

- Industry growth
- Medium levels of fixed costs
- High exit barriers

Bargaining Power of Buyers

- Large Construction Companies/ Government: HIGH
- Small Contractors: LOW

Threat of Substitute Products
LOW

- Cement as a building material has no direct substitutes. Its properties in the concrete cannot be replaces by other materials

Figure 5.7 Porter's Five Forces for the Dutch cement industry

Threat of New Entrants
LOW – MEDIUM

- Highly connected with distribution channels
- Low switching costs
- High capital requirements for virgin materials and low for RA

Technologies lead to new entrants in the industry of aggregates.
ADR outputs can replace coarse aggregates while the fine part of HAS can replace fine aggregates.

Bargaining Power of Suppliers

- Suppliers for aggregate extraction: LOW
- Suppliers for recycled aggregates: HIGH

Industry Rivalry
MEDIUM – HIGH

- Large number of aggregate extractors
- The growth in the sector is highly connected with a sustainable future in the Netherlands

Bargaining Power of Buyers

- Large Construction Companies/ Government: HIGH
- Small Contractors: LOW

Threat of Substitute Products
LOW

- Aggregates, coarse and fine, constitute 2 out of the 4 main components for concrete production

Figure 5.8 Porter's Five Forces for the Dutch Industry of Aggregates

The following table presents the market position of the technologies in each industry in accordance with the current power of competitors. The industry of aggregates is of paramount importance on account of the fact that the materials originated from concrete's separation, constitute a noteworthy percentage of virgin sand and gravel in the concrete.

Table 5.7 *The market position of novel technologies in each industry related to concrete production*

Industry	Market position
Concrete	New suppliers They provide construction projects with recycled materials. Suppliers' bargaining power in the sector is 'medium' and as a consequence, technologies have a moderate impact on the industry's competition.
Cement	New suppliers Despite the fact that the recycled products constitute a part of cement in the production of new concrete, they cannot be characterized as new entrants but as new suppliers. They supply ultrafine particles that can replace a percentage of limestone as well as additives. Cement plants should cooperate with the suppliers of recycled materials for the production of new cement, targeting to achieve lower CO_2 emissions.
Aggregates	New entrants Gravel and sand extractors are not in support of applying these technologies in the market. The rivalry in this sector is 'medium to high' and this is translated into the fact that novel technologies should compete already established companies or extractors in the aggregate sector.

5.2.2 Stakeholders' Engagement

Concrete recycling in the building sector is a relatively new concept that is developing in the last decade. Consequently, a social context analysis is necessary for the examination of the information flow in the supply chain of concrete by considering the diversity of actors. They play an important role since the maintenance of material value requires communication and collaboration along the value chain. In this section, a stakeholder analysis is conducted and questionnaires are distributed with the purpose of assessing the feasibility of introducing the novel technologies to the market.

In the beginning, the Stake/Power/Knowledge (SPK) Framework is developed and afterward, a Power Interest Grid is designed. Stakeholders can be categorized based on their influence/power, stake, and knowledge on the decision process (Susskind, McKearnan & Thomas-Larmer, 1999). According to Moore (2008), stakeholders with high stakes, are able to add legitimacy and community acceptance to the project. Stakeholders with high levels of knowledge can support the scientific and technical analysis, while stakeholders with power can lead to the viability of the project.

Actors involved in the pre-building phase, building phase and post-building as well as their role in the supply chain are identified (Table 5.8). Additionally, a list of companies related to the CS in the Dutch environment is reported in Appendix E.

Table 5.8 *Stakeholder Classification based on SPK Framework – Stakeholders' power and interest*

SPK – Power & Interest
Cement producers: *Raw material supplier of concrete - Stakeholders with economic influence* As a result of the limited availability of limestone in the Dutch geographic area, there are only one integrated and three grinding plants for cement production, belonging to ENCI company (ENCI, 2019), which is operated by the German company Heidelberg Cement. The novel technologies regarding successful concrete recycling will have an impact on the cement industry since the fine particles originated from HAS will replace a small percentage of cement's raw materials. Currently, no recycled materials are used for cement production. As a consequence, cement producers have **high power** and **high interest** regarding the new technologies and their introduction to the market.
Aggregate extractors: *Raw material supplier of concrete - Stakeholders with economic influence* Excavation companies produce about 90 million tons of sand and 5 million tons of gravel per year from the Dutch subsurface. These materials can be used immediately, without further processing, or as raw materials in the building materials industry ("Sand, gravel and clay extraction | TNO", 2019). Nevertheless, the Netherlands is not self-supporting for aggregates (Van der Meulen, Van Gessel, & Veldkamp, 2005) since it has a lack of natural resources. In the current market, recycled materials for concrete production are used in a percentage equal or less to 20% of the total amount of aggregates (Paul & Van Zijl, 2012). Thus, RA from new technologies constitute a new entrant in the market and a threat to the industry of aggregates. The aggregate extractors have a **low power** since RA constitute a much more cost-efficient option than virgin materials. Their **interest** is **high** due to their key role in the concrete's supply chain; aggregates is one of concrete's raw materials.
Concrete producers: *The core of the concrete chain* Each category of concrete producers has a different stake in the value chain. Site-cast concrete producers constitute a small percentage of the market, thus, their interest is not that high compared to the prefabricated or ready-mixed ones. Overall, the concrete industry has **high interest** and **high power**, Once the market accepts the changes and new regulations are established, concrete producers will go along in the recycling standards (Bakker & Hu, 2015).
Architects and designers: *Part of the planning part of the construction project - Decision-makers* Architects and designers make decisions crucial for the project's long term efficiency. Meanwhile these technologies are not launched in the market yet, their daily schedule is unaffected and as a result, their **interest is low**. However, they have great knowledge regarding the construction process and they are opinion influencers towards a more controlled project. Thus, a **medium power** regarding the technological application can describe them.
Construction companies: *Contractors - Decision-makers* They are responsible for the activities realized in the construction site and they have a great impact regarding the material selection as well as the transportation and logistics of the project. Their choices are related to the RA selection, leading to **high power** and a **medium interest** of leveraging recycled materials.
Clients: *The starting point of the construction project* Clients are the starting point of the construction project and they have an impact on the design phase of the project. They have a **medium power** since they can request for recycled materials from the designers and the construction companies. Nevertheless, their insufficient knowledge concerning concrete's recycling formulates a **low-interest-profile** towards the novel technologies.
Construction Logistic Coordinators (CLCs): *The coordinator among the stakeholders of the concrete value chain*

A CLCs is responsible for the logistics management, who monitors and sends all required materials to the construction site in accordance with the project planning. Raw materials suppliers are usually cooperating with CLCs targeting to cost-efficient transportation. They have **high interest** since their role will change with the introduction of these technologies in the market as well as a **low power** since they cannot get involved in the decision making of the project.

Demolition companies: EoL concrete suppliers
Demolishers have a key role regarding the recycle of concrete since they are the EoL concrete supplies. For a more efficient separation process, demolishers should use smart demolition technologies towards a better pre-sorting. And thus, they can influence directly the construction project's specifications. They have a **high interest** while their **power** is **medium.**

Recycling companies: Future investors of recycling plant
Recycling companies are responsible for the crushing and sorting of the EoL concrete materials before it is reused. Based on Eurostat percentages of treated wastes, 99% of CDW in the Netherlands is recycled mainly for road filling (Deloitte, 2017). Consequently, all the concrete rubble from construction and demolition is retrieved for recycling (Hu, Kleijn, Bozhilova-Kisheva, & Di Maio, 2013). With the introduction of these technologies in the market, recycling companies need to invest in aiming to be part of concrete's value chain and provide high-quality materials not only for landfilling but also for building construction from EoL concrete. Therefore, they have **medium power** and a **high interest** in the recycling market.

Researchers: Knowledge-producers
Researchers can be a part of universities or research institutions and they are the knowledge holders regarding the future potentials of concrete's recycling (TU Delft). They have an absolutely **high interest** in applying and introducing to the market, technologies that can lead to lower CO_2 emissions and utilize EoL concrete to its highest value. However, they have a **low to medium power** since they cannot control the market decisions.

Dutch Government: Stakeholders with political influence
The Dutch government plays a significant role in the value chain of concrete. The 'non-hazardous CDW by 2020' as well as the 'Circular Economy Vision in the Netherlands by 2050' have an impact on the construction companies' operation and the material selection. Both their **power** as well as **interest** are very **high**.

European Commission: Stakeholders with political influence
The European Commission is one of the biggest funders of research in the field of concrete recycling. Projects based on technologies for concrete recycling (C2CA, HISER & VEEP) have received substantial financing for research and application testing. Moreover, of paramount importance are the European standards that they set concerning the concrete's composition and the CO_2 emissions during its production as well as transportation. Consequently, they have both **high power** as well as **high interest**.

MVO Nederlands: Dutch Government's initiative with political influence
In November 2012, more than 20 companies from the MVO Network Concrete have signed the first 10 concrete ambitions in the Green Deal Concrete with the ultimate purpose of a 100% sustainable concrete chain in 2050 ('Green Deal Beton wordt concreet', 2019). This initiative is operating in accordance with the Dutch Government's circular visions and targets to a green value chain through obtaining **high interest** for a more sustainable environment. Its **power is medium** since the companies of the concrete chain decide if they desire to get involved in it.

A power – interest matrix is a frequently used tool in actor analysis proposed by Mendelow (1991). It targets to categorize stakeholders according to their role in the value chain based on the two dimensions; power and interest. The above-referred stakeholders according to their ratings towards concrete's recycling technologies, are placed in the following matrix (Figure 5.9).

Figure 5.9 Power – Interest matrix for concrete's recycling technologies

Aiming to evaluate the above-referred analysis and examine the obstacles and enables of introducing the novel technologies to the market, questionnaires were sent by e-mails to companies with different roles in the supply chain of concrete. The received answers were equal to 10% of the total questionnaires sent. 10 stakeholders from 6 different companies (Table 5.9) participated in the results of the current thesis by answering the questionnaire of Appendix D. Moreover, the director of the organization New Horizon - Urban Mining was interviewed through a phone call.

Table 5.9 *Personal Details of stakeholders in the value chain who participated in the research*

Interviewer's name	**Job position**	**Company's name**	**Company's role in the value chain of concrete**
Wouter van den Berg	Marketing Product Manager	ENCI - HeidelbergCement Benelux	Cement producer – Concrete's raw material supplier
Peter de Vries	Senior Technical Advisor		
Carlo Neve	Technical Advisor		
Marcel Bruin	Manager S&D		
Klaas Ellens	Sales Manager	Haitsma Beton B.V.	Prefabricated concrete producer
Leo Dekker	Manager Technology & Sustainability	Mebin B.V.	Concrete producer
Ronel Dielissen	General Manager		

Leonie van der Voort	Director	Cascade	Sand and gravel producers
Thies van der Wal	Sustainability CSR	VBI	Prefabricated flooring producer
Michel Baars	Director	New Horizon – Urban Mining	Network organization based on recycling

The results are presented in the following pies and charts.

Regarding the part ‘Circular Vision in the Netherlands’, the obtained answers indicate the followings:

- Most of the participants are working in companies that follow Circular Vision and are informed of the Dutch targets concerning recycling and circularity.
- Impressive is that Q3 and Q4 (Figure 5.10) reached the same percentage of positive answers but the answers were originated from different candidates.
- Most of the negative answers are derived from RA competitors.
- 7 of the participants belong to companies that take part in ‘the Concrete Agreement Betonakkoord’ (Available in https://www.betonakkoord.nl/) in terms of the ‘Green Deal Sustainable Concrete Chain’. As a consequence, they are totally informed about concrete recycling.

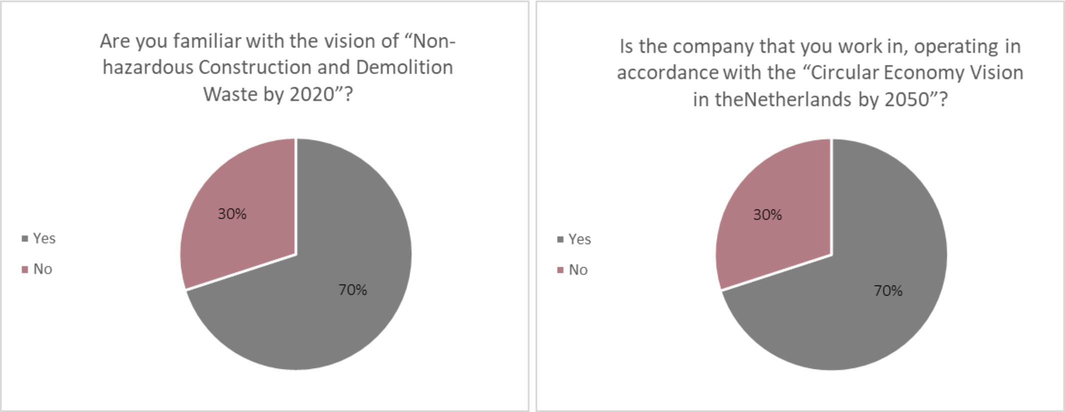


Figure 5.10 Results of (a) Q3 and (b) Q4 of the questionnaire

Regarding the part ‘Concrete Recycling and Technologies’, the obtained answers indicate the followings:

- The most acknowledged technology and extensively used is SmartCrusher. ADR follows and lastly, HAS has the lowest percentage of positive answers as the most recently developed technology.
- Many companies use RA for their production instead of virgin sand and gravel, with the implication that the additives or other materials have been abstracted from the RA. Percentages of RA in the companies that answered the questionnaire vary from 10-30%.
- Whereas most of the participants are informed that these technologies can lead to high-quality materials (Q8), not the same percentage is in favor of investing in them (Q6).

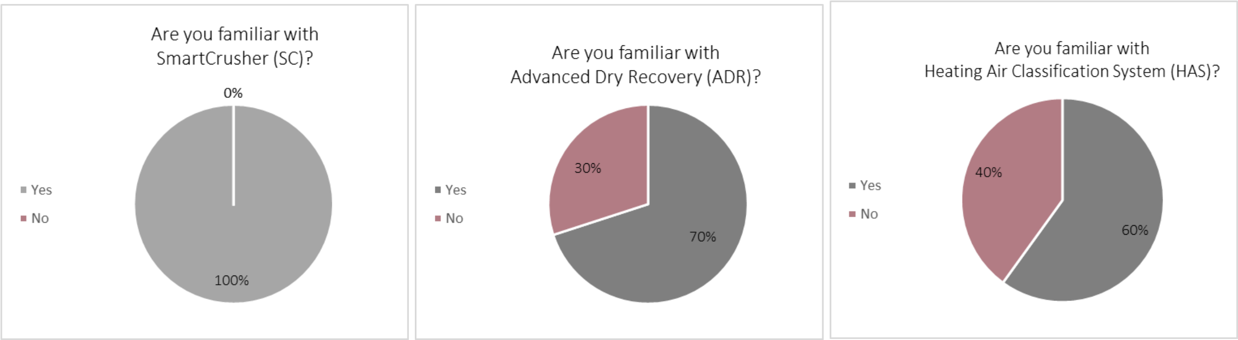


Figure 5.11 Results of Q5 of the questionnaire

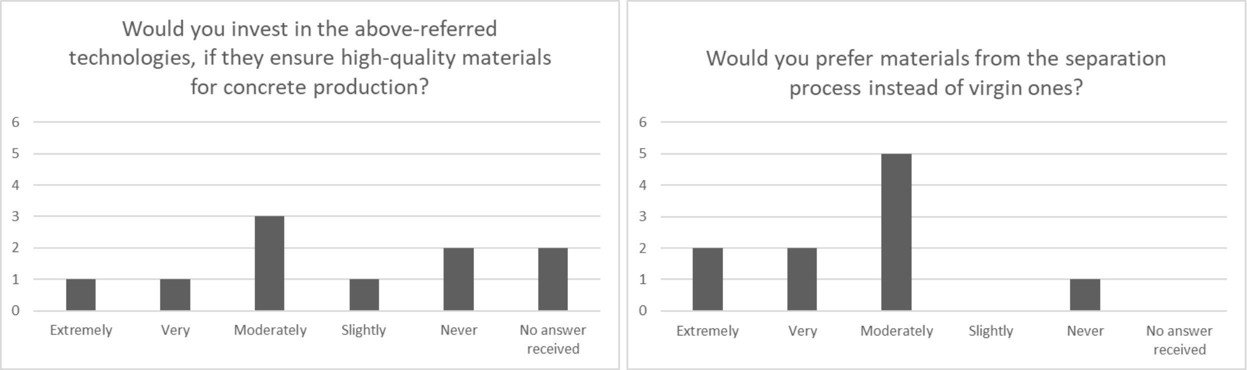


Figure 5.12 Results of (a) Q6 and (b) Q7 of the questionnaire

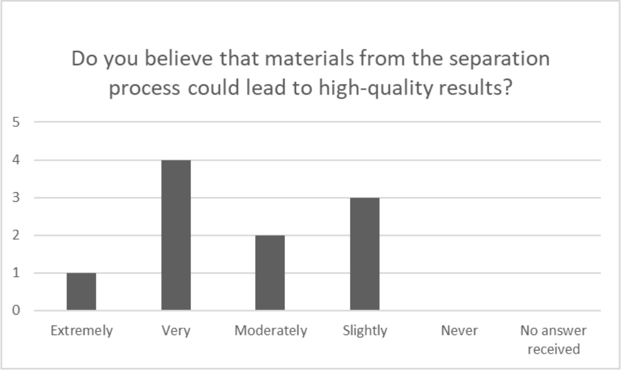
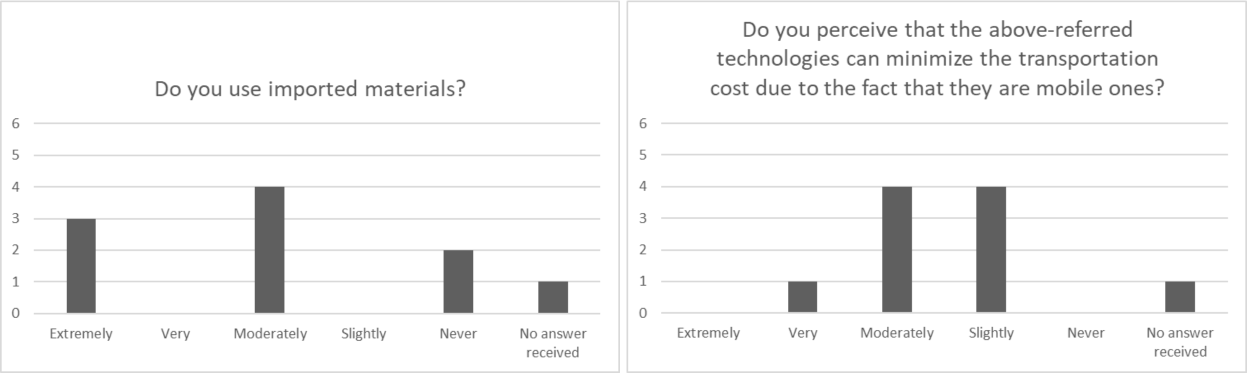


Figure 5.13 Results of Q8 of the questionnaire

Regarding the part ‘Transportation and Logistics’, the obtained answers indicate the followings:

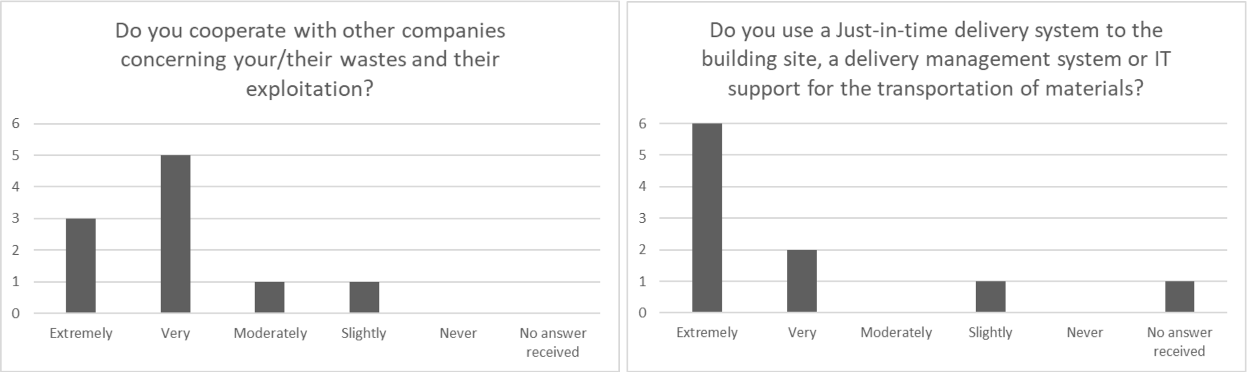
- Most of the stakeholders are cooperating with other companies for their waste exploitation. This is certainly important in the CS since the different processes and transportation are highly interconnected.
- As it concerns the construction logistic concepts, most of the companies use a JIT delivery system while few of them are cooperating with CCCs and CLCs or they use BIM as a digital tool. JIT delivery is highly important for obtaining concrete quality.



Do you use imported materials?

Do you perceive that the above-referred technologies can minimize the transportation cost due to the fact that they are mobile ones?

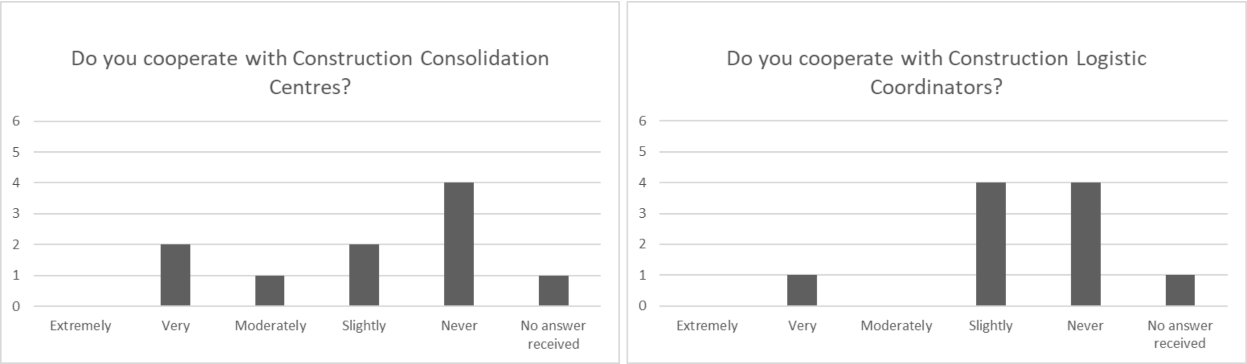
Figure 5.14 Results of (a) Q9 and (b) Q10 of the questionnaire



Do you cooperate with other companies concerning your/their wastes and their exploitation?

Do you use a Just-in-time delivery system to the building site, a delivery management system or IT support for the transportation of materials?

Figure 5.15 Results of (a) Q11 and (b) Q12 of the questionnaire



Do you cooperate with Construction Consolidation Centres?

Do you cooperate with Construction Logistic Coordinators?

Figure 5.16 Results of (a) Q13 and (b) Q14 of the questionnaire

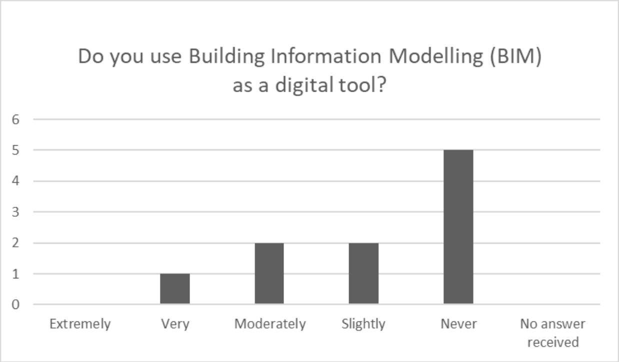


Figure 5.17 Results of Q15 of the questionnaire

The following observations are abstracted from the collected answers:

- Companies that answered are in a particular way involved in the recycling of concrete. As a consequence, the survey does not cover the viewpoint of each stakeholder in the value chain.
- Impressive is that stakeholders from the same company but from different departments or different positions gave dissimilar answers according to their job position.
- RA' competitors supported a standpoint against the integration of analyzing technologies to the market.

One step further, the distributed questionnaires strive to connect the theoretical level of development with the realization of the analyzing project. In particular, the following conclusions are drawn from the collected answers:

- On average, cement and concrete companies are working in line with a circular and sustainable vision and are willing to use a high percentage of RA in their materials.
- Technologies for concrete recycling are commonly known in the CS.
- Aggregate extractors are not in favor of concrete recycling.

5.3 Conclusions and contribution of Chapter 5

The calculation model is developed in order to identify the points of difference among the Cases 1 and 4 (conventional concrete production) with Cases 2, 3, 5 and 6 (closed-loop concrete production) as well as assess the feasibility of the development of a 'Concrete-to-concrete Recycling Plant' (Cases 2, 3, 5 and 6), which constitutes the proposed solution to the problem of EoL concrete waste treatment.

The main benefits of utilizing a 'Concrete-to-concrete Recycling Plant' (Cases 2, 3, 5 and 6), compared to applying conventional concrete production (Cases 1 and 4) are the followings:

- The only major cost of the process is the transportation costs since CDW is a really low-cost input.
- The geographic area of the Netherlands has the appropriate size (41,543 km^2) for materials' transshipment around the country since the maximum distance of transporting RA (Michel Baars, 'New Horizon – Urban Mining', 2019) is:
  - By boat: 80-100km

- By truck: 25-30km

Concerning logistics concepts, the construction logistic costs in the concrete production depend on the stakeholders' decisions, the quantity of concrete, the project's location and the percentage of RA in the final product. Transport costs are responsible for more than 65% of the total logistics costs, while personnel costs for around 20%.

From a financial point of view, a recycling plant can provide high-quality materials from a low-value input waste. Despite the fact that the plant requires an investment of 1M €, this cost does not constitute an obstacle. Mortar companies and demolition centers should cooperate and increase trustworthiness; recycling constitutes an act of collaboration among the stakeholders in the concrete supply chain.

From an environmental point of view, the amount of CaO in the recycled finer fraction is similar to the amount of CaO in low-quality limestone. By taking advantage of the finer fraction, the CO_2 emissions can be reduced and it is estimated that a ton of recycled cement paste can save at least 500 kg of CO_2 emissions in cement production.

The design approach in Chapter 4 identified the transportation movements and led to the development of a Value Stream Mapping for the processes executed on a 'Concrete-to-concrete Recycling Plant'. The selected example was a building constructed by 13,000 tons of concrete. The value-added time calculated equal to 211 days; a quite high number. Hence, it is worth mentioning that around 72% of this duration, and more specifically, 152 days, are attributed to HAS operation. Consequently, it is recognized that a huge issue in a recycling plant is the separation speed of the HAS technology.

The above results and calculations led to the conclusion that an investment in a 'Concrete-to-concrete Recycling Plant' is worth for the following cases:

- Cases 2: *'Prefabricated concrete with a Concrete-to-concrete Recycling Plant operating near the prefabricated concrete industry'* and
- Case 5: '*Site-cast/ Ready-mixed concrete with a Concrete-to-concrete Recycling Plant operating near the mortar plant'*

They are the most cost-efficient cases for each category of concrete respectively since fewer transportation movements are realized and the technological outputs are leveraged immediately without storage. Otherwise, improvements and research experiments are required in order to increase HAS' separation speed.

The organizational perspective is crucial for this topic in order to examine the feasibility of integrating the analyzing technologies to the market in accordance with the current industry's performance. It essentially connects the theoretical level of development with the level of viability of the analyzing project.

The impact of the technologies for concrete recycling on the current market conditions as well as the viewpoints of the involved stakeholders are summarized with the developed schemes of Porter's Five Forces model (Figures 5.6 – 5.8) and the Power-Interest Matrix (Figure 5.9). More specifically with respect to the type of each examining industry, the actors who are responsible for the outputs of technologies have a respective role in the value chain.

Stakeholder engagement influences the technology implementation process. Cement producers have high power and interest and thus, they can control the market decisions and the use of RA. The same stands for concrete producers; each of them can use different materials in the production process. The aggregate extractors have the highest interest since the RA may decrease their revenues. Nevertheless, their power is the lowest among the involved industries, since RA constitutes a more sustainable option than material extraction.

Concrete recycling is a process that requires a high level of cooperation among the involved industries. Focusing on the questionnaire answers, most of the stakeholders are cooperating with other companies for CDW exploitation. Overall, stakeholders with high power and stake in the CS are operating in accordance with integrating RA to their processes.

Table 5.10 *Exploratory results based on an organizational perspective*

Industry	Position in the market	Stakeholders' power and interest in the technologies	Questionnaires' answers
Concrete	Role of technologies: new suppliers of recycled sand and gravel Current bargaining power of suppliers: MEDIUM	Power: HIGH - they control the use of RA since technological outputs constitute one of the industry's suppliers Interest: HIGH	In line with a circular vision and in favor of using RA in their production process.
Cement	Role of technologies: new suppliers – limestone and additives suppliers Current bargaining power of suppliers: MEDIUM		
Aggregates	Role of technologies: new entrants Current threat of new entrants: LOW – MEDIUM	Power: LOW – they are RA competitors and they cannot influence immediately the decision of using the technologies Interest: HIGH	Aggregate extractors are against introducing RA in the CS

In the following table and in terms of the organizational perspective, with an '✓' are marked the cases that stakeholders of the relevant industry are in favor of their implementation. The table is filled based on the received questionnaire answers combined with the most efficient location of the recycling plant.

Table 5.11 *Industry position for each developed case*

Industry	Case 1 Prefabricated concrete production	Case 2 Prefabricated concrete production with a 'Concrete-to-concrete Recycling Plant' operating near prefabricated	Case 3 Prefabricated concrete production with a 'Concrete-to-concrete Recycling Plant'	Case 4 Site-cast/ Ready-mixed concrete production	Case 5 Site-cast/ Ready-mixed concrete production with a 'Concrete-to-concrete Recycling Plant'	Case 6 Site-cast/ Ready-mixed concrete production with a 'Concrete-to-concrete Recycling Plant'

		concrete industry	operating at the demolition site		operating near mortar supplier	operating at the demolition site
Concrete		✓			✓	
Cement		✓			✓	
Aggregates	✓			✓		

Consequently, the stakeholders with great influence in the production process of concrete are in favor of using recycled materials. On the other hand, aggregate extractors do not support novel technologies since they will substitute part of their production. Nonetheless, their low power in the sector constitutes the use of RA and the development of a recycling plant feasible.

The major obstacle is that the technologies have not been communicated sufficiently in the constructor sector. This thesis aims to tackle this problem since parts of this work will be used in handbooks which are currently developing by the 'Resource and Recycling Laboratory' in the faculty of Civil Engineering in TU Delft. The aim is to inform the constructor sector concerning the benefits of RA in the production of concrete.

Contribution of Chapter 5

The examination of feasible solutions concerning concrete recycling lay the groundwork for further scientific work. From a social perspective, this chapter investigates the possibilities of applying novel technologies to the market by reducing CO_2 emissions. Additionally, a spreadsheet model with the required information concerning these innovations establishes a valuable tool for future use in the constructor sector.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The exploratory starting line of this work is described in the following design objective:

Supply chain mapping for concrete recycling

The design of a closed-loop supply chain concerning the integration of novel technologies in conventional concrete production in the Netherlands.

More precisely, the objective of this research was the design of a closed-loop supply chain for concrete production in the Netherlands. The selected design approach consists of five stages and was developed throughout the entire thesis report. The research highlights developing technologies that aim to change conventional concrete production and manage circular concrete. In this Chapter the development of the last stage is presented and the design activities in parallel with the design stages are summarized.

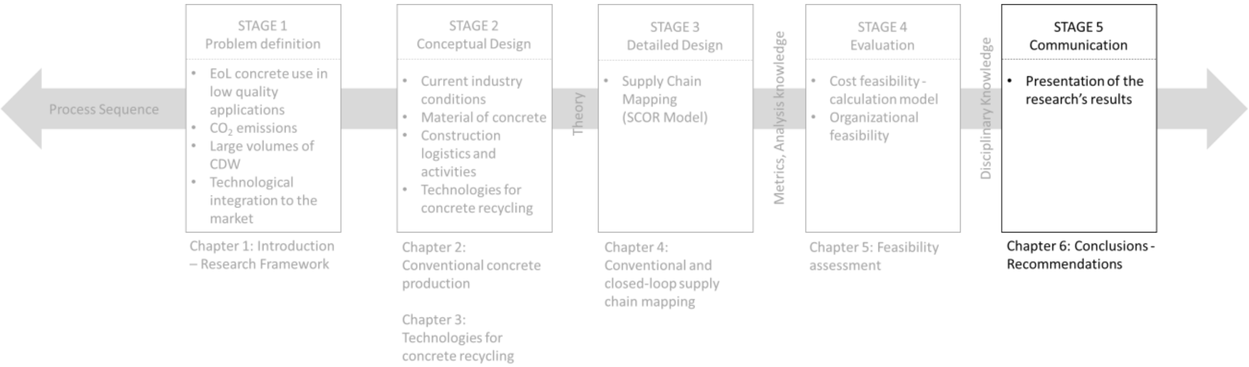


Figure 6.1 Stage of the design approach for Chapter 6

STAGE 1. PROBLEM DEFINITION

Regarding the first stage of the design approach, the problem of EoL concrete treatment in the Netherlands, as well as the insufficient communication concerning the technologies for concrete recycling, were identified. In terms of CE and industrial symbiosis, it has been recognized that the supply chain systems should be introduced in real-world problem and consequently, cooperation among companies is required.

STAGE 2. CONCEPTUAL DESIGN

In relation to the next stage of conceptual design, two Chapters were developed. In Chapter 2, the foundations for design objectives that considered in the supply chain mapping of concrete production, were identified. The current industry conditions in the CS and the concepts concerning the production of concrete and its transportation along the supply chain were identified. In addition, the enormous field of cement types and concrete categories were narrowed down with a focus on the Dutch geographic area.

More specifically, the results indicate that cement is the material with the highest complexity of concrete components and its most common type is the Portland one, while the two main categories of concrete production are the i) prefabricated concrete and the ii) site-cast/ ready-mixed concrete. The emphasis was given on the determination of the flow of materials in accordance with the related costs, by focusing on the three main logistic activities in concrete manufacturing; i) procurement, ii) transportation, and iii) loading.

In Chapter 3, the attention was on the most promising technologies that can ensure the utmost percentage of CDW exploitation in the Dutch environment and the management of circular concrete in close proximity. i) 'Crusher – Smart Dismantling and Demolishing', ii) 'Advanced Dry Recovery (ADR)' technology as well as iii) 'Heating Air Classification System (HAS)' crush and separate EoL concrete to its raw materials, through evaporating moisture and ensuring high-quality outputs. Concerning these technologies, the highest interest was attributed to HAS, since it could replace additives (e.g. fly ash) as well as a percentage of limestone, and can result in lower CO_2 emissions. The following Figure 6.2 depicts the conversions of the conventional supply chain of concrete through leveraging ADR and HAS technologies and creating a closed-loop concrete production.

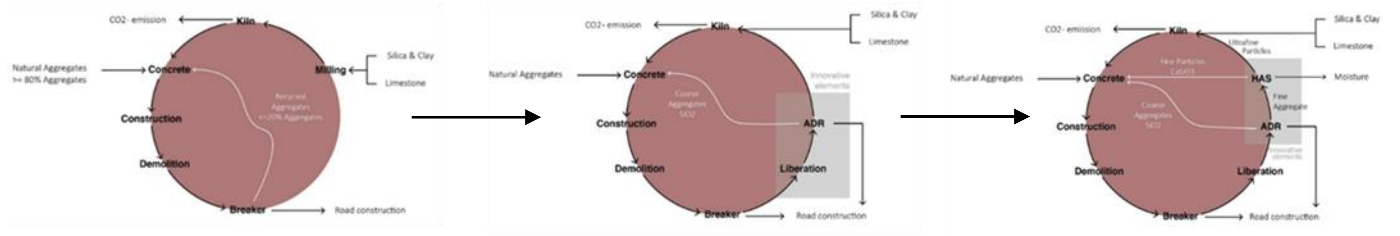


Figure 6.2 Levels of converting a conventional supply chain of concrete to a closed-loop one

IDENTIFICATION OF FEASIBLE OPTIONS FOR CIRCULAR CONCRETE MANAGEMENT

The fact that these technologies are mobile ones and can be transported, led to the proposed solution to the main research problem. The solution was extensively discussed with experts from the 'Resource and Recycling laboratory' in the Faculty of Civil Engineering at the Technical University of Delft and it was not a random selection. Accordingly, a 'Concrete-to-concrete Recycling Plant', which consists of technologies that separate and control concrete's RA, was suggested. With regard to the location of the recycling plant, the following two extreme cases were examined:

- Recycling plant is operating near the prefabricated concrete industry.
- Recycling plant is operating at the demolition site.

STAGE 3. DETAILED DESIGN

IDENTIFICATION OF THE CURRENT AND FUTURE FEASIBLE OPTIONS FOR CONCRETE PRODUCTION

In Chapter 4, the detailed design was presented. Aiming to examine the changes in the conventional supply chain in accordance with the feasible ways of concrete recycling, the examined cases are presented in the following flow chart (Figure 6.3). The location of the recycling plant and the categories of concrete production formulate six extreme cases (Table 6.1).

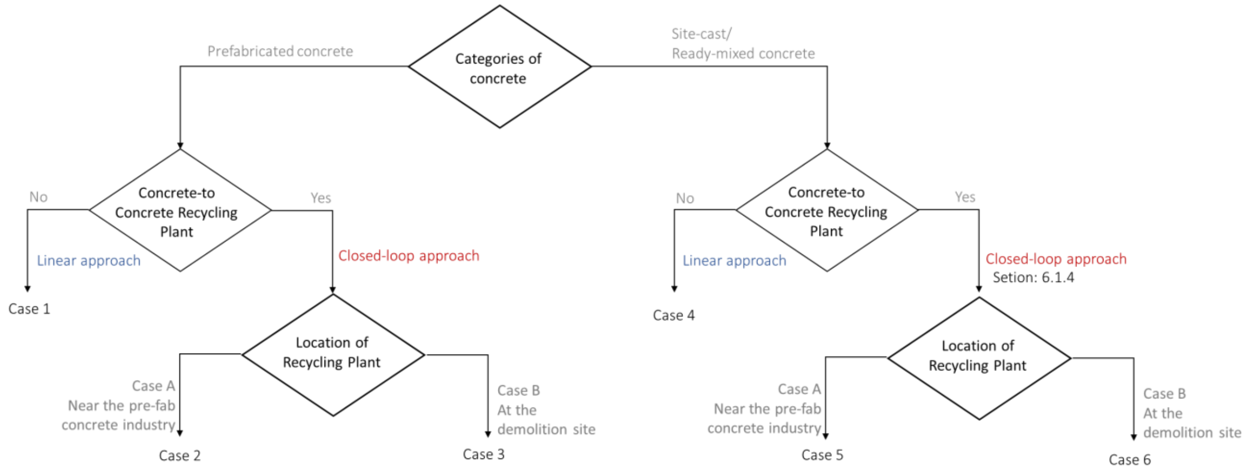


Figure 6.3 Flow chart with the developed cases

Table 6.1 *Developed cases for the possible options of concrete production*

Category of concrete production	Supply Chain approach	Analysis
Prefabricated	Conventional	Case 1: Prefabricated concrete production
	Closed-loop	Case 2: Prefabricated concrete production with a 'Concrete-to-concrete Recycling Plant' operating near prefabricated concrete industry
	Closed-loop	Case 3: Prefabricated concrete production with a 'Concrete-to-concrete Recycling Plant' operating at the demolition site
Site-case/ Ready-mixed	Conventional	Case 4: Site-cast/ Ready-mixed concrete production
	Closed-loop	Case 5: Site-cast/ Ready-mixed concrete production with a 'Concrete-to-concrete Recycling Plant' operating near mortar supplier
	Closed-loop	Case 6: Site-cast/ Ready-mixed concrete production with a 'Concrete-to-concrete Recycling Plant' operating at the demolition site

Supply Chain Mapping for each Feasible Case for Concrete Production

The supply chain mappings based on a Business Process Management approach and the SCOR Model in Level 2 and 3, set the basis for the identification of the differences among the developed scenarios. More precisely, the production of prefabricated concrete (Case1) is the only category that includes return processes in the case that the final product is not conforming to the project's specifications. Additionally, it requires more Engineer-to-order processes and therefore, more stakeholders are involved in the production process. The above-referred remarks are observed in the conventional (Case 1) as well as the closed-loop approach (Cases 2 and 3).

Concerning the closed-loop supply chain approach, the differences among the cases are described in the following Table 6.2.

Table 6.2 *Differences among cases with a 'Concrete-to-concrete Recycling Plant'*

	Closed-loop supply chain	
Critical points	**Case 2 and Case 5** The recycling plant is operating near mortar supplier or near prefabricated concrete industry	**Case 3 and Case 6** Mobile version of the recycling plant is transported at the demolition site
Absence of transportation costs	No transportation between the recycling and the mortar plant. BENEFIT Less transportation shipment between the mortar plant and the cement factory.	No transportation between the demolition site and the recycling plant. DRAWBACK Extra transportation movement to the cement factory for the shipment of ultrafine particles.
Stakeholders	BENEFIT The use of a recycling plant is done by specific stakeholders. Trustworthiness is easier to be developed among the involved actors. Additionally, the plant's transportation is not dependent on the realization of demolition and construction projects, but to the industry's performance, which is a more stable parameter.	DRAWBACK Various stakeholders can be involved in each recycling process, according to the available projects and their location.
CDW recycling	DRAWBACK The transportation of CDW depends on truck shipments. A % of CDW does not reach the plant, and waste is reusing in low-quality applications	BENEFIT CDW does not need warehousing; there is a higher chance of leveraging wastes for the production of high-value materials.
Warehousing	BENEFIT There is no inventorying after material separation. Technologies are operating at different speeds and the materials can be	DRAWBACKS After separation, the recycled materials should be inventoried either to the recycling or the concrete plant.

	used directly after the technological activities.	
	Ultrafine particles can be transported directly to the cement plant since there is an available truck (the one that has transported cement for the concrete production).	Ultrafine particles should be inventoried for a long period of time. The separation speed of HAS is really low compared to the other novel technologies.

STAGE 4. EVALUATION

In Chapter 5, the evaluation stage of the design approach was explored. A feasibility assessment was conducted and two different approaches were examined in order to clarify the proposed solution.

Initially, a calculation model for concrete recycling gathered valuable information in order to evaluate the different steps and processes that are including in the detailed design. The findings identified that the modifications in the conventional supply chain with regards to the recycling plant integration, are mostly attributed to the truck shipments and inventory. The main benefit of utilizing a ‘Concrete-to-concrete Recycling Plant’ is that the major costs refer to the transportation costs since CDW is a really low-cost input. Moreover, the geographic area of the Netherlands has the appropriate size (41,543 km^2) for materials’ transshipment around the country. From a financial point of view, despite the fact that the plant requires an investment of 1M €, mortar companies and demolition centers could collaborate and operate in terms of the CE. Furthermore, from an environmental point of view, the amount of CaO in the recycled finer fraction is similar to the amount of CaO in low-quality limestone. By taking advantage of the finer fraction, the CO_2 emissions could be reduced since a ton of recycled cement paste could save at least 500 kg of CO_2 emissions in cement production.

The design approach in Chapter 4 identified the transportation movements and led to the development of a Value Stream Mapping for the processes executed on a ‘Concrete-to-concrete Recycling Plant’. These activities constitute additional processes compared to a conventional supply chain. The selected example was a building constructed by 13,000 tons of concrete. The value-added time calculated equal to 211 days; a quite high number. Hence, it is worth mentioning that around 72% of this duration, and more specifically, 152 days, are attributed to HAS operation. Consequently, it is recognized that a huge issue in a recycling plant is the separation speed of the HAS technology.

IDENTIFICATION OF THE MOST EFFICIENT SOLUTION FOR A SUSTAINABLE WAY OF CONCRETE PRODUCTION

In respect to the closed-loop approach, the most efficient proposal for each category of concrete production was identified. Different criteria that are already analyzed, are summarized in the following Tables 6.3 and 6.4. The comparison was realized among Cases 2 and 3, as well as 5 and 6, and the most efficient option is marked with an ‘✓’. Four main critical points were distinguished based on the detailed design:

- the transportation costs and warehouse costs in terms of a financial aspect
- the % of CDW that is recycled in terms of quality

- the HAS duration in terms of time.

Table 6.3 *Criteria evaluation for a closed-loop approach in prefabricated concrete production*

	Prefabricated concrete production	
	Case 2 Prefabricated concrete production with a 'Concrete-to-concrete Recycling Plant' operating near prefabricated concrete industry	**Case 3** Prefabricated concrete production with a 'Concrete-to-concrete Recycling Plant' operating at the demolition site
Transportation costs	✓	
Warehouse costs	✓	
CDW recycling %		✓
HAS operating time	✓	

Table 6.4 *Criteria evaluation for a closed-loop approach in site-cast/ ready-mixed concrete production*

	Site-cast/ Ready-mixed concrete production	
	Case 5 Site-cast/ Ready-mixed concrete production with a 'Concrete-to-concrete Recycling Plant' operating near mortar supplier	**Case 6** Site-cast/ Ready-mixed concrete production with a 'Concrete-to-concrete Recycling Plant' operating at the demolition site
Transportation costs	✓	
Warehouse costs	✓	
CDW recycling %		✓
HAS operating time	✓	

The above results and calculations led to the conclusion that an investment in a 'Concrete-to-concrete Recycling Plant' is worth for Cases 2 and 5. Hence, *'Prefabricated concrete with a Concrete-to-concrete Recycling Plant operating near the prefabricated concrete industry'* and *'Site-cast/ Ready-mixed concrete with a Concrete-to-concrete Recycling Plant operating near the mortar plant'* are the most cost-efficient ones for each category of concrete, respectively. Fewer transportation movements are realized and the main problem of HAS' operating time has been overcome. Otherwise, improvements and research experiments are required in order to increase HAS' separation speed.

Concerning the organizational perspective, the feasibility of introducing a 'Concrete-to-concrete Recycling Plant' in the CS was assessed. The current market situation and stakeholder engagement influence impressively the implementation process of the technologies for concrete recycling into concrete production. Each industry involved in manufacturing has a different role and several actors affect accordingly the recycling expectations. Focusing on the questionnaire analysis, the stakeholders with great influence in the production process of concrete are in favor of using recycled materials. On the other hand, aggregate extractors do not support novel technologies since they will substitute part of their production.

Nonetheless, their low power in the sector constitutes the use of RA and the development of a recycling plant feasible.

STAGE 5. COMMUNICATION

The existing major obstacle is that the technologies have not been communicated sufficiently in the CS. This research aims to tackle this problem. Parts of this work will be used in handbooks which are currently developing by the 'Resource and Recycling Laboratory' in the faculty of Civil Engineering in TU Delft, in order to inform the SC for the benefits of RA in the production of concrete through a transition to a closed-loop economy. At this point, it is worth referring that this aspect influenced a lot the final structure of the report and the methodology that was followed.

To conclude, this work was developed in accordance with the 2020 WFD goal, whereupon the minimum recycling percentage of non-hazardous CDW should be at least 70% by weight. EoL concrete is known to be the heaviest component of the CDW and through recycling part of the concrete fraction of CDW into high-quality construction materials, it is possible to get closer to the above-mentioned target. Additionally, the described proposals contribute to the Netherlands' Circular Vision by 2050.

6.2 Recommendations

After the conduction of this research some recommendations regarding the developed technologies for concrete recycling and consequently, their future integration to the market are proposed:

- On a laboratory scale, more research is required concerning the exact amount of RA that can be used in concrete production. A specific percentage of RA that can guarantee a high-quality material performance should be defined for each type of cement, W/C ratio and category of concrete production.
- Time scheduling of HAS upgrades should be conducted since it is operating in a truly low speed compared to the other novel technologies in the 'Concrete-to-Concrete Recycling Plant'.
- On an industrial scale, more applications of RA different compositions should be tested. Highly organized pilot testing is mandatory since the analysis of concrete's quality is a time-consuming process; the strength of concrete should be tested after 28 days of its production aiming to check its durability.
- Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) on specific cases regarding the application of technologies ADR and HAS could bring benefits with regards to the environmental and financial assessment.
- Investigation of the relationships among construction industries, raw materials' suppliers and demolition companies should prove useful for the increase of cooperation along the supply chain.
- Efforts to increase awareness and acceptance of RA in the industry of aggregates through collective quantitative data that can convince all parts of the concrete supply chain are required.
- Examination of mortar and prefabricated concrete plant locations in the Dutch environment in order to examine possible locations for the 'Concrete-to-Concrete Recycling Plant', and bring one step further the realization of the thesis' proposals.

6.3 Reflections

This research has been initiated by the author and the first supervisor of this thesis Marcel Ludema in April 2019. The initial goal has been to develop a calculation tool regarding the supply chain and logistics concepts in the recycling of concrete and examine the feasible trade-offs based on the conventional supply chain. The initial inspiration was to come in contact with people from the constructor sector and focus on a specific case study. However, after thorough literature research, the scope of this work has been narrowed down to specific technologies that leverage EoL concrete and produce high-quality materials. These technologies are developing in the faculty of Civil Engineering in the 'Resource and Recycling Laboratory' of TU Delft. Consequently, the collaboration with professors from this department was essential for the continuance of this project. Peter Berkhout and Peter Rem found really interesting my field of exploration since more research was required in terms of supply chain management. Parts of my report was developed in accordance with a handbook that the laboratory wants to design in order to increase awareness in the CS regarding the technologies. This brought slight differences in the already developed technical parts. Moreover, while the topic was examining, exploratory findings proved necessary. At that point, questionnaires sent by e-mails to stakeholders in different industries related to concrete production. However, few answers were received compared to the total number sent. A better outcome would have been brought by conducting face-to-face interviews. Moreover, it has to be mentioned that due to the lack of a specific body of literature for technologies, more time than planned has been spent on reviewing the relevant information and many meetings were realized. Additionally, the mapping process was really time-consuming and it proved that not all of the parts which were initially developed, were finally useful for the scope of this project. If this research was re-done, less time should have been spent on the literature study of cement and concrete production as well as on construction logistic concepts and more time should be planned for conducting interviews with experts on the field in order to attain more data.

In conclusion, the results of this research can be considered to fulfill the expectations of the research goal and develop a design approach that can be a subject for future research. The field of concrete recycling is currently developing and there are a lot of aspects that require improvements.

REFERENCES

ACM. (2016). Annual Report ACM in 2016. Retrieved from https://www.acm.nl/sites/default/files/documents/2019-01/2016-acm-annual-report.pdf

Agamuthu, P. (2008). Challenges in sustainable management of construction and demolition waste. *Waste Manage,* 26 (6), 491–492.

Agapiou, A., Clausen, L. E., Flanagan, R., Norman, G., & Notman, D. (1998). The role of logistics in the materials flow control process. *Construction Management & Economics*, *16*(2), 131-137.

APICS. (2017). Supply Chain Operations Reference Model SCOR V12.0

ASTM International. (2019a). Standard Performance Specification for Hydraulic Cement. Retrieved from: https://www.astm.org/Standards/C1157

ASTM International. (2019b). Standard Specification for Expansive Hydraulic Cement. Retrieved from: https://www.astm.org/Standards/C845.htm

ASTM International. (2019c). Standard Specification for Masonry Cement. Retrieved from: https://www.astm.org/Standards/C91

Atradius. (2019). Market monitor, Focus on construction sector performance and outlook. Retrieved from: https://atradius.nl/rapport/market-monitor-construction-netherlands-2019.html

Augiseau, V., & Barles, S. (2017). Studying construction materials flows and stock: A review. *Resources, Conservation and Recycling*, *123*, 153-164.

Bakker, M., & Hu, M. (2015). Closed-loop economy: case of concrete in the Netherlands. *Delft University of Technology, Delft, Netherlands*.

Bakker, M., Di Maio, F., & Rem, P., (2013). Advances in Solid Waste Recycling and the Bridging Scenario of Land-Storage. In *2nd International Academic Symposium on Enhanced Landfill Mining*, 1–14.

Balm, S., Berden, M., Morel, M., & van Amstel, W. P. (2018). Smart construction logistics.

Bijleveld, M.M., Bergsm, G.C., van Lieshout, M. (2013). Milieu-impact van betongebruik in de Nederlandse bouw, Status quo en toetsing van verbeteropties. CE Delft, Delft.

BioIS. (2016). Resource Efficient Use of Mixed Wastes: Improving Management of Construction and Demolition Waste [WWW Document]. URL http://ec.europa.eu/environment/waste/studies/pdf/construction/Minutes.pdf

Bogers, E., Weijers, S., Postulart, R., & van Amstel, W. P. (2017). Smart construction logistics-the case of a Dutch inner city hospital and university.

Brighton, J. L., & Richards, T. E. (2010). Assess the design of lorries and quarries for aggregates transport. Report to the Minerals Industry research Organisation.

C2CA Project. (2019). Retrieved from: http://www.c2ca.eu/activities/the-recycling-process/

CBR-Lixhe. (2019). Retrieved from https://www.cbr.be/nld/cbr-lixhe

CBS, PBL, & Wageningen, UR. (2012). Vrijkomen en verwerking van afval per doelgroep, 1990-2010. (indicator 0206, versie 11, 10 september 2012). CBS, Den Haag; Planbureau voor de Leefomgeving, Den Haag/Bilthoven and Wageningen UR, Wageningen. Retrieved from www.compendiumvoordeleefomgeving.nl

Cement Composition. (2019). Retrieved from http://www.theconcreteportal.com/cem_compn.html

Cement in Belgium and the Netherlands. (2012). *Global Cement*. Retrieved from http://www.globalcement.com/magazine/articles/663-cement-in-belgium-and-the-netherlands

Christopher, M. (2005). *Logistics and Supply Chain Management: Creating Value-Adding Networks.* 3rd Edition. FT: Prentice Hall. Harlow, England UK.

Circular Economy. (2015). *Circular Construction, The Foundation under a Renewed Sector*. Retrieved from https://www.circle-economy.com/wp-content/uploads/2016/06/Circle-Economy_2015_002_Rapport_Circulair-Construction_1-21.pdf

Claisse, P. (2016). Civil engineering materials.

Connekt. (2017). Outlook City Logistics, Topsector Logistiek.

Cooper, M. C., & Ellram, L. M. (1993). Characteristics of supply chain management and the implications for purchasing and logistics strategy. The International Journal of Logistics Management, 4(2), 13-24.

Cooper, M. C., Lambert, D. M., & Pagh, J. D. (1997). Supply Chain Management: More Than A New Name For Logistics. *The International* Journal of Logistics Management, 8(1), 1-14.

Corinaldesi, V. & Moriconi, G. (2009). Behaviour of Cementitious Mortars Containing Different Kinds of Recycled Aggregate. *Construction and Building Materials*, 23, 289-294. http://dx.doi.org/10.1016/j.conbuildmat.2007.12.006

CSI. (2011). Cement sustainability Initiative – Recycling Concrete. Geneva: World Business Council for Sustainable Development.

Dakhli, Z., & Lafhaj, Z. (2018). Considering materials management in construction: An exploratory study. *Logistics*, *2*(1), 7.

Darwin, D., Dolan, C. W., & Nilson, A. H. (2016). *Design of concrete structures*. McGraw-Hill Education

De Angelis, R., Howard, M., & Miemczyk, J. (2018). Supply chain management and the circular economy: towards the circular supply chain. *Production Planning & Control*, *29*(6), 425-437.

De Angelis, R., Howard, M., & Miemczyk, J. (2018). Supply chain management and the circular economy: towards the circular supply chain. *Production Planning & Control*, *29*(6), 425-437.

De Brito, J., & Saikia, N. (2013). Recycled aggregate in concrete, green energy and technology. *London: Springer-Verlag. doi*, *10*, 978-1.

De Mulder, E, F. J., Geluk, M. C., Ritsema, I., Westerhoff, W. E. & Wong, Th. E. (2003). De ondergrond van Nederland. Wolters Noordhof (Groningen, NL), 379.

Defee, C. & Stank, T. P. (2005). Applying the strategy-structure-performance paradigm to the supply chain environment. The International Journal of Logistics Management, 16(1), 28-50.

Deloitte. (2017). *Resource Efficient Use of Mixed Wastes, Improving management of construction and demolition waste* (p.183). Final Report. Prepared for the European Commission: DG ENV.

Di Maio, F., Rem, P., Lofti, S., Serranti, S., Bonifazi, G., & Hu, M. et al. (2012). Cement and Clean Aggregates from CDW: The C2CA Project. In *27th international conference on solid waste technology and management*. Philadelphia, U.S.A., Widener University School of Engineering.

Dijkmans, T. J. A., van Merriënboer, S. A., Moolenburgh, E. A., Smit-Rietveld, C. J. C., Vos, P. M., & Waldhauer, N. (2014). *Samenwerking in Amsterdamse bouwlogistiek. Succesvolle samenwerking in bouwlogistieke ketens in Amsterdam leidt tot minder transporten en meer duurzaamheid* (No. TNO 2014 R10228). TNO.

Directive, E. C. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. *Official Journal of the European Union L*, *312*(3). http://eurlex.europa.eu/procedure/EN/201859

Dunuweera, S. P., & Rajapakse, R. M. G. (2018). Cement Types, Composition, Uses and Advantages of Nanocement, Environmental Impact on Cement Production, and Possible Solutions. *Advances in Materials Science and Engineering, 2018.*

Ekeskär, A., & Rudberg, M. (2018). Third-party logistics in construction: Perspectives from suppliers and transport providers.

ENCI. (2010). *Biomass use in the Dutch cement industry ENCI, Maastricht, The Netherlands*

ENCI. (2017). ENCI Rotterdam / IJmuiden Veiligheid en milieu, Feiten & cijfers 2017.

ENCI. (2019). Retrieved from https://www.enci.nl/nl

Energy consumption in the Netherlands. (2019). Retrieved from https://www.worlddata.info/europe/netherlands/energy-consumption.php

European Aggregates Association. (2017). *Annual Review 2016-2017.*

European Aggregates Association. (2018). *Annual Review 2017-2018.*

European Commission (2013). C2CA Report Summary. Retrieved November 21, 2014 from http://cordis.europa.eu/result/rcn/54373_en.html.

European Commission. (2016). Construction & Demolition Waste Management Protocol. Retrieved from file:///C:/Users/Kelly/Downloads/Protocol%20Ares(2016)5840668-101016.pdf

European Commission. (2019). Retrieved from: https://cordis.europa.eu/project/rcn/97549/factsheet/en

European Committee For Standardization. (2000). *European Standard EN 197-1 (Cement - Part 1: Composition, specifications and conformity criteria for common cements)*. Retrieved from http://www.rucem.ru/yabbfiles/Attachments/EN-197-1.pdf

Fang, Y., & Ng, S. T. (2011). Applying activity-based costing approach for construction logistics cost analysis. *Construction Innovation*, *11*(3), 259-281.

Gholampour, A., Gandomi, A., & Ozbakkaloglu, T. (2017). New formulations for mechanical properties of recycled aggregate concrete using gene expression programming. *Construction And Building Materials*, *130*, 122-145. doi: 10.1016/j.conbuildmat.2016.10.114

Gibbs, M.J., Soyka, P., Conneely, D. and Kruger, M. (2000). CO_2 Emissions from Cement Production. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.

Government of the Netherlands. (2017). *National Agreement on the Circular Economy, Letter of intent to develop transition agendas for the Circular Economy together*. Retrieved from http://www.government.nl/circular-economy

Green Deal Beton wordt concreet. (2019). Retrieved from https://mvonederland.nl/nieuws/green-deal-beton-wordt-concreet

Greenspec. (2019). Concrete: Cement Substitutes. Retrieved from: http://www.greenspec.co.uk/building-design/concrete-cement-substitutes/)

Habert, G. (2014). Assessing the environmental impact of conventional and ‘green’cement production. In *Eco-efficient Construction and Building Materials* (pp. 199-238). Woodhead Publishing.

Harland, C. M. (1996). Supply Chain Management: Relationships, Chains and Networks. British Journal of Management, 7(1), 63-80.

Hines, P., Lamming, R., Jones, D., Cousins, P., & Rich, N. (2000). *Value stream management: Strategy and excellence in the supply chain*. Financial Times Prentice Hall.

Holgado, M., Morgan, D., & Evans, S. (2016). Exploring the scope of industrial symbiosis: Implications for practitioners. In: Setchi, R., Howlett, R., Liu, Y., and Theobald, P. (Eds.), Sustainable Design and Manufacturing, 169-178.

Holgado, M., Morgan, D., & Evans, S. (2016). Exploring the scope of industrial symbiosis: Implications for practitioners. In: Setchi, R., Howlett, R., Liu, Y., and Theobald, P. (Eds.). *Sustainable Design and Manufacturing*, 169-178.

Home | C2CA. (2019). Retrieved 11 September 2019, from http://www.c2ca.eu/

Home | HISER Project. (2019). Retrieved 11 September 2019, from http://www.hiserproject.eu/

Home | VEEP Project. (2019). Retrieved 11 September 2019, from http://www.veep-project.eu/.

Hu, M., Kleijn, R., Bozhilova-Kisheva, K. P., & Di Maio, F. (2013). An approach to LCSA: The case of concrete recycling. *International Journal of Life Cycle Assessment,* 18(9), 1793–1803.

Hu, M., Kleijn, R., Bozhilova-Kisheva, K. P., & Di Maio, F. (2013). An approach to LCSA: the case of concrete recycling. *The International Journal of Life Cycle Assessment*, *18*(9), 1793-1803.

Hult, G. T. M., Ketchen, D. J., & Arrfelt, M. (2007). Strategic Supply Chain Management: Improving Performance Through a Culture of Competitiveness and Knowledge Development. Strategic Management Journal, 28(10), 1035-1052.

Ike, P. (2007). Minerals Planning in The Netherlands compared to the UK. *BHM Berg-und Hüttenmännische Monatshefte*, *152*(12), 403-409.

Kim, J-J, Rigdon, B., & Graves, J. (1998). Sustainable architecture module: qualities, use, and examples of sustainable building materials. *National Pollution Prevention Center for Higher Education*, Ann Arbor, United States.

Kleijn, R. (2012). PhD thesis: Materials and energy: a story of linkages. Netherlands, Leiden University, p.135

Kolkman, S., Molenaar, P. & van Berchum, M. (2008). Business case TOP-bouw: Logistiek coordinator. Amsterdam.

Korre, A., & Durucan, S. (2009). Life Cycle Assessment of Aggregates, EVA025–Final Report: Aggregates Industry Life Cycle Assessment Model: Modelling Tools and Case Studies. *Waste and Resources Action Programme, Oxon*.

Krutwagen, B., & van Broekhuizen, F. (2010). Milieuanalyses Bouw- en sloopafval. IVAM.

Kubbinga, B., Bamberger, M., van Noort, E., van den Reek, D., Blok, M., & Roerners, G. (2018). *A FRAMEWORK FOR CIRCULAR BUILDINGS, Indicators for possible Inclusion In BREEAM*, 20.

Kumar, S., & Malegeant, P. (2006). Strategic Alliance in a Closed-Loop Supply Chain, A Case of Manufacturer and Eco-Non-Profit Organization. *Technovation*, 26(10), 1127- 1135.

Li, J. (2015). Wastes could be resources and cities could be mines. *Waste Manage*, 33 (4), 301–302.

Loomba, A. P., & Nakashima, K. (2012). Enhancing value in reverse supply chains by sorting before product recovery. Production Planning & Control, 23(2-3), 205-215.

Lotfi, S. (2016). C2CA Concrete Recycling Process, From Development to Demonstration.

Lotfi, S., & Rem, P. (2016). Recycling of end of life concrete fines into hardened cement and clean sand. *Journal of Environmental Protection*, *7*(06), 934

Lotfi, S., Deja, J., Rem, P. C., Mroz, R., Van Roekel, E., & Van der Stelt, H. (2013). A mechanical process for in situ recycling of Eol concrete.

Lotfi, S., Deja, J., Rem, P. C., Mroz, R., Van Roekel, E., & Van der Stelt, H. (2013). A mechanical process for in situ recycling of EoL concrete. In *Proceedings of the SB 13 Singapore "Realising Sustainability in the Tropics", Singapore, 9-10 September 2013*. SB13 Organisers.

Lotfi, S., Deja, J., Rem, P., Mróz, R., van Roekel, E. and van der Stelt, H. (2014) Mechanical Recycling of EOL Concrete into High-Grade Aggregates. *Resources*, *Conservation and Recycling*, 87, 117-125. http://dx.doi.org/10.1016/j.resconrec.2014.03.010

Lotfi, S., Deja, J., Rem, P., Mróz, R., van Roekel, E. and van der Stelt, H. (2014) Mechanical Recycling of EOL Concrete into High-Grade Aggregates. *Resources*, *Conservation and Recycling*, 87, 117-125. http://dx.doi.org/10.1016/j.resconrec.2014.03.010

Lotfi, S., Eggimann, M., Wagner, E., Mróz, R. and Deja, J. (2015) Performance of Recycled Aggregate Concrete Based on a New Concrete Recycling Technology. *Construction and Building Materials*, 95, 243-256. http://dx.doi.org/10.1016/j.conbuildmat.2015.07.021

Lotfi, S., Rem, P., Di Maio, F., Teklay, A., Hu, M., van Roekel, E., & van der Stelt, H. (2017). Closing the loop of EOL concrete.

Lotfi, S., Rem, P., Di Maio, F., Teklay, A., Hu, M., van Roekel, E., & van der Stelt, H. (2017). Closing the loop of EOL concrete.

Ludema, M. (2015). Bouwlogistieke hub, zin of onzin?, Proceedings Vervoerslogistieke Werkdagen. Breda.

Lundesjö, G. (ed.) 2015. Supply chain management and logistics in construction - delivering tomorrow's built environment. Kogan Page Limited.

Meijer, F., Itard, L., & Sunikka-Blank, M. (2009). Comparing European residential building stocks: performance, renovation and policy opportunities. *Building Research & Information,* 37(5–6), 533–551.

Mendelow, A. (1991). Stakeholder Mapping. *Proceedings of the 2nd International Conference on Information Systems, Cambridge, MA*.

Min, W., & Pheng, L. S. (2006). EOQ, JIT and fixed costs in the ready-mixed concrete industry. *International Journal of Production Economics*, *102*(1), 167-180.

Moore, K. (2008). Value mapping framework involving stakeholders for supply chain improvement when implementing information technology projects.

Müller, D. B. (2006). Stock dynamics for forecasting material flows – case study for housing in The Netherlands. *Ecological Economics*, *59*(1), 142-156.

Neville, A. (2012). *Properties of concrete*. Harlow: Pearson Education.

Pacheco-Torgal, F. (2013). Introduction to the recycling of construction and demolition waste (CDW). In *Handbook of recycled concrete and demolition waste* (pp. 1-6). Woodhead Publishing.

Pacheco-Torgal, F., Tam, V., Labrincha, J., Ding, Y. and de Brito, J. (2013) Handbook of Recycled Concrete and Demolition Waste. Elsevier, UK. http://dx.doi.org/10.1533/9780857096906

Papaprokopiou, D. (2010). An application of construction logistics analysis: The case of the new Delft train station and City Hall.

Paul, S. C., Van Zijl, G. P. A. G. (2012). Strength of recycled aggregate concrete for structural uses. Conference proceeding of concrete repair, rehabilitation and retrofitting III, South Africa.

Porter, M. E. (1979). How Competitive Forces Shape Strategy. Harvard Business Review 57(2).137-145

Porter, M. E. (2008). The Five Competitive Forces That Shape Strategy, Boston MA: Harvard Business Review, Harvard Business Publishing.

Quak, H. J., Klerks, S. A. W., Aa, S., de Ree, D. A., van Amstel, W. P., & Merriënboer, S. A. (2011). *Bouwlogistieke oplossingen voor binnenstedelijk bouwen*. Delft: TNO.

Rao, A., Jha, K. N., Misra, S. (2007). Use of aggregates from recycled construction and demolition waste in concrete. *Resources*, *Conservation and Recycling*, 50:71–81.

Rem Peter. (2019). Interview.

Rother, M., & Shook, J. (2003). *Learning to see: Value Stream Mapping to Add Value and Eliminate Muda*. Cambridge, Mass.: Lean Enterprise Institute.

Rother, M., & Shook, J. (2003). *Learning to see: Value Stream Mapping to Add Value and Eliminate Muda*. Cambridge, Mass.: Lean Enterprise Institute.

Sand, gravel and clay extraction | TNO. (2019). Retrieved from https://www.tno.nl/en/focus-areas/ecn-part-of-tno/roadmaps/geological-survey-of-the-netherlands/geological-survey-of-the-netherlands/sand-gravel-and-clay-extraction/

SCOR Supply Chain Operations Reference Model | SCOR Framework | APICS. (2018). Retrieved from https://www.apics.org/apics-for-business/frameworks/scor

Segeren, D. (2010). Logistieke centra in de bouwnijverheid. Eindhoven: Eindhoven University of Technology.

Segerstedt, A., & Olofsson, T. (2010). Supply chains in the construction industry. *Supply chain management: an international journal*, *15*(5), 347-353.

Shi, C., Jiménez, A. F., & Palomo, A. (2011). New cements for the 21st century: the pursuit of an alternative to Portland cement. Cement and Concrete Research, 41(7), 750-763.

SmartCrusher bv - Concrete recycling - c2c. (2019). Retrieved from https://www.slimbreker.nl/smartcrusher.html

Sobotka, A., Sagan, J., Baranowska, M., & Mazur, E. (2017). Management of reverse logistics supply chains in construction projects. *Procedia engineering*, *208*, 151-159.

Sobotka, A., Sagan, J., Baranowska, M., & Mazur, E. (2017). Management of reverse logistics supply chains in construction projects. *Procedia engineering*, *208*, 151-159.

Susskind, L., McKearnan, S., & Thomas-Larmer, J. (1999). *The consensus building handbook*. Thousand Oaks, Calif: SAGE.

Tavakoli, D., Heidari, A., & Karimian, M. (2013). Properties of concretes produced with waste ceramic tile aggregate. *Asian Journal of Civil Engineering*, *14*(3), 369–382. https://doi.org/10.1016/j.cemconres.2003.12.019

Tavakoli, M., & Soroushian, P. (1996). Strengths of recycled aggregate concrete made using field-demolished concrete as aggregate. *Materials Journal*. 93(2), 178-181.

Taylor, G. D. (2000). *Materials in Construction – An introduction.* 3rd Edition Publ. Longman. UK.

TfL. (2008). *London Construction Consolidation Center.* Transport for London.

The Ministry of Infrastructure and the Environment & the Ministry of Economic Affairs. (2016). *A Circular Economy in the Netherlands* (pp. 58-62). Retrieved from http://www.government.nl/circular-economy

TLB. (2010). *Construction Industry Logistics benefit from Environmental Concerns.* The Logistics Business.

Tommelein, I. D., & Li, A. (1999, July). Just-in-time concrete delivery: mapping alternatives for vertical supply chain integration. In *Proceedings IGLC* (Vol. 7, p. 97).

Tripathi, S. (2015). Supply Chain - Logistical Problem & Solutions in Cement Distribution. Retrived from https://www.linkedin.com/pulse/supply-chain-3-2-logistical-problem-solutions-cement/

U.S. Geological Survey (2007). Mineral commodity summaries 2007: U.S. Geological Survey, 195.

Ufemat. (2008). Vision on sustainable logistics for building materials. Retrieved from: https://balance-result.nl/.../vision_on_sustainable_logistics_for_building_materials.pdf

Van Amstel, W. P. (2015). Lectorale rede city logistics. Amsterdam: AUAS.

Van der Meulen, M. J., Van Gessel, S. F., & Veldkamp, J. G. (2005). Aggregate resources in the Netherlands. *Netherlands Journal of Geosciences*, *84*(4), 379-387.

Van Goor, A. R., van Amstel, M. J. P. & van Amstel, W. P. (2014). Fysieke distributie: werken aan toegevoegde waarde. Houten: Noordhoff.

Van Goor, A. R., van Amstel, M. J. P., & van Amstel, W. P. (2003). *European distribution and supply chain logistics*. Groningen: Stenfert Kroese.

Van Lieshout, M., M. (2015). Update Prioritering handelings-perspectieven verduurzaming betonketen 2015. CE Delft report.

Vidalakis, C., Tookey, J. E., & Sommerville, J. (2011). Logistics simulation modelling across construction supply chains. *Construction innovation*, *11*(2), 212-228.

Vilasini, N., & Gamage, J. R. (2010). Implementing value stream mapping tool in the construction industry. In *International Research Conference on Sustainability in Built Environment* (pp. 256-265).

Wassink, J. (2017). The last step in concrete recycling. Retrieved from https://www.delta.tudelft.nl/article/last-step-concrete-recycling

Weidema, B., Hischier, R., Althaus, H.J., Bauer, C., Doka, G., Dones, R. and Wernet, G. (2012) Code of Practice. Final Report Ecoinvent Data v2. 1 No. 2. Swiss Centre for Life Cycle Inventories, Duebendorf.

Whitlock, K., Abanda, F. H., Manjia, M. B., Pettang, C., & Nkeng, G. E. (2018). BIM for Construction Site Logistics Management. *Journal of Engineering, Project, and Production Management*, *8*(1), 47.

Wilson, A. (1993). Cement and Concrete: Environmental considerations. *Environmental Building News*, 2(2), 1-11.

Zuñiga, R., Wuest, T., & Thoben, K. D. (2015). Comparing mining and manufacturing supply chain processes: challenges and requirements. *Production Planning & Control*, *26*(2), 81-96.

Media

Types of Cement. (2019). Retrieved from https://www.youtube.com/watch?v=cApoqFALh8s&t=133s

Appendix A

Main components of Portland Cement and their properties (Taylor, 2000)

Shorthand form	*Formula*	*Properties*
C_3S - Tricalcium silicate	$3CaO.SiO_2$	• Rapid strength development • Responsible for early cement strength (e.g. 7 days)
C_2S - Dicalcium silicate	$2CaO.SiO_2$	• Slow development of strength • Responsible for the ultimate strength of cement
C_3A - Tricalcium aluminate	3CaO.Al2O3	• Rapid hydration (controlled by the presence of gypsum)
C_4AF - Tetracalcium aluminoferrite	$4CaO.\ Al_2O_3.Fe_2O_3$	• Small contribution to coagulation or strength • Responsible for the gray color of the cement

Appendix B

27 types of cement based on EN 197-1 (European Committee for Standardization, 2000)

Main Types	Notation of the 27 products (types of common cement)		Composition (% by mass)										
			Main constituents										**Minor additional constituents**
			Clinker (K)	Blast furnace slag (S)	Silica flour (D)	Natural pozzolana (P)	Natural calcined pozzolana (Q)	Siliceous fly ash (V)	Calcareous fly ash (W)	Burnt shale (T)	Limestone (L)	Limestone (LL)	
CEM I	Portland cement	CEM I	95-100	-	-	-	-	-	-	-	-	-	0-5
CEM II	Portland cement with blast furnace slag	CEM II/A-S	80-94	6-20	-	-	-	-	-	-	-	-	0-5
		CEM II/B-S	65-79	21-35	-	-	-	-	-	-	-	-	0-5
	Portland cement with silica flour	CEM II/A-D	90-94	-	6-10	-	-	-	-	-	-	-	0-5
	Portland cement with pozzolana	CEM II/A-P	80-94	-	-	6-20	-	-	-	-	-	-	0-5
		CEM II/B-P	65-79	-	-	21-35	-	-	-	-	-	-	0-5
		CEM II/A-Q	80-94	-	-	-	6-20	-	-	-	-	-	0-5
		CEM II/B-Q	65-79	-	-	-	21-35	-	-	-	-	-	0-5
	Portland cement with fly ash	CEM II/A-P	80-94	-	-	-	-	6-20	-	-	-	-	0-5
		CEM II/B-V	65-79	-	-	-	-	21-35	-	-	-	-	0-5
		CEM II/A-W	80-94	-	-	-	-	-	6-20	-	-	-	0-5
		CEM II/B-W	65-79	-	-	-	-	-	21-35	-	-	-	0-5

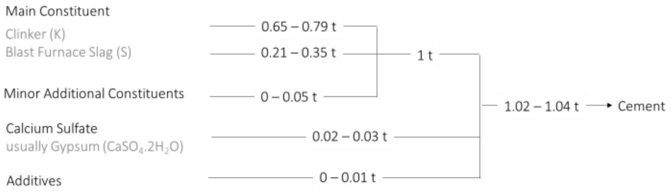
	Portland cement with burnt shale	CEM II/ A-T	80-94	-	-	-	-	-	-	6-20	-	-	0-5
		CEM II/ B-T	65-79	-	-	-	-	-	-	21-35	-	-	0-5
	Portland cement with limestone	CEM II/ A-L	80-94	-	-	-	-	-	-	-	6-20	-	0-5
		CEM II/ B-L	65-79	-	-	-	-	-	-	-	21-35	-	0-5
		CEM II/ A-LL	80-94	-	-	-	-	-	-	-	-	6-20	0-5
		CEM II/ B-LL	65-79	-	-	-	-	-	-	-	-	21-35	0-5
	Portland cement – composite	CEM II/ A-M	80-94	< ----------------------------------6-20---------------------------------- >									0-5
		CEM II/ B-M	65-79	< ----------------------------------21-35---------------------------------- >									0-5
CEM III	Cement with slag	CEM III/ A	35-64	36-65									0-5
		CEM III/ B	20-34	66-80	-	-	-	-	-	-	-	-	0-5
		CEM III/ C	5-19	81-95	-	-	-	-	-	-	-	-	0-5
CEM IV	Cement with pozzolana	CEM IV/ A	65-89	-	< -----------------11-35----------------- >					-	-	-	0-5
		CEM IV/ B	45-64	-	< -----------------36-55----------------- >					-	-	-	0-5
CEM V	Composite cement	CEM V/ A	40-64	18-30	-	< ---------18-30--------- >			-	-	-	-	0-5
	Composite cement	CEM V/ B	20-38	31-50	-	< ---------31-50--------- >			-	-	-	-	0-5

Appendix C

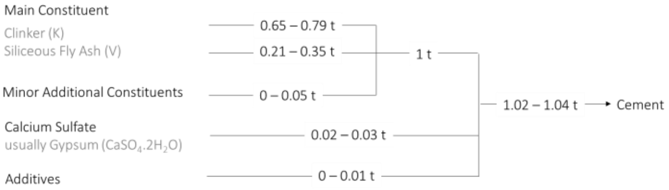
Material flows (in tons) for the different types of cement which are produced in the Netherlands

The following Figures constitute part to the calculation model of Chapter 7 (Sheet 1).

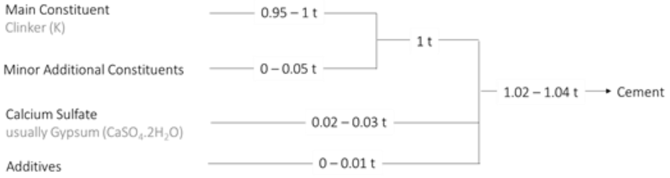
Portland Composite Cement CEM II / B-S



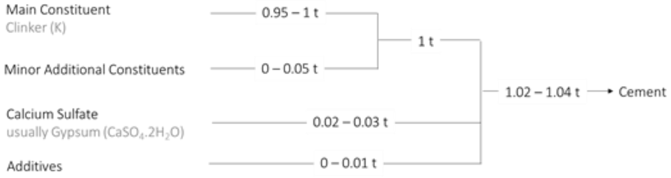
Portland Composite Cement CEM II / B-V



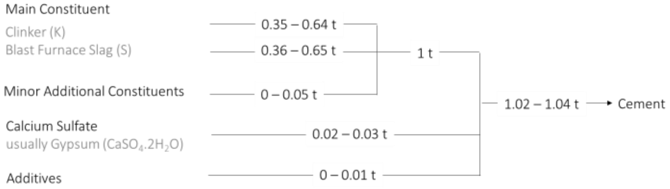
Portland Cement CEM I



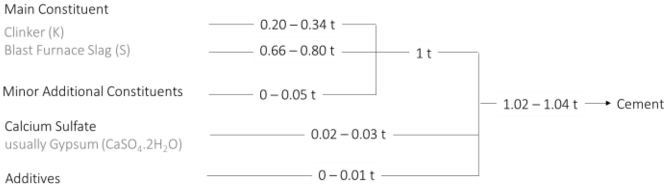
Portland Cement CEM I



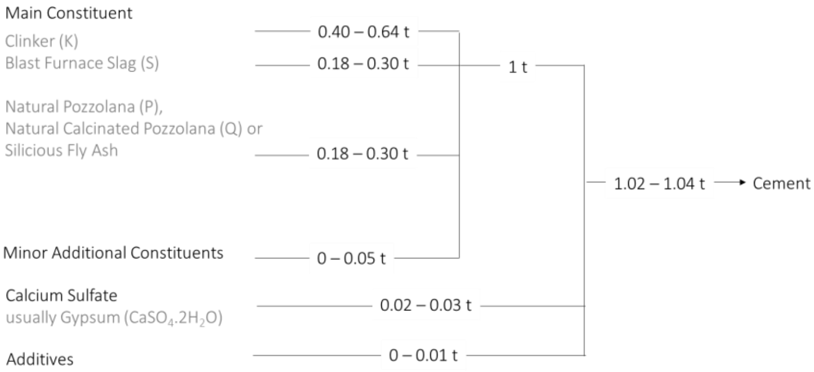
Blast Furnace Cement CEM III / A



Blast Furnace Cement CEM III / B



Composite Cement CEM V / A (SV)



Appendix D

Survey Questionnaire regarding the recycling of concrete

This survey is part of the thesis project of the MSc student Kelly Kalioupi in the "Management of Technology" Program in TU Delft.

Please complete the following questionnaire.

Feel free not to answer questions that will make you feel inconvenient or are not related to the company's role in the supply chain of concrete.

Personal Details

Name	
Job Position	
Company's Name	

PART I

Circular Vision in the Netherlands

1. Are you familiar with the vision of "Non-hazardous Construction and Demolition Waste by 2020"?

☐ Very ☐ Slightly ☐ Not at all

2. Is the company that you work in, operating in accordance with the "Circular Economy Vision in the Netherlands by 2050"?

☐ Yes ☐ No ☐ I don't know / I don't want to answer

3. Which is your company's vision in terms of Circular Economy?

Concrete Recycling & Technologies

4. Are you in favour of using recycled aggregates for the production of concrete? If yes, what type of aggregates, at which percentage and for which purpose do you use them?

5. Are you familiar with any of the following developed technologies for concrete's material separation?

☐ SmartCrusher (SC)
☐ Advanced Dry Recovery (ADR)
☐ Heating Air Classification System (HAS)

These technologies target the separation of concrete into its raw materials in order to reuse them in the construction sector as high-quality materials.

PART II

Technologies

6. Would you invest in the above-referred technologies, if they ensure high-quality materials for concrete production?

☐ Extremely ☐ Very ☐ Moderately ☐ Slightly ☐ Never

7. Would you prefer materials from the separation process instead of virgin ones?

☐ Extremely ☐ Very ☐ Moderately ☐ Slightly ☐ Never

8. Do you believe that materials from the separation process could lead to high-quality results?

☐ Extremely ☐ Very ☐ Moderately ☐ Slightly ☐ Never

Transportation & Logistics

9. Do you use imported materials?

☐ Extremely ☐ Very ☐ Moderately ☐ Slightly ☐ Never

10. Do you perceive that the above-referred technologies can minimize the transportation cost due to the fact that they are mobile ones?

☐ Extremely ☐ Very ☐ Moderately ☐ Slightly ☐ Never

11. Do you cooperate with other companies concerning your/their wastes and their exploitation?

☐ Extremely ☐ Very ☐ Moderately ☐ Slightly ☐ Never

12. Do you use a Just-in-time delivery system to the building site, a delivery management system or IT support for the transportation of materials?

☐ Extremely ☐ Very ☐ Moderately ☐ Slightly ☐ Never

13. Do you cooperate with Construction Consolidation Centres?

☐ Extremely ☐ Very ☐ Moderately ☐ Slightly ☐ Never

14. Do you cooperate with Construction Logistic Coordinators?

☐ Extremely ☐ Very ☐ Moderately ☐ Slightly ☐ Never

15. Do you use Building Information Modelling (BIM) as a digital tool?

☐ Extremely ☐ Very ☐ Moderately ☐ Slightly ☐ Never

16. From how far and in which way do you source *aggregates, recycled aggregates and cement* for the concrete production or the construction of a building?

Appendix E

List of companies related to the construction sector

The following table contains 76 companies related to the construction sector from different industries which are related to concrete production.

Company’s role in the value chain of concrete	Company’s Name	
Aggregates – Cascade Raw material supplier	Dekker Grondstoffen B.V.	Roelofs Zandwinning
	K3Delta	Sagrex – Heidelberg Cement Group
	Kuypers Kessel	Smals Bouwgrondstoffen B.V.
	L'Ortye Zand en Grindwinning	Terraq
	Netterden Zan en Grind B.V.	Teunesen Zand en Grind B.V.
	Niba productie B.V.	Van Nieuwpoort Bouwgrondstoffen
Cement producer Raw material supplier	ENCI B.V.- HeidelbergCement Benelux	Ecocem Benelux B.V.
Concrete producers	Atsma Sierbeton B.V.	Meglio Stone Art
	B.V. De Meteoor	MicroBeton B.V.
	Bakker Betonwaren V.O.F.	Molenaar Betonindustrie B.V.
	Beton- en Steenindustrie "De Aam" B.V.	Mombarg Betonelementen B.V.
	Betonfabriek Vrijenban B.V.	Monier B.V.
	Betonindustrie Efko B.V.	Nimis Exclusieve Betonwaren
	Betonwarenindustrie De Adelaar B.V.	Noppert Beton B.V.
	Bosma Beton B.V.	Prefab Beton Heerenveen B.V.
	BS Beton B.V.	Prefab Beton Soest B.V.
	Clement Beton Weert B.V.	Prefunko B.V.
	De Jong Beton B.V.	PSD Beton
	De Jong's Betonbedrijf B.V.	Romein
	Dyckerhoff Basal	Schellevis Beton B.V.
	Fydro B.V.	Spaansen Bouwsystemen B.V. - Harlingen
	Gebr. Lensink Betonwaren	Steenhuis Beton B.V.
	Haitsma Beton B.V.	Stoter Beton B.V.
	Heesakkers Beton B.V.	Strukton Prefab Beton B.V.
	Holcim Prefab Wanden B.V.	Struyk Verwo Aqua B.V.
	Hop Prefab B.V.	TBS Soest B.V.
	HPSchroefpaal Systems B.V.	Thijssen - den Brok BV
	J. Duister Betonprodukten B.V.	Vlassak Betonbedrijf B.V.
	Jannink Beton	Waco
	Lammers Beton B.V.	Wester Beton B.V.
	Mebin B.V.	Zoontjens Beton B.V.

Construction Companies	BAM	Van Der Spek B.V.
	Strukton	
Architects & Designers	Turntoo	VBI B.V.
Dutch Government	Gemeente of different cities	
Recycling companies	Beelen	REPAiR
Research	BAMB	Metabolic
Network Organization	New Horizon – Urban Mining	

Appendix F

Processes of SCOR Model in Level 2

sP PLAN	**sP1** – Plan Supply Chain **sP2** – Plan Source **sP3** – Plan Make **sP4** – Plan Deliver **sP5 –** Plan Return
sS SOURCE	**sS1** – Source Stocked Product **sS2** – Source Make-to-Order Product **sS3** – Source Engineer-to-Order Product
sM MAKE	**sM1** – Make-to-Stock **sM2** – Make-to-Order **sM3** – Engineer-to-Order
sD DELIVER	**sD1** – Deliver Stocked Product **sD2** – Deliver Make-to-Order Product **sD3** – Deliver Engineer-to-Order Product **sD4** – Deliver Retail Product
sR RETURN	**sSR1** – Source Return Defective Product **sSR2** - Source Return MRO Product **sSR3** – Source Return Excess Product
	sDR1 – Deliver Return Defective Product **sDR2** – Deliver Return MRO Product **sDR3** – Deliver Return Excess Product

Appendix G

Processes of SCOR Model in Level 3

sP1 – Plan Supply Chain	**sP1.1**: Identify, Prioritize, and Aggregate Supply Chain Requirements **sP1.2**: Identify, Prioritize, and Aggregate Supply Chain Resources **sP1.3**: Balance Supply Chain Resources with Supply Chain Requirements **sP1.4**: Establish and Communicate Supply Chain Plans
sP2 – Plan Source	**sP2.1**: Identify, Prioritize, and Aggregate Product Requirements **sP2.2**: Identify, Assess, and Aggregate Product Resources **sP2.3**: Balance Product Resources with Product Requirements **sP2.4**: Establish Sourcing Plans
sP3 – Plan Make	**sP3.1**: Identify, Prioritize, and Aggregate Production Requirements **sP3.2**: Identify, Assess, and Aggregate Production Resources **sP3.3**: Balance Production Resources with Production Requirements **sP3.4**: Establish Production Plans
sP4 – Plan Deliver	**sP4.1**: Identify, Prioritize, and Aggregate Delivery Requirements **sP4.2**: Identify, Assess, and Aggregate Delivery Resources **sP4.3**: Balance Delivery Resources with Delivery Requirements **sP4.4**: Establish Delivery Plans
sP5 – Plan Return	**sP5.1**: Identify, Prioritize, and Aggregate Return Requirements **sP5.2**: Identify, Assess, and Aggregate Return Resources sP5.3: Balance Return Resources with Return Requirements sP5.4: Establish and Communicate Return Plans
sS1 – Source Stocked Product	sS1.1: Schedule Product Deliveries sS1.2: Receive Product sS1.3: Verify Product sS1.4: Transfer Product sS1.5: Authorize Supplier Payment
sS2 – Source Make-to-Order Product	sS2.1: Schedule Product Deliveries sS2.2: Receive Product sS2.3: Verify Product sS2.4: Transfer Product sS2.5: Authorize Supplier Payment

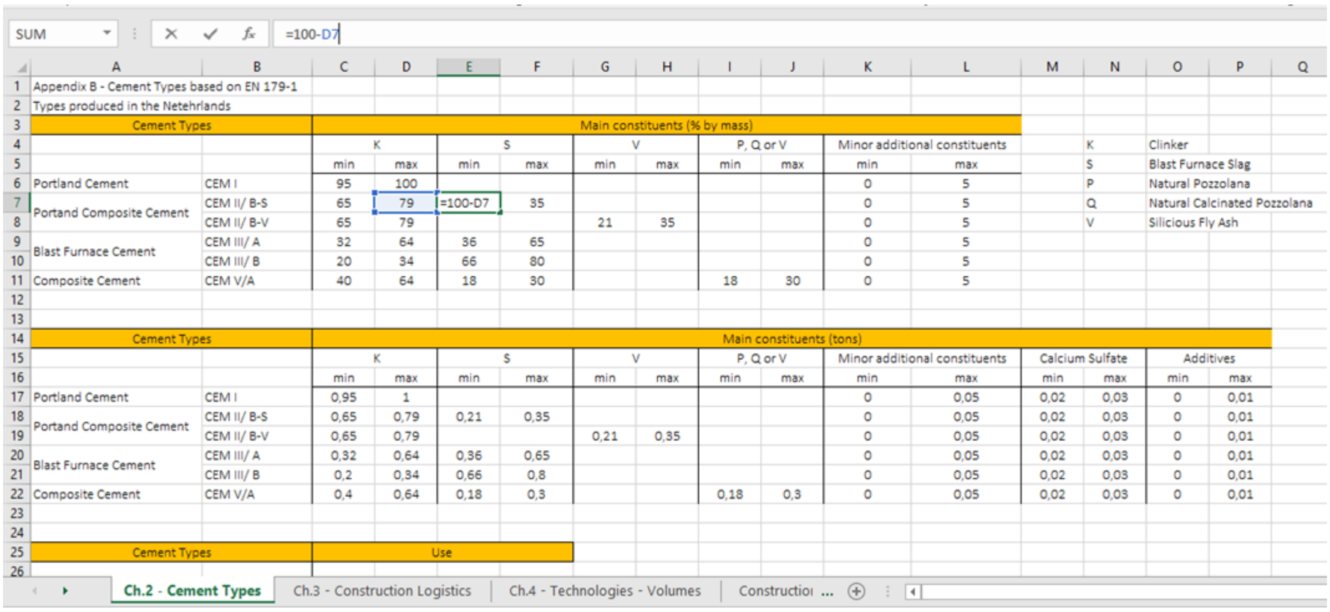
sS3 – Source Engineer-to-Order Product	sS3.1: Identify Sources of Supply sS3.2: Select Final Supplier(s) and Negotiate sS3.3: Schedule Product Deliveries sS3.4: Receive Product sS3.5: Verify Product sS3.6: Transfer Product sS3.7: Authorize Supplier Payment
sM1 – Make-to-Stock	sM1.1: Schedule Production Activities sM1.2: Issue Product sM1.3: Produce and Test sM1.4: Package sM1.5: Stage Product sM1.6: Release Product to Deliver sM1.7: Waste Disposal
sM2 – Make-to-Order	sM2.1: Schedule Production Activities sM2.2: Issue Product sM2.3: Produce and Test sM2.4: Package sM2.5: Stage Finished Product sM2.6: Release Finished Product to Deliver sM2.7: Waste Disposal
sM3 – Engineer-to-Order	sM3.1: Finalize Production Engineering sM3.2: Schedule Production Activities sM3.3: Issue Product sM3.4: Produce and Test sM3.5: Package sM3.6: Stage Finished Product sM3.7: Release Product to Deliver sM3.8: Waste Disposal
sD1 – Deliver Stocked Product	sD1.1: Process Inquiry and Quote sD1.2: Receive, Enter, and Validate Order sD1.3: Reserve Inventory and Determine Delivery Date sD1.4: Consolidate Orders sD1.5: Build Loads sD1.6: Route Shipments sD1.7: Select Carriers and Rate Shipments sD1.8: Receive Product from Source or Make sD1.9: Pick Product sD1.10: Pack Product sD1.11: Load Vehicle and Generate Shipping Docs sD1.12: Ship Product sD1.13: Receive and Verify Product by Customer

	sD1.14: Install Product sD1.15: Invoice
sD2 – Deliver Make-to-Order Product	sD2.1: Process Inquiry and Quote sD2.2: Receive, Configure, Enter, and Validate Order sD2.3: Reserve Inventory and Determine Delivery Date sD2.4: Consolidate Orders sD2.5: Build Loads sD2.6: Route Shipments sD2.7: Select Carriers and Rate Shipments sD2.8: Receive Product from Source or Make sD2.9: Pick Product sD2.10: Pack Product sD2.11: Load Product and Generate Shipping Docs sD2.12: Ship Product sD2.13: Receive and Verify Product by Customer sD2.14: Install Product sD2.15: Invoice
sD3 – Deliver Engineer-to-Order Product	sD3.1: Obtain and Respond to RFP/RFQ sD3.2: Negotiate and Receive Contract sD3.3: Enter Order, Commit Resources, and Launch Program sD3.4: Schedule Installation sD3.5: Build Loads sD3.6: Route Shipments sD3.7: Select Carriers and Rate Shipments sD3.8: Receive Product from Source or Make sD3.9: Pick Product sD3.10: Pack Product sD3.11: Load Product and Generate Shipping Docs sD3.12: Ship Product sD3.13: Receive and Verify Product by Customer sD3.14: Install Product sD3.15: Invoice
sD4 – Deliver Retail Product	sD4.1: Generate Stocking Schedule sD4.2: Receive Product at the Store sD4.3: Pick Product from Backroom sD4.4: Stock Shelf sD4.5: Fill Shopping Cart sD4.6: Checkout sD4.7: Deliver and/or Install
sSR1 – Source Return Defective Product	sSR1.1: Identify Defective Product Condition sSR1.2: Disposition Defective Product sSR1.3: Request Defective Product Return Authorization sSR1.4: Schedule Defective Product Shipment sSR1.5: Return Defective Product

sSR2 - Source Return MRO Product	sSR2.1: Identify MRO Product Condition sSR2.2: Disposition MRO Product sSR2.3: Request MRO Return Authorization sSR2.4: Schedule MRO Shipment sSR2.5: Return MRO Product
sSR3 – Source Return Excess Product	sSR3.1: Identify Excess Product Condition sSR3.2: Disposition Excess Product sSR3.3: Request Excess Product Return Authorization sSR3.4: Schedule Excess Product Shipment sSR3.5: Return Excess Product
sDR1 **– Deliver Return Defective Product**	sDR1.1: Authorize Defective Product Return sDR1.2: Schedule Defective Return Receipt sDR1.3: Receive Defective Product (Includes Verify) sDR1.4: Transfer Defective Product
sDR2 **– Deliver Return MRO Product**	sDR2.1: Authorize MRO Product Return sDR2.2: Schedule MRO Return Receipt sDR2.3: Receive MRO Product sDR2.4: Transfer MRO Product
sDR3 – Deliver Return Excess Product	sDR3.1: Authorize Excess Product Return sDR3.2: Schedule Excess Return Receipt sDR3.3: Receive Excess Product sDR3.4: Transfer Excess Product

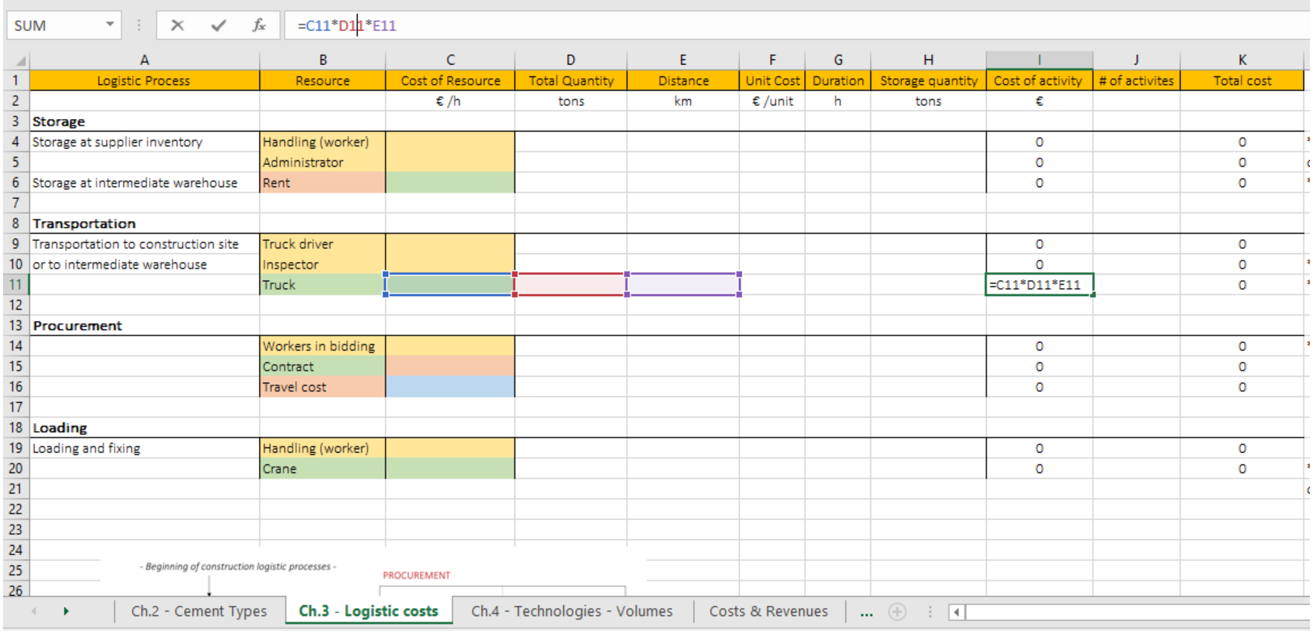
Appendix H

Parts of the spreadsheet calculation model



=100-D7

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Appendix B - Cement Types based on EN 179-1																
2	Types produced in the Netehrlands																
3	Cement Types		Main constituents (% by mass)														
4			K		S		V		P, Q or V		Minor additional constituents			K	Clinker		
5			min	max	min	max	min	max	min	max	min	max		S	Blast Furnace Slag		
6	Portland Cement	CEM I	95	100							0	5		P	Natural Pozzolana		
7	Portand Composite Cement	CEM II/ B-S	65	79	=100-D7	35					0	5		Q	Natural Calcinated Pozzolana		
8		CEM II/ B-V	65	79			21	35			0	5		V	Silicious Fly Ash		
9	Blast Furnace Cement	CEM III/ A	32	64	36	65					0	5					
10		CEM III/ B	20	34	66	80					0	5					
11	Composite Cement	CEM V/A	40	64	18	30			18	30	0	5					
12																	
13																	
14	Cement Types		Main constituents (tons)														
15			K		S		V		P, Q or V		Minor additional constituents		Calcium Sulfate		Additives		
16			min	max	min	max	min	max	min	max	min	max	min	max	min	max	
17	Portland Cement	CEM I	0,95	1							0	0,05	0,02	0,03	0	0,01	
18	Portand Composite Cement	CEM II/ B-S	0,65	0,79	0,21	0,35					0	0,05	0,02	0,03	0	0,01	
19		CEM II/ B-V	0,65	0,79			0,21	0,35			0	0,05	0,02	0,03	0	0,01	
20	Blast Furnace Cement	CEM III/ A	0,32	0,64	0,36	0,65					0	0,05	0,02	0,03	0	0,01	
21		CEM III/ B	0,2	0,34	0,66	0,8					0	0,05	0,02	0,03	0	0,01	
22	Composite Cement	CEM V/A	0,4	0,64	0,18	0,3			0,18	0,3	0	0,05	0,02	0,03	0	0,01	
23																	
24																	
25	Cement Types		Use														
26																	



=C11*D11*E11

	A	B	C	D	E	F	G	H	I	J	K
1	Logistic Process	Resource	Cost of Resource	Total Quantity	Distance	Unit Cost	Duration	Storage quantity	Cost of activity	# of activites	Total cost
2			€ /h	tons	km	€ /unit	h	tons	€		
3	**Storage**										
4	Storage at supplier inventory	Handling (worker)							0		0
5		Administrator							0		0
6	Storage at intermediate warehouse	Rent							0		0
7											
8	**Transportation**										
9	Transportation to construction site	Truck driver							0		0
10	or to intermediate warehouse	Inspector							0		0
11		Truck							=C11*D11*E11		0
12											
13	**Procurement**										
14		Workers in bidding							0		0
15		Contract							0		0
16		Travel cost							0		0
17											
18	**Loading**										
19	Loading and fixing	Handling (worker)							0		0
20		Crane							0		0
21											
22											
23											
24											
25											
26											