# Concrete valorization for a Circular Economy

## The exploration of an integrated RFID-based material passport system in the Netherlands

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# List of Abbreviations

| | |
|---|---|
| ACA | Academia |
| AMA | Amsterdam Metropolitan Area |
| ADR | Advanced Dry Recovery |
| BAMB | Buildings as Material Banks |
| BIM | Building Information Model/Modelling |
| CDW | Construction and Demolition Waste |
| CE | Circular Economy |
| CON | Construction |
| CP | Concrete production |
| DEM | Demolition |
| DEV | Property development |
| ECI | Environmental Cost Indicator |
| EEA | Environmental Energy Agency |
| EoL | End of Life |
| EPD | Environmental Product Declaration |
| EWDIC | Electronic Waste Declaration Information and Communication |
| FCQ | Foundation for Construction Quality |
| GOV | Government |
| HAS | Heating and Air classification System |
| IE | Industrial Ecology |
| IMPS | Integrated Material Passport System |
| INFO | Information system development |
| LCA | Life Cycle Analysis |
| MLP | Multi-Level Perspective |
| MPS | Material Passport System |
| NED | National Environmental Database |
| NGO | Non-governmental organization |
| NWR | National Waste Registry |
| PAP | Primary aggregate producer |
| REC | Recycling |
| RFID | Radio Frequency IDentification |
| SRM | Secondary Raw Materials |
| WIA | Waste Incineration Ashes |

# 1. Abstract

The use of concrete, the world's most applied construction material, has significant environmental impact in its sourcing and end-of-life stages. Closing the concrete loop prevents devalorization of concrete (aggregates) and has environmental benefits. In the European Union, the recently published Green Deal provides additional stimulus to the circular economy ambitions of its member states. In the Netherlands, information systems that store data on material stocks and flows, known as material passport systems, are considered vital in the transition to a circular (construction) economy. However, the digital representation of our physical world is only as good as the translation into digital data. Radio Frequency IDentification (RFID) technology bridges the gap between the digital and physical world. Therefore, this thesis assesses the opportunities and challenges of a proposed RFID-based Integrated Material Passport System (IMPS) for concrete (aggregates) in the Netherlands. The development and diffusion of this innovation were analyzed using Geels' Multi-Level Perspective framework. A mixed-methods approach was applied to assess the Dutch concrete chain's perception of such a system, and test the performance of an RFID material passport for concrete on a lab scale.

The ambition and need to develop information systems for a circular economy is shared by the public and private sector; the majority of respondents (79%) think it is important to receive more information from the concrete chain, especially information regarding the concrete's composition, and environmental performance. Moreover, 85% of the respondents were interested in an information system for concrete that provides them with this information. However, the intra-sectoral information infrastructure is currently insufficient for the required digital communications. Although the RFID-based system tested in this thesis showed opportunities for real-world applications, its performance is currently insufficient in terms of resistance to external forces. The development of RFID technology and an IMPS requires changes in economic incentives, policy, and technological performance.

The development and communication of knowledge are considered the most crucial factors for developing and diffusing the IMPS in the Netherlands. Developments should focus on gathering lead users, research institutes, and investors, in a 'coalition of the willing,' for experimentation with decentralized information systems, and RFID technology. Regarding the MPS, a sector-wide approach for the normalization, sharing, and security of information is required. The focus of the approach should be on information logistics and access, rather than information registration. However, for the transition from the EoL to the sourcing phase, additional objective quality information registration is required.

Although new technological innovations allow us to close the concrete loop further, the majority of secondary materials exits the cycle to road construction activities. While it has value as a road-base, the application of secondary concrete currently prohibits its re-introduction into the concrete chain. The current demand for concrete outweighs all secondary concrete supply. Taking the national infrastructure budget into account, construction activities will increase in the next five years, meaning the Netherlands will require additional virgin concrete resources in the coming years. These background activities provide opportunities and urgency for the development of innovative methods for the transition to a circular concrete chain and a circular economy.

# 2. Introduction

In the last decades, global human population growth has resulted in significant social and environmental changes (European Environmental Agency (EEA) 2015). Simultaneously, there is a global trend towards industrialization, a resource-intensive process. As a result, the 2015 global resource consumption is estimated to double by 2030. Although industrialized societies arguably provide more well-being to their citizens, their “escalating resource use also imposes an increasing burden on the environment through impacts related to resource extraction, use, and disposal” (EEA 2015, p.74). In fact, the scale of human activity in some cases already exceeds that of natural forces. Surpassed only by water erosion, humankind is the second-largest yearly displacer of rock and soil (roughly 42 billion metric tons), a little less than oceanic volcanoes, mountain building, glaciers, and wind erosion combined (McNeill 2001).

## 2.1 Concrete

It is estimated that roughly 30 billion tons/year of coarse aggregate (mostly gravel) and fine aggregate (mostly sand) were extracted for concrete production in 2012 (United Nations Environment Program 2014). Aggregates are mixed with a binder (mostly Portland cement) to produce concrete, the most used construction material and second most consumed substance on earth after water (World Business Council for Sustainable Development 2009). Concrete is an attractive construction material because it is versatile, cheap to produce, and has excellent load-bearing and weather-resistant properties. However, the use of concrete has a significant environmental impact. According to Huang et al. (2018), the global construction sector emits 23% of all CO2 emissions from economic activities, and the production of cement alone accounts for 7% of all anthropogenic CO2 emissions (International Energy Agency 2018).

Due to global urban population growth, urban areas accumulate large stocks of construction materials (Haas et al. 2015; Hu et al. 2010). Although concrete structures can maintain their structural integrity for over centuries (Gagg 2014), the average lifespan of an urban concrete building is generally several decades as a result of continuous dynamic urban development (Hu et al. 2010). Therefore, construction materials are the most substantial fraction in the global End of Life (EoL) materials (Haas et al. 2015) and are expected to increase drastically over the coming decades as buildings from the second half of the previous century reach their EoL (Hu et al. 2010). While land-filling remains the predominant global means of Construction and Demolition Waste (CDW) management, it is one of the least preferred EoL practices because it devaluates the materials, and prevents them from re-entering the construction sector as Secondary Raw Materials (SRM) (De Brito and Silva, 2016). Moreover, it competes with other land uses and results in ever-larger pressure on the natural environment to provide virgin resources. Also, due to the relatively low cost of natural aggregates -which does not include the costs of environmental externalities- and a high gate fee, illegal dumping of CDW still occurs (De Brito and Silva 2016; Marzouk et al. 2017).

In the European Union, CDW accounts for 25-46% of all solid waste and is one of the most massive waste streams by weight and volume, of which concrete is the single most substantial fraction (12-40% of CDW; 3-18% of all solid waste) (EC 2019, Gálvez-Martos et al. 2018a). Although the majority of CDW is considered non-hazardous by itself, the emissions, environmental degradation, and resource depletion associated with its upstream production, logistics, and disposal are of significant concern (Gálvez-Martos et al. 2018). While most of the CDW is landfilled, it is a waste stream with high potential value because it contains various SRMs. As a result, the European Commission has set a target of 70% CDW recycling by 2020 (EC 2019). While some member states already exceed this target on paper, none of the states would meet the 70% recycling target if low-value applications for CDW, such as backfilling, are taken into account. “Backfilling is a recovery operation where waste is used as a substitute for non-waste materials to reclaim excavated areas or for engineering purposes in landscaping” (Collectors 2019).

## 2.2 The Netherlands

According to Eurostat, the Netherlands has a CDW recovery rate of 100% (this includes backfilling), one of the highest recycling rates of the European Union (Eurostat 2019). In the Netherlands, 95% of concrete waste is crushed as a foundation for road construction, and 2-5% returns to the concrete production sector, as a coarse aggregate substitute for gravel (Bukvić 2018). While crushed concrete waste has a value in the road construction sector, once applied, it is (currently) unable to re-enter the concrete chain. While one ton of raw materials for concrete is worth € ~38, the same volume of crushed EoL concrete is worth € ~12-15, a minimum 60% value loss (Di Maio 2018). While this process leads to high mass-based recycling rates, its value loss is of significant concern, especially since road construction and infrastructure demolition are expected to increase until 2024 (Infrastructuurfonds 2019).

The Circular Economy (CE) is an (economic) system that strives for value maximization by cyclically keeping goods in the economic loop for as long as possible. This is in contrast to the current linear extract-use-dispose throughput flow of materials in the economy (Korhonen et al. 2018). In light of the Dutch ambition to develop a CE by 2050 (Rijksoverheid 2016), a nation-wide “resource agreement” was signed that confirms the willingness by the Dutch government, industry, unions, knowledge institutes, and financers to transition towards a CE (Rijksoverheid 2017).

In terms of concrete, the voluntary “concrete agreement” was signed, which provides the basis for targets regarding the sustainability of the Dutch concrete chain. Besides a minimum 30% reduction of $CO_2$ (with 1990 as a baseline), chain cooperation, and consistent demand for sustainable concrete, it mentions the ambition for 100% high-value reuse of ‘waste’ concrete, with transparency regarding the origin and composition of the material by 2030 (Industry partners and Government 2018).

Social and technological innovations are being developed to reach these policy goals. Initiatives such as Platform CB ’23 aim to connect organizations with circular ambitions to develop national agreements for circular construction by 2023. It connects organizations such as the Dutch normalization institute, industry members, and the national government to formulate standards and regulations. Technological solutions, on the other hand, provide innovation in terms of recycling technologies and information technology. For example, recent technological innovations from the TU Delft, such as the Advanced Dry Recovery (ADR) machine and the Heated Air Classification System (HAS), cooperate to separate concrete into its primary aggregates; coarse, fine, and ultrafine (containing the binder) (Lotfi et al. 2014, 2017a, 2017b). This 'reverts' concrete back into virgin-quality aggregates in contrast to conventional crushing methods that produce smaller concrete chunks. The high-quality secondary coarse and fine aggregates, can immediately be reused in concrete production. The ultrafine fraction, containing a mix of (un)reacted cement, can be used as a partial replacement of virgin cement in new concrete, or as a limestone replacement in the cement production process.

In terms of information technology, digital innovations allow the tracking and management of society's material stocks and flows for decision-making. This occurs by registering, organizing, storing, and exchanging data (Madaster 2019). Others apply cross-disciplinary data analysis for the spatial mapping and tracking of society's flows to inform decision-making (Geofluxus 2019; REPAiR 2019).

## 2.3 Material Passports

By adding descriptive digital information to a material (a concrete element, f.e.), it receives an identity, which is stored in its digital file, a material passport. In this thesis, a system that manages such information is referred to as a Material Passport System (MPS). The Dutch circular transition agenda for the construction sector explicitly mentions an MPS as a first step towards providing insight into the materials in constructions, facilitating the reuse of resources during demolition and deconstruction, and adding value to constructions in a CE.

As mentioned in a position paper drafted by several major construction companies in the Netherlands (Mol et al. 2019), the time has come to discuss the topic of MPSs. Although the responsibility, funding, maintenance, and operationalization of an MPS remain topics for discussion, the paper mentions that their potential for the sourcing of secondary materials needs to be explored since the physical infrastructure provides an excellent source of high-quality SRMs. The optimal exploitation of SRMs requires more information regarding their location, characteristics, value, owner, quality, and environmental impact. While these data are recorded for virgin resources, such as sand (Maljers et al. 2010; Maljers and Stafleu 2010), no coherent system exists for SRMs, such as concrete.

While some of the necessary information for an MPS for concrete is already recorded, it is stored in various unrelated information systems. For example, while the information system of the government's National Waste Registry (NWR) (*Landelijk Meldpunt Afvalstoffen* or LMA in Dutch) records the origin, destination, and processing method of waste concrete, it does not contain any consistently relevant, or verified information regarding its quality. Concrete rubble from a demolished building will be recorded, but leaves the system once it is processed into a product, such as standardized concrete granules. If these granules become certified, this information is recorded in the National Environmental Database (NED) (*Nationale Milieudatabase* or NMD in Dutch), which only contains information applicable to products, not waste. Although materials may undergo several lifecycles, their flows through society are fragmentarily recorded depending on whether we view them as 'waste' or 'products.' From a resource management perspective, this hampers their continued high-value application.

While a pilot project is transforming the NWR database into an SRM database by adding a quality component to each waste flow, the information upon which the quality assessment is based is not independently verifiable (Gemeente Amsterdam, 2020, unpublished). Therefore, a method for registering independently verifiable data quality is required. While this would be the first step towards reliable data entry in digital systems, a disconnection between the digital registration and the physical material remains. In essence, there is currently no method for linking digital information with the physical material. By providing the material with a unique identifier -a physical material passport- the information from several databases can be linked to the material in question. The use of Radio Frequency IDentification (RFID) technology for concrete-specific applications appears promising (Consolis 2019; Wang 2008).

While the government literature generally uses the term "material passport" to refer to a digital material information registration system (Rijksoverheid 2018), a distinction between both type of systems is required; in this thesis, this digital system is referred to as a "material passport system" while the physical material passport will be referred to as a "material passport." The combination of both the digital and physical passports will be referred to as an "integrated material passport system" (IMPS). According to Iacovidou et al. (2018), such an integrated system "would be an innovative disruption in the construction sector … [and promote] circularity in the supply chain" (p. 802).

Mol et al. (2019) argue that the transition towards a CE can only be successful if we simultaneously innovate, act, and exchange information regarding visions, culture, technology, and processes. This view is supported by transitions theory literature (Köhler et al. 2019; Geels 2011, 2019), which studies how new technologies -such as IMPSs- interact within the existing socio-technical context to bring about change. Specifically, the Multi-Level Perspective (MLP) framework allows for the practical analysis of such topics (Geels 2019). This interdisciplinary approach coincides with the principles of Industrial Ecology and its three pillars; engineering, governance, and economics, and is therefore considered a suitable framework for understanding the Dutch transition towards a CE. As Geels (2011) mentions: "[t]he core analytical puzzle is to understand how environmental innovations emerge and how these can replace, transform or reconfigure existing systems."

This thesis aims to contribute to the Dutch CE ambition by exploring the barriers and opportunities of an integrated (physical and digital) material passport information system for concrete, testing and developing practical solutions to shortcomings of the system, and providing strategic recommendations for the continued development of such a system in the Dutch context. The main research question guiding this thesis is:

*"How to develop and diffuse an integrated RFID-based material passport system for concrete in the Dutch context?"*

Additional sub questions were formulated according to Geels' MLP (2019) to answer this question.

Sub Research Question (SRQ) 1 provides insight into the societal context and the general perception of material passport systems:

*"What are the perceptions, requirements, and (dis)advantages of a material passport system for concrete according to actors who affect/are affected by this innovation?"*

SRQ 2 aims to explore practical technological solutions in the TU Delft civil engineering laboratory:

*"What are the strengths and weaknesses of an RFID-based material passport for storing information in concrete aggregates on a lab-scale?"*

Lastly, SRQ 3 aims to understand how to incorporate the technological developments in the Dutch societal context:

"*What are the main opportunities and barriers for the diffusion of an integrated RFID-based material passport system, and which strategy could be adopted to optimize diffusion?"*

The next chapter will delve deeper into the relevant literature regarding the CE, transitions theory, concrete reuse, and RFID technology. It is followed by the construction of the methodological approach, the interview and laboratory results, the development of an appropriate diffusion strategy, discussion of the research, and the conclusion.

# 3. Theories and concepts

This chapter provides the theoretical foundation of this thesis and consists of three parts; literature on the CE, transitions theory, and sustainability in the construction sector. This will provide essential background information regarding the theory and frameworks used to develop the methodology of this thesis and identify knowledge gaps in the existing literature.

Although the introduction touched upon the concept of the CE, the following section provides a summary of the concept of CE and its related academic fields. The transitions theory section will introduce the Multi-Level Perspective framework and Strategic Niche Management for understanding the factors influencing transitions, and an operational tool for the management of technological innovation, respectively. Third, an overview of the literature regarding sustainability in the construction sector will review trends in CDW management and identify knowledge gaps.

## 3.1 Circular Economy

The CE is an economic system that strives for value maximization by cyclically keeping goods in the economic loop for as long as possible, contrary to the current linear extract-use-dispose throughput flow of materials in the economy (Korhonen et al. 2018).

The goal of the CE is to decouple damaging resource use from economic growth (Ghisellini et al. 2016; Korhonen et al. 2018). Central to this goal is closing the material cycles in the economy. The concept of a circular economy derives from various schools of thought, one of which is Industrial Ecology (IE) (Ehrenfeld 1997; Ghisellini et al. 2016). Contrary to viewing humans as being separate from nature, IE considers humans to be part of the same system, in which materials, energy, and information flow between natural environments (the biosphere) and human-made environments (the technosphere) (Erkman 1997). Therefore, solutions to (environmental) problems should seek to better integrate human activities within the planet's physical and nutrient boundaries (Rockström et al. 2009). In this thesis, the technosphere is considered a system with four interacting elements; the material, organizational, informational, and time layers (Figure 1).

The biosphere is considered indispensable to sustaining the technosphere and the CE. Moreover, the CE aims to mitigate greenhouse gas (GHG) emissions, maintain maximum material value, and minimize (solid) waste (Haas et al. 2015; Korhonen et al. 2018). The challenge, however, is translating the theoretical concept to real-world actions in all fields of society.

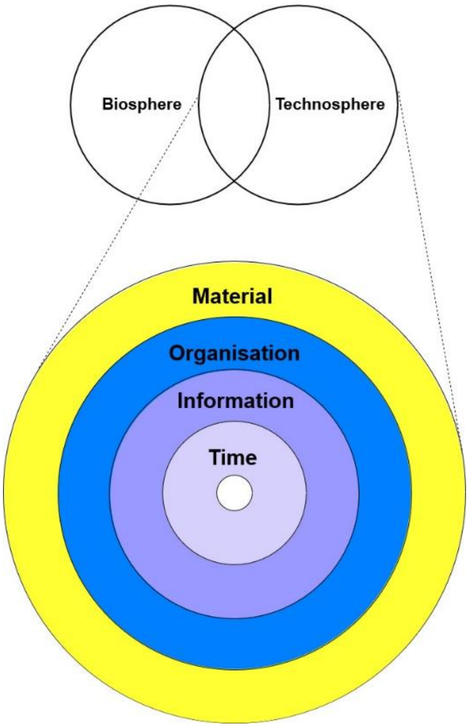


**Figure 1:** Simplified relationship between the biosphere and the technosphere's material, organization, information, and time layers.

## 3.2 Transitions Theory

At this moment in time, the Netherlands is transitioning from a linear to a circular economy (Rijksoverheid 2016). This requires profound societal changes in virtually all fields; construction, manufacturing, agriculture, energy, transport, and others (Geels 2011, 2019). The realization of such changes requires a transition in institutions, policy, technology, business models, cultural norms & values, infrastructure, scientific knowledge, and others. Some of these fields mainly concern people, others concern technology. Rather than perceiving society as discretely divisible sectors, transitions can be understood as an interplay of these various fields. Due to the inherent interrelation of these systems, societal changes can be seen as 'socio-technical transitions.'

Socio-technical transitions occur at various levels of organization, ranging from technological innovation in a startup to a European-wide policy implementation. In order to understand the dynamic interaction of societal sectors in their respective transition contexts, Geels (2011, 2019) developed the Multi-Level Perspective (MLP) (Figure 2). On the vertical axis, the MLP depicts three levels of scale in the structuration of activities, from small to large, niche-innovations, the socio-technical regime, and the socio-technical landscape. The interplay of the elements in each vertical level is viewed through time on the horizontal axis.

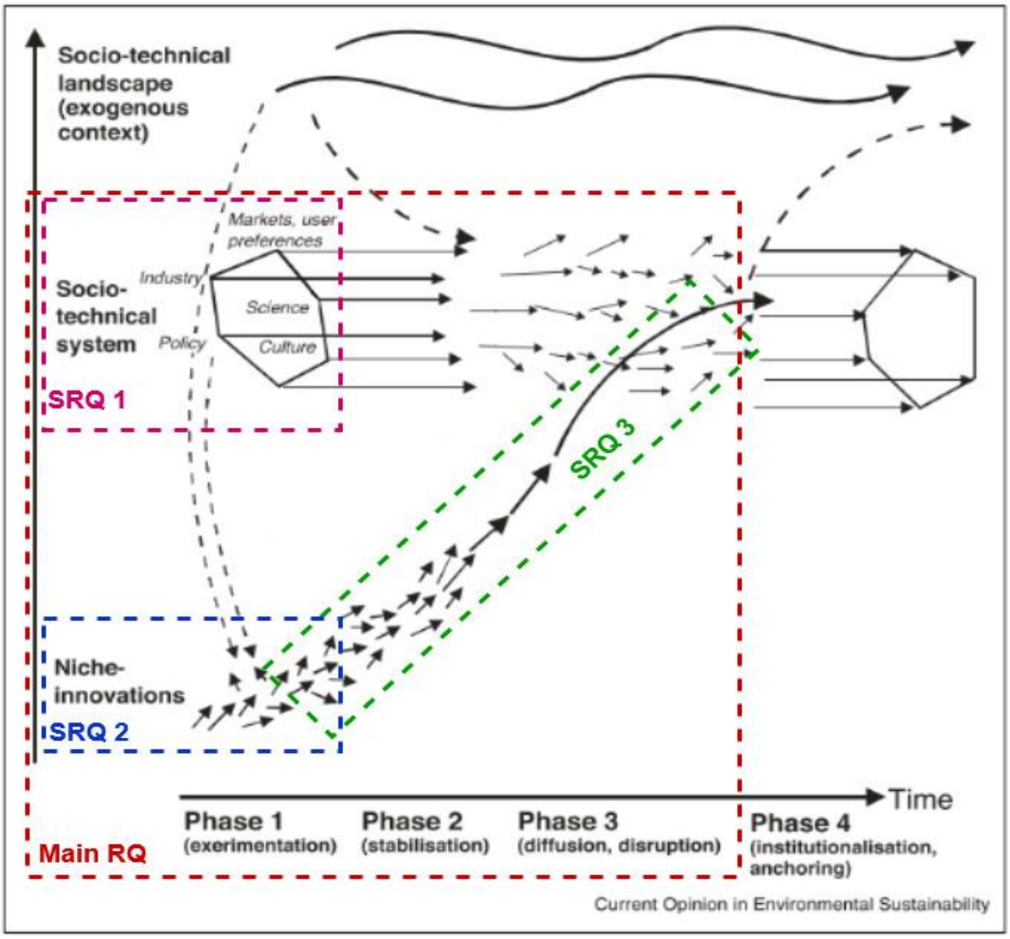


**Figure 2***:* Simplified MLP (Geels 2019) with the corresponding scope of the (sub)research questions

In the background, there is the socio-technical landscape. The landscape-level contains macro-economic trends, supra-national policy, demographical trends, and can be understood as the larger contextual “zeitgeist.” Niche-innovations and the regime do not influence the landscape in the short term; rather, the landscape exerts its top-down influence on both the regime and niches. However, due to this landscape pressure, a regime can destabilize and allow for the emergence of niche-innovations to transition the regime. Niche-innovations are not the sole driver for change, multiple facets in the landscape, and regime ‘allow’ for the emergence of new niches.

The socio-technical regime is the status-quo which undergoes the transition. It is influenced by both niche-innovations and the socio-technical landscape. The existing regime is a relatively stable system that is governed by a “semi-coherent set of rules that orient and coordinate the activities of the social groups that reproduce the various elements of socio-technical systems” (Geels 2011, p. 27).

Similar to a physical niche -a small, sheltered place- a niche-innovation is a new technology or practice developed in a sheltered place, such as a university laboratory, or a-small scale demonstration project. These spaces allow for the technology to grow, develop, and suit small niche markets before they are exposed to the outside world, the regime. Although they start small, niche-innovations are the source for bottom-up (technological) change within the regime and are vital for kindling transitions.

Whereas the MLP provides a useful overview of the complexity and interconnectedness of socio-technical regime transitions towards sustainability, its use for the management and operationalizing of niches is limited. Strategic Niche Management (SNM), on the other hand, can be seen as a tool to manage the improvement, growth, and diffusion of niche-innovations (Hoogma et al. 2005). Technological development in and of itself does not lead to sustainable transitions; therefore, it is necessary to (slowly) connect and expose the sheltered niche-innovation to regime factors. In essence, SNM concerns itself with the question: “how and under what circumstances is the successful emergence of a technological niche possible?” (Schot and Geels 2008, p. 540). This approach has successfully been deployed for understanding the failures and successes of a wide range of technologies in the fields of energy, mobility, infrastructure, and food production (Caniëls and Romijn 2008). Given this thesis, it will be used to understand the requirements for the successful development of an IMPS for concrete.

## 3.3 Concrete and the circular economy

This section reviews the relevant literature regarding concrete in a circular economy. First, a general review of the literature regarding CE and CDW will be discussed, followed by an overview of the relevant literature regarding sustainable concrete practices.

### Construction and demolition waste in a circular economy

Ghisellini et al. (2018) explored the literature on the costs and benefits of a CE approach for CDW. They concluded that CE principles, such as prevention, reuse, and recycling, contribute to environmental and economic benefits in the reduction of global warming potential, energy use, acidification, and eutrophication. However, they mention a dominant academic focus on recycling (reuse on a material level), compared to higher-value alternatives that focus on reuse on the component or construction level. As Iacovidou and Purnell (2016, p.794) point out, reuse can be limited by the lack of confidence in the materials' structural properties, rules and regulations (building codes/standards), underdeveloped SRM markets, and prejudice against the potential benefits of reuse, making it a more complicated topic than recycling. Other barriers to the implementation of CE principles include the lack of knowledge about the composition, characteristics, quality, reuse/recycling potential as well as the lack of knowledge about the environmental benefits of CE principles (Ghisellini et al. 2018, p. 637; Hradil et al. 2014). This thesis will assess to what degree these factors play a role in the Dutch context, and suggest an appropriate strategy to overcome them.

There are two types of carbon emissions; embedded carbon (emissions during the sourcing and production of construction materials) or operational carbon (emissions from heating/cooling, lighting, and others) (Iacovidou and Purnell 2016). Although the operational carbon is responsible for the majority of a building's emissions (Ng et al. 2012), this is beyond the scope of an IMPS for concrete. Such an information system, however, could contribute to the registration, tracking, and prevention of embedded carbon emissions. Therefore, the primary focus of the IMPS is to contribute towards the reduction and management of embodied emissions.

### Concrete recycling technologies

Once concrete hardens, it irreversibly loses its versatile fluid properties, which inherently decreases the possibilities (and thereby its value) for continued use in the construction sector. Concepts such as design-for-reuse aim to maximize the value of construction materials by facilitating complete reuse of building components (walls, floors, support columns), rather than recycling of their individual materials (brick, wood, concrete, etc.) (Akanbi et al. 2018; Akinade et al. 2017; Ghisellini et al. 2018). The vast majority of the current construction stock does not feature such design considerations. In the Netherlands, this results in its use as a road base. Concrete waste is preferred over other types of stony waste (such as masonry) because of its density and the residual unreacted cement that stabilizes the structure. Other factors contributing to this trend are the less stringent quality regulations for road base constructions in comparison with structural constructions such as bridges or buildings (Ministry of Infrastructure and Water Management 2017).

The current crushing method breaks concrete indiscriminately, meaning it also breaks the coarse aggregate, which irreversibly lowers the value of the coarse fraction. A series of CDW recycling technologies have been developed at the TU Delft during various European research projects, which can separate concrete into its constituent parts to prevent the value loss of these aggregates (Di Maio et al. 2012; Lotfi and Rem 2016).

The ADR machine separates concrete into a coarse fraction (>4mm) containing gravel, a fine fraction (0-4mm) containing sand, and an ultra-fine fraction (0-0.250mm) containing cement and ultra-fine sand . These materials may be reused in separate applications or can be used to produce new concrete. While the gravel and sand can be reused immediately for the production of new concrete, the ultra-fine fraction needs to be separated further.

Using the HAS system, this fraction is separated into sand (which can be used for concrete production) and ultra-fine cementitious powder, which can be used as a partial replacement of cement in concrete production or as a partial replacement of limestone in the cement production process (Lotfi & Rem, 2016). In the case of limestone, this results in three times less $CO_2$ emissions than conventional limestone. In addition, the ADR can be combined with sensor technology to provide fully automated quality analysis in terms of “characteristics, degree of liberation of the constituents, quality and quantity of fine material, [and] presence of contaminants and/or ‘pollutants,’” without human intervention (Di Maio et al. 2012, p. 7). The ADR and HAS are currently exploited on the market through the C2CA Technology spin-off company. The sensor and monitoring technology is currently being developed for industrial applications under patent application #N2021751, “Method and system to convert demolished concrete into a readily recyclable product”.

While the ADR and HAS provide opportunities for recycling concrete by overcoming barriers related to the liberation, separation, and quality analysis of waste concrete aggregates, the increase in high-quality SRMs supply alone is not sufficient for stimulating the Dutch SRM market (Deloitte 2014). Remaining barriers include the lack of quality gradations for SRM and solid business cases for the recycling of materials (Deloitte 2014). Therefore, recycling could be improved by providing information about the materials to stakeholders in the value chain.

## RFID technology

Radio Frequency IDentification (RFID) tags are electronic devices that store digital information. The technology was first developed during the 1970s in the United States for an automated highway toll system but quickly spread to other sectors around the globe (Cardullo 2003). Its current uses include tracking goods in supply chain management, contactless payment systems, access and security management, for example. An RFID tag consists of at least a microchip that stores and processes information, an antenna to send/receive signals, and a means of powering the tag. Passive RFID technology uses the transmitting signal of the reader as an energy source, meaning no batteries in the tag are required, which decreases the size, complexity, and cost of the tags. However, passive tags require a stronger signal than active tags to power the device, and the reading range is limited when reading through metal or liquid.

Several authors have suggested using RFID tags to identify and track construction materials (Iacovidou, Purnell, & Lim 2018; Sardroud 2012). Wang (2008) integrated RFID tags in concrete for tracking and storing information about concrete samples in a lab environment.

An unpublished exploratory study at the TU Delft is one of the first, and only, studies available regarding the use of modern RFID technology as a basis for a material passport for concrete (Bheemireddy 2018, unpublished). The study assessed the function of a passive RFID tag in a concrete cube. Since the study only featured one sample, no definitive conclusions could be drawn. There is a considerable knowledge gap regarding the use of RFID technology for physically connecting digital information to concrete aggregates. While the ‘circular overpass’ project demonstrates that RFID technology can be successfully used for the storing of information on construction elements (Consolis 2019), the challenge is using RFID technology for its use with the (secondary) concrete aggregates, the most abundant form of waste concrete. In other words, while the use of RFID technology seems promising for new precast construction elements, its potential for the use in providing information about the secondary aggregates from demolition concrete remains unexplored.

## 3.4 Chapter conclusion

In order to maintain the highest value of constructions in a CE, more information about their composition, quality, use, and environmental performance is required (Ghisellini et al. 2018). In the Netherlands, BIM-based MPSs have been developed (Madaster 2019). Although the use of BIM can be considered a first step, there remains a disconnection between the digital model and the physical material. As suggested by (Iacovidou and Purnell 2016), an integrated BIM/RFID system allows for the registration and tracking of construction materials throughout their lifecycles. Few systems that physically track construction materials exist, with none in place for concrete aggregates. The uncertainty regarding material quality and type makes it notoriously difficult to recycle crushed concrete and is a substantial gap in the literature, which merits more research. Especially since the high-quality reuse of concrete aggregates has environmental and economic benefits. Therefore, this thesis will explore the use of an RFID-based IMPS for storing and tracking information on concrete (aggregates).

# 4. Methodology

This chapter relates the research questions to the MLP (Figure 2), and discusses the methodologies for each (sub-)research question (Figure 3).

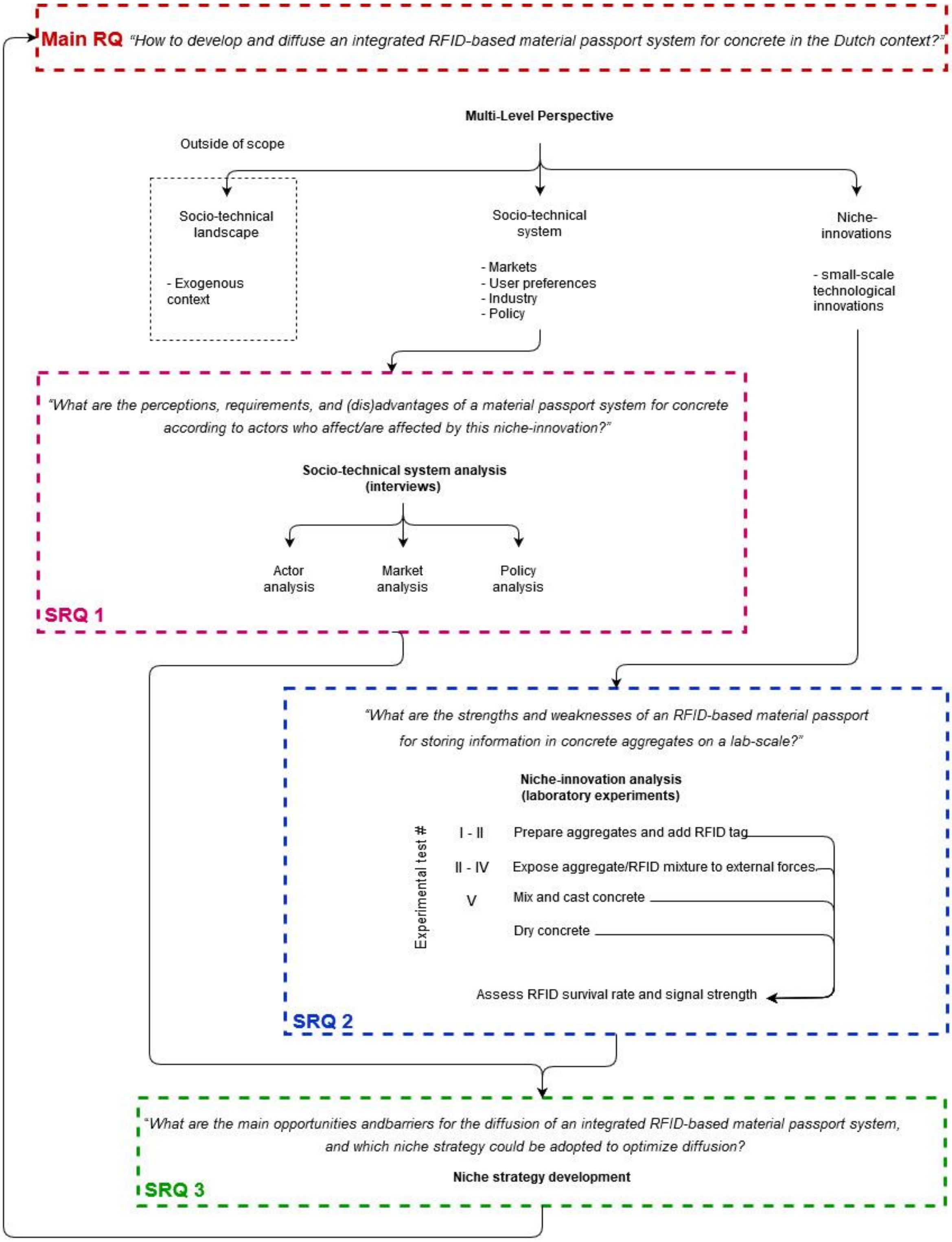


**Figure 3:** Overview of the complete methodological framework

First, the main research question and sub-questions are re-formulated using the appropriate terminology from the transitions literature (niche-innovation and niche-strategy instead of innovation and strategy in SRQ 1 and 3, respectively).

Main RQ) *"How to develop and diffuse an integrated RFID-based material passport system for concrete in the Dutch context?"*

SRQ 1) *"What are the perceptions, requirements, and (dis)advantages of a material passport system for concrete according to actors who affect/are affected by this niche-innovation?"*

SRQ 2) *"What are the strengths and weaknesses of an RFID-based material passport for storing information in concrete aggregates on a lab-scale?"*

SRQ 3) "*What are the main opportunities and barriers for the diffusion of an integrated RFID-based material passport system, and which niche strategy could be adopted to optimize diffusion?*

## 4.1 SRQ 1

The methodology for SRQ 1 is based on the work by Bukvić (2018), who performed interviews with actors in the Dutch stony supply chain. Similarly, the data required for the actor analysis of this research was qualitative and collected using semi-structured interviews. First, a product chain analysis determined the type of actors involved using Bukvić's findings (2018), and the actor analysis framework by Hermans and van der Lei (2012). Based on this, the appropriate branch organizations were approached. Also, the network of both supervisors of this thesis project, who have been involved in several European research projects, was utilized to contact relevant actors in the chain (Di Maio et al. 2012; Lotfi et al. 2017b).

Contact with branch organizations and individual companies was requested by email. They were invited to participate in a 30-60 minute interview, or a 10-15 minute online questionnaire. Interviews were conducted in person or by telephone, and the online questionnaire was conducted using SurveyMonkey software. These two collection methods provided actors with two alternatives, depending on their time availability. Considering the EU's General Data Protection Regulation requirements, the research proposal was reviewed and approved by the Human Research Ethics Committee of the TU Delft. Before the interview took place respondents received a thesis research information sheet, and an informed consent form which allowed them to decide how their information was used and stored (Appendix A, B).

Geels' MLP (2019), was used to structure the interview questions (Appendix C). They were categorized according to their objective, and the various elements which make up the socio-technical regime of the concrete value chain (Table 1). The socio-technical regime is characterized by (at least) six elements; industry, markets & user preferences, science, policy, culture, and technology (Figure 2).

**Table 1:** Interview question structure, objective, and MLP elements.

| Category | Objective | Question # | MLP elements |
|---|---|---|---|
| 1 | Locate the respondent's position in the chain and inventory the current state of circular activities related to concrete | 0, 1, 2 | Industry, culture, science, technology |
| 2 | Identify the perceived relevance of an information system for concrete for their organization | 7 | markets and user preferences, science |
| 3 | Inventory their information requirements, and their perception of the information requirements of others, to facilitate circular processes | 4, 5, 6 | Markets and user preferences, industry, policy |
| 4 | Identify the perceived responsible actors for the development and maintenance of an information system for concrete | 8 | Industry, policy |
| 5 | Identify the perception of the opportunities and barriers for a circular concrete chain | 3, 9 | All elements |

## 4.2 SRQ 2

The methodology for SRQ 2 is based on the preliminary experiment by Bheemireddy (2018, unpublished), who examined the properties of the RFID technology in terms of the physical limits to the RFID technology when incorporated into gravel, and concrete. The examination includes the range and angles at which the tags can be detected. The experiments were conducted at the Stevinlab 2 of the Civil Engineering faculty of the TU Delft. This thesis research applied the same type of metrics (reading angle and distance) and RFID technology (tags and reader) as the unpublished test by Bheemireddy.

The NORDIC ID EXA51e RFID reader model was used for the experiment. It was used at its maximum capacity (1000mW) to provide maximum power to the passive RFID tags. The reader works in the ultra-high frequency range 868 MHz, which meets European standards. The Abracon ART915X050503OP-IC passive RFID tag was selected due to its small size (5x5x3mm) and durability. Its ceramic outer shell makes it more resilient to external forces than other tags. Passive tags were selected because they do not require an internal energy source. This allows them to be smaller, cheaper, and easily integrate within the concrete.

The laboratory experiment consisted of five tests, which are summarized in Table 2. A visual representation of the methodology for SRQ 2 can be found in Appendix D. These tests were designed to assess the influence of external forces on the readability of the RFID tags.

**Table 2:** SRQ 2, laboratory tests overview.

| Test # | Test objective | # of tags | Tag group # |
|---|---|---|---|
| I | Assess the maximum RFID reading ranges in concrete aggregates | 1 | ‘3-3-1’ |
| II | Assess the influence of external forces by simulating the handling of coarse aggregate. The RFID tags are placed into 12.5 kg of gravel and dropped 15x from 2.5 m | 15 | ‘3’ |
| III | Assess the influence of abrasion on RFID performance by mixing RFID tags with a dry concrete mixture | 15 | ‘2’ |
| IV | Assess the influence of water on RFID performance after exposure to external forces | 45 (3 x 15) | ‘3’ ‘2’ ‘1’ |
| V | Assess the potential difference in RFID performance in concrete between manually placed tags, tags that have been tumbled with a wet concrete mixture, and tags in samples with rebar | 50 (3 x 15, 1 x 5) | ‘3’ ‘2’ ‘1’ ‘0’ |

I. The purpose of the first test was to determine the individual effect of the concrete aggregates on the RFID reading distance per angle. The following components were selected; gravel (8-16mm), gravel (8-12 mm), sand (2-4 mm), sand (0.25-0.50 mm), cement, and water. The RFID tag and components were placed in a plastic cylinder (radius = 6 cm), after which the maximum reading distance was determined in 30° increments. The RFID tag was placed at the height of 6 cm with the antenna pointing downwards, after which the cylinder was filled to 12 cm to ensure equal enclosure of the tag. Reading distance was measured from the cylinder wall.

For the next tests (II-V), fifty RFID tags were used. The tags were subdivided into four main groups labeled ‘1’, ‘2’,’ 3’, and a control group ‘0’. Each group contained 15 tags, except the control group, which contained five tags. The number of each group reflected the number of tests they underwent before being placed in concrete. Group ‘3’ underwent three tests, while group ‘0’ underwent no tests. Per test, the groups were divided into three sub-groups of five tags to experiment with the exposure rates. These sub-groups were indicated by a hyphen, ‘3-1’, ‘3-2’, ‘3-3’. Individual tags per subgroup were indicated by another hyphen, ‘3-1-1’, ‘3-1-2’, ‘3-1-3’.

II. The second test aimed to assess the influence of external forces on the RFID tags during the simulated handling of the coarse aggregate. The test simulates the picking up and dropping of coarse aggregate by a truck or bulldozer. It was simulated by dropping coarse aggregate (8-16 mm) mixed with RFID tags from 2.5 meters. Group ‘3’ was mixed with 12.5 kg of coarse aggregate, and dropped 15 times. After every fifth drop, the survival rate of tags was measured.

III. In the third test, the abrasive influence of a dry concrete mixture on the RFID tags was assessed. Groups ‘3’ and ‘2’ were mixed with a dry concrete mix for 60 seconds (subgroups

‘3-1’ and ‘2-1’), 90 seconds (subgroups ‘3-2’ and ‘2-2’), or 120 seconds (subgroups ‘3-3’ and ‘2-3’). Appendix E summarizes the mixture’s specifications. After mixing, they were sieved for 120 seconds to separate them from the dry concrete mixture. Once separated, the survival rate was measured. This test was designed to assess the potential damage from abrasion in the dry mixing process.

IV. In this test, the tags were placed in water for sixty minutes to determine their sensitivity to water after having sustained physical damage from the dropping and mixing. At this point, several tags were chipped. Their survival rate was measured at the end of the test.

V. Finally, the tags were placed in concrete to measure the RFID performance when encompassed in concrete. For this test, two different standard sizes of concrete samples were selected; cubes (15x15x15 cm) and rectangular prisms (10x10x40 cm). Out of group ‘3-3’, three tags were placed in cubes’ center, and one in the rectangular prism’s center. The same was done for ‘2-3’ and ‘0’. Three tags from ‘1-1’ were placed into a rectangular prism containing 8 mm rebar to test if the presence of rebar would affect the RFID signal (Appendix F). Lastly, to simulate the mixing and transport of concrete by truck, three tags from group 1 were placed in a wet concrete mixture and tumbled for 20 minutes before being cast into the rectangular prisms.

After casting, the maximum reading ranges were determined. Once demolded (24 hours after casting), the RFID tags were checked for survivability. Because water decreases the RFID signal strength, the first maximum reading range measurements took place after sufficient drying, 72 hours after casting. The next measurements took place after 7, 14, 21, and 28 days. The maximum reading ranges were determined on each of the six sides of each sample. The sides were numbered according to a dice (Figure 4). The tags which were manually placed in the samples were positioned with their antennas pointing downwards, towards side #6.

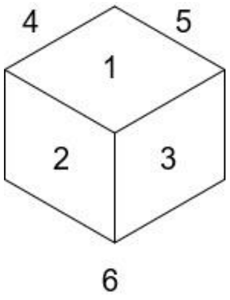


**Figure 4:** numbering of the concrete samples

## 4.3 SRQ 3

The methodology for SRQ 3 is based on the SNM literature, which describes strategies and pathways for niches to reach and influence the regime (Ortt et al. 2012; Ortt 2012). Specifically, the literature on strategies to commercialize new high-tech products will be used to answer SRQ 3 (Ortt et al. 2013a). Based on the results from SRQ 1 and SRQ 2, the most suitable strategy will be selected and applied in the discussion chapter.

According to Ortt et al. (2013b), the most appropriate strategy derives from assessing twelve factors that are essential for the large-scale diffusion of niche-innovations. Six factors have direct impact on the diffusion; the high-tech product itself, its production system, its complementary products and services, suppliers, customers, and institutional aspects (laws, rules, and standards). The six indirect factors are knowledge of the technology, natural resources and labor, knowledge of the application, socio-cultural aspects, macro-economic aspects, and accidents or events. The results of SRQ 1 and 2 will be used to assess the twelve factors and used to select the most appropriate niche-strategy.

# 5. Findings

This chapter will present the results and discussion per research question. Based on the findings of the previous two SRQs, the third research question will be answered.

## 5.1 SRQ 1 results

*"What are the perceptions, requirements, and (dis)advantages of a material passport system for concrete according to actors who affect/are affected by this niche-innovation?"*

In total, 34 responses were collected; 25 interviews, and 9 survey responses. The overall response rate for this research was 11%, with the highest response rate from the construction sector (33%), and lowest from the property development sector (1%). The distribution of respondents was highest for the concrete sector, recycling sector, and government (Figure 5). Although most respondents fulfilled multiple positions in the chain, Figure 5 is based on their primary activity. A full overview of respondents and their multiple activities can be found in Appendix G. When referring to interviews, the identification number of the respondent will be used in the following format "ID# [*identification number*]".

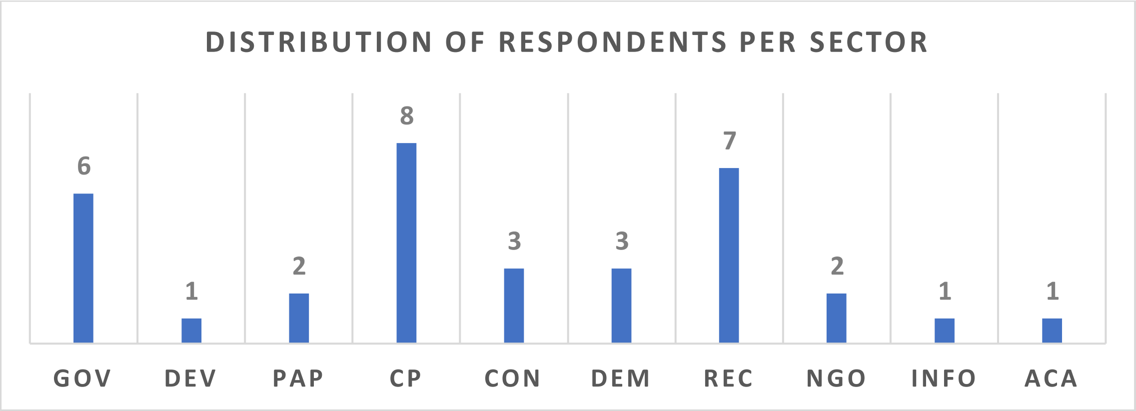


**Figure 5:** Distribution and quantity of respondents per sector. From left to right: government (both municipal and national), property development, primary aggregate production, concrete production, construction, demolition, recycling, non-governmental organization, information system development, and academia.

The results will be discussed according to the five categories constructed in section 4.1. The corresponding information can be found in Appendices G through K.

**Category 1**) *Locate the respondent's position in the chain and inventory the current state of circular activities related to concrete* (interview question # 0, 1, and 2)

The most common circular practices are the production and use of concrete granules in new concrete (52% of answers), and the contractual demand for concrete in procurement (20% of answers) (Appendix G). These two practices are elaborated upon in the following paragraphs.

Currently, concrete is predominantly recycled into concrete granules for use as a road base, or, in limited amounts, as a coarse aggregate for new concrete. Although the production of concrete granules for road construction requires less effort and investment in the demolition and recycling phases, recycling companies are gradually steering their processes towards the production of clean granules for the concrete industry due to increasing business opportunities (ID# 4). A respondent who makes use of the ADR technology mentioned that the integration of this technology into the current supply chain is expected to be completed within a year (ID# 17), which will yield the first results regarding the reuse of high-quality aggregates in the Dutch concrete sector. Challenges remain in the handling and processing of the fine fraction, which behaves differently due to the reaction potential of the residual unhydrated cement. In conclusion, use as a road base remains most common, but shifts in the circular reuse of concrete are taking place.

Municipal governments throughout the Netherlands are contractually demanding the reuse of concrete in their procurement contracts. While some municipalities only ask for its reuse, they do not mention how, generally resulting in the most economical option, recycling into a road-base (ID# 19, 21). Therefore, municipal governments have started experimenting with various contract forms to ensure sustainable procurement. One respondent from a municipal government (ID# 22) mentioned there are currently two primary contract forms for sustainable procurement, which depend on the distribution of responsibility between client and contractor. In both contracts, the Environmental Cost Indicator (ECI) (*milieukostenindicator* or MKI in Dutch) plays an essential role in decision-making. The ECI expresses the overall environmental impact of a product, construction, or method based on a Life Cycle Analysis (LCA) (Rijkswaterstaat 2019). All environmental impacts are combined into euros, a single value. The lower the ECI, the better.

In the first type of contract, the municipal engineering bureau designs a project with a minimum ECI. The tendering challenge is to achieve even lower environmental impact. Although this provides the municipality with more control regarding the design, it requires internal resources in terms of labor, money, and time. The second type of contract is an integrated contract that comprises multiple activities to ensure a streamlined process. The most common type is *Design & Construct*, in which the contractor takes on the responsibility of both processes. The role of the municipality is oriented towards the functional description of the construction, which leaves more room for contractors to make decisions in terms of the design, and how this affects the overall ECI.

**Category 2**) *Identify the perceived relevance of an information system for concrete for their organization* (interview question # 7).

As a response to whether it would be interesting to know the characteristics of concrete and its constituents during the entire lifecycle, 56% of the respondents answered 'yes,' 40% 'no,' and 4% mentioned it was not yet relevant (Appendix H). Virtually all sectors had both positive and negative reactions, except for the primary aggregate producers, and property development sector, who unanimously were not interested. Of the respondents who answered 'yes,' six elaborated on their answer by mentioning that knowing the material's characteristics would be vital for selective demolition, high-quality re-use, recycling, the composition, and the ECI values. A prefabricated concrete producer mentioned that the material characteristics would only be of interest if they remained the owner of the material, taking back the product for further use (ID# 17). However, the current business models remain focused on the sale of products, not their renting or leasing.

When asked about their interest in an information system that would provide the characteristics and quality of the concrete product and its constituents during the entire lifecycle, 85% answered 'yes' and 15% 'no.' Of the respondents who expressed interest in such an information system and elaborated upon their answer, 42% mentioned its importance for quality control. Other respondents mentioned its use for asset management, monitoring, high-quality reuse, and the selective use of materials. Two respondents elaborated by saying they would only be interested if the market demanded such a system. Similar to the first question in this category, virtually all sectors were interested in an information system except for the property developer, a primary aggregate producer, and two concrete producers.

**Category 3**) *Inventory their information requirements, and their perception of the information requirements of others, to facilitate circular processes* (interview question # 4, 5, and 6).

When asked about the importance of receiving more information from the concrete chain for the success of their organization, 79% confirmed it is important, 10% not important, 7% as conditionally important (not relevant unless requested by a client), and 4% was unsure (Appendix I). Virtually all sectors considered the reception of additional information important, except for the primary aggregate producers, and the property development sector.

The three most frequently mentioned answers in response to what type of information they would like to receive from the chain are discussed in the following paragraphs. These three responses were mentioned more than once or twice out of all 23 answers.

The most frequently demanded type of information (39% of the answers) was material composition. In particular, respondents mentioned the importance of knowing whether waste incineration ashes (WIA) are present in the concrete (18% of the answers). WIA are the bottom ashes from waste incineration plants and are used as a substitute for sand and gravel in concrete (Bodemrichtlijn 2019). WIA contain various environmentally dangerous compounds, and can only be applied using isolation, containment, and control (ICC) measures (SIKB 2019). One of such measures is mixing them into non-structural concrete. Although concrete with WIA is also used as a road-base, WIA should be prevented from entering the structural concrete industry since the Ministry of Infrastructure and Water Management (2017) does not allow their use in civil engineering structures. The government and waste incinerators are currently collaborating to develop processes to upgrade WIA into a non-ICC material by 2020 (Ministry of Infrastructure and Water Management 2012).

Respondents also mentioned the need for information regarding the concrete's ECI (9% of all answers). The Foundation for Construction Quality (FCQ) (*Stichting Bouwkwaliteit* or SBK in Dutch) manages the development and storage of ECI's and their supplementary information. This foundation is responsible for the management of collective quality labels in the construction sector, in line with European norms. The FCQ ensures that the Environmental Product Declarations (EPDs) of companies comply with standardized frameworks, and store these data in their NED. This database provides essential information for ECIs on a product and construction level and is used by many actors in the construction industry for decision-making.

When asked about the type of information they could pass on to others in the chain, actors mentioned 21 types of information (Appendix I). Only three types were mentioned more than once; the material's composition (21% of answers), ECI (14% of answers), and the LCA of concrete aggregates (7%). The type of information which can be passed on to others aligns well with the demand for the same type of information in the chain.

**Category 4**) *Identify the perceived responsible actors for the development and maintenance of an information system for concrete* (interview question # 8).

In terms of responsibility, most respondents (32%) agreed that the client of the construction -who is usually the owner- should bear the responsibility for the development and maintenance of a material passport system for concrete (Appendix J). Owning a construction with ample information about its materials should be in the owner's best interest for asset management and value conservation. The next most mentioned actor (28%) is the national government. Lastly, 16% placed the responsibility on the concrete sector. Others said that rather than picking one actor, it should be chain cooperation (12%).

**Category 5**) *Identify the perception of the opportunities and barriers for a circular concrete chain.* (interview question # 3 and 9).

In contrast to previous categories, this category yielded a wide range of dispersed answers. Most answers mentioned the barriers, rather than the opportunities. Responses were grouped into four general themes; *material passport system* (52% of the answers), *cooperation* (24%), *concrete* (12%), and *rules and regulations* (12%) (Appendix K). These themes are discussed in the following paragraphs.

Most barriers were perceived to be part of the material passport system itself. Three actors questioned the added value of a material passport system for concrete (ID# 8, 19, 32). They wondered if we should invest in a system whose (by then outdated) information might be used after several decades. Another actor mentioned that the system should be easy to use and preferably integrate with existing systems for ease of use (ID# 15). These points mainly relate to future uncertainties, the relevance of the data, practical use, and costs. Other concerns regarded the scope of information that should be recorded, the digitalization of information, and information validation. The unbiased nature of the platform was considered paramount. Due to the various interests within the concrete chain, some actors will influence the system to their benefit. For example, if the presence of an element in a composite material negatively affects the value of the composite, an actor might not be willing to maintain reliable data entry out of economic self-interest (ID# 4). Lastly, in order for the system to accurately reflect the status of the concrete, continuous updating of information should take place throughout the concrete lifecycle to take into account refurbishment, renovation, and the continued (chemical) reaction of concrete with its environment.

Cooperation was considered the second-largest challenge to the material passport system. Successful cooperation in the chain depends on the inputs of all actors. This means that the material passport system should provide ample incentives for actors to cooperate. Closely related to this point are the necessary complementary rules and regulations. One actor mentioned that we should not wait for the concrete industry to change by itself, but rather develop stimulating rules and regulations to guide them into the CE transition (ID# 11). Currently, the government, the Dutch normalization organization, and industry actors are discussing the structure and basic informational requirements of a material passport system for the construction industry (Platform CB’23 2019). Clear rules and regulations are crucial if such a system becomes mandatory due to the inherent implications regarding financial, time, and human resources.

Lastly, there are challenges related to the concrete itself. For example, the material passport system allows differentiation between concrete types. If these types are treated separately, their separation and storage will require additional investments into machinery and storage space. Also, concrete structures are not designed with secondary use in mind, meaning that the design process should incorporate considerations regarding high-value reuse.

In terms of opportunities, actors mentioned the usefulness of insight into the quantity and quality of concrete and the benefits that digitalization offers their business practices. One actor mentioned that a material passport system facilitates the use of sustainably produced concrete, by using bio-based binders with a lower ECI, for example. Lastly, the material passport system increases connectivity in the chain, which stimulates the exchange of experiences and best practices.

## 5.2 SRQ 1 discussion

This section discusses the current status of the concrete sector's socio-technical regime, which is necessary for understanding how niche innovations, such as a material passport for concrete, can be integrated. By examining the concrete chain in terms of its material-, organizational-, information- and time cycles, bottlenecks can be identified (Figure 6). As explained by one stakeholder, the current concrete chain is a material chain; i.e., the sectors interact through the handling and use of a physical material (ID# 6). Simultaneously, information about the material is produced and used by organizations in each link of the chain. Unlike concrete, however, this information does not flow throughout the chain due to the use of (partly) isolated software and database systems (Table 3). Adjustments in terms of informational and organizational structure are required to realize a material passport system. These structures should take the difference in time between each lifecycle phase into account, of which the use phase is by far the most lengthy (20-100 years).

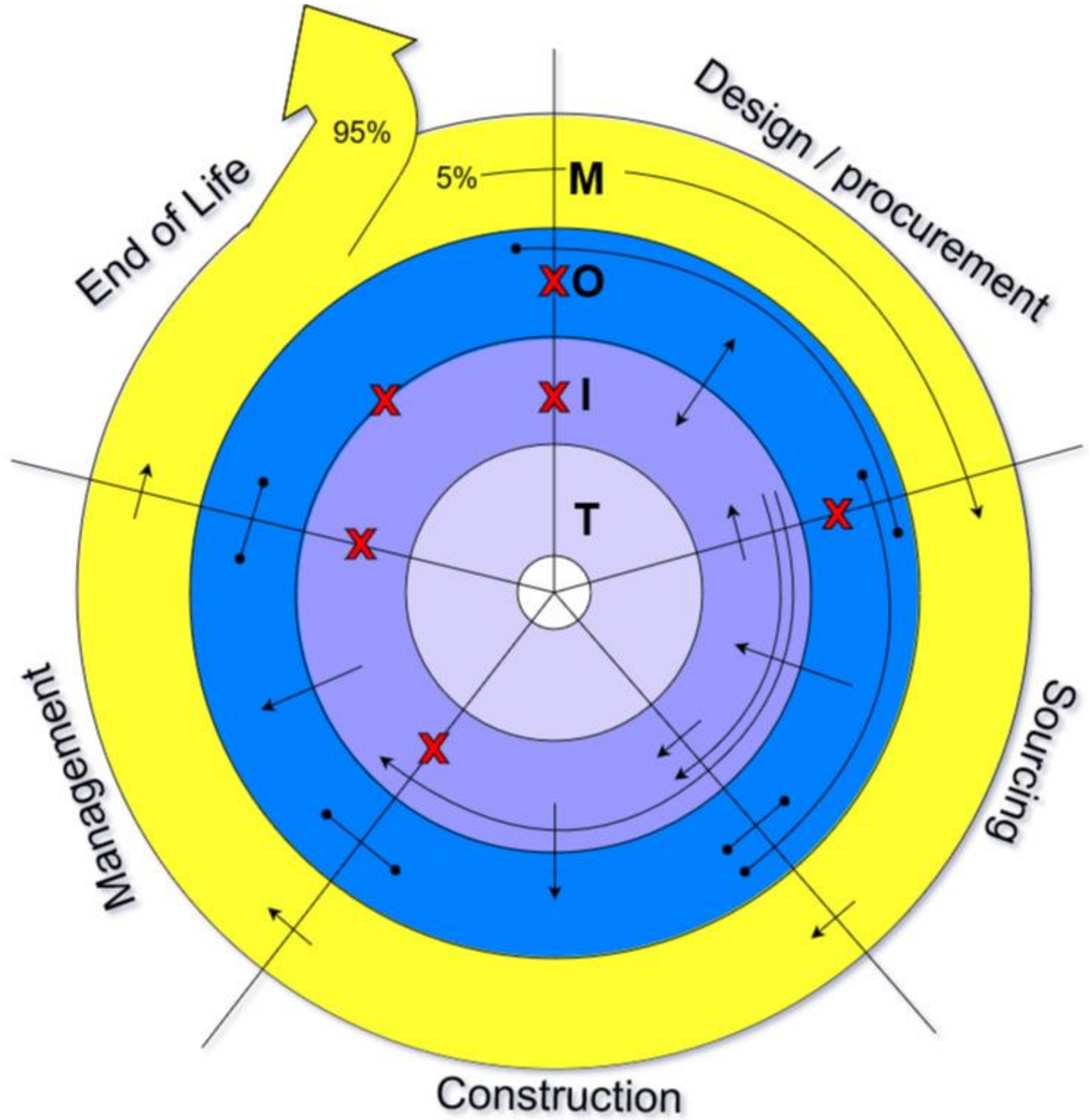


**Figure 6***:* Generalized view of the concrete chain and its cycles: material cycle (M), organizational cycle (O), information cycle (I) and time cycle (T). This figure is extended from personal communication with respondent #6. Flows of materials and information are represented by black arrows, indicating the direction of the flow. Lines with dotted ends represent social interaction in the organizational cycle. A red X represents the absence of a flow, meaning no action takes place. Additional information is provided in Table 3.

**Table 3**: The concrete value-chain sectors, their material, information, organization, and life-cycle flows. The information requirements in this table exclude costs since this is a universal factor across the chain.

Abbreviations: BIM = Building Information Model, ECI = Environmental Cost Indicator, EPD = Environmental Product Declaration, EWDIC = Electronic Waste Declaration Information and Communication, FCQ = Foundation for Construction Quality, NED = National Environmental Database, NWR = National Waste Registry, WIA = Waste Incineration Ashes

| | *Design / procurement* | *Sourcing* | | *Construction* | | *Management* | *End of Life* | |
|---|---|---|---|---|---|---|---|---|
| *Material* | - | gravel, sand, cement, additives | concrete rubble | concrete (prefab elements or in-situ) | concrete (prefab elements or in-situ) | concrete (prefab elements or in-situ) | concrete rubble | concrete elements |
| *Organization* | landowner, designer, government, developer | primary aggregate / cement / additive producer | recycler / SRM company | concrete producer | construction company | owner, manager | demolition company | deconstruction company |
| *Requested information (from the chain)* | material ECI | source location, quality, quantity, composition | source location, quality, quantity, composition (use of WIA, f.e.) | quality, quantity, composition (use of WIA, f.e.) | construction design | maintenance requirements | recycling requirements, type of concrete, composition (use of WIA, f.e.), quality | BIM, type of concrete, composition (use of WIA, f.e.), quality |
| *Information source* | NED | NED, private databases (Deltares system for coastal sand, f.e.) | NED, non-public sources, sometimes the info is not available | NED / BIM | BIM | BIM | - | BIM |
| *Information generation (which could be passed on)* | construction design, construction ECI | source location, quality, EPD, ECI | source location, quality, EPD, ECI | composition, quality, EPD, ECI | - | - | source location, quantity, (visual-based) quality | source location, quantity, (visual-based) quality |
| *Information registration system* | BIM / NED | private information systems, NED | private information systems, NED | BIM / NED | - | BIM / private information systems | EWDIC, quality is not (yet) recorded in this database, private information systems | EWDIC, quality is not (yet) recorded in this database, private information systems |
| *System / database owner* | private database / FCQ | private database / FCQ | private database / FCQ | / FCQ | - | | NWR, private owner | NWR, private owner |
| *Time in life-cycle phase* | 1-10 years | 1 year | | 1-5 years | | 20-100 years | 1-2 years | |

Although the generation, registration, and communication of information between organizations in the early stages of the cycle are well-established (design/procurement, sourcing, and construction), this information is generally not passed on beyond the construction stage. While some managers aim to use BIM for maintenance -to see which parts need inspection/replacement at what time- interviewees mentioned that this rarely happens due to the excessive size and details of a construction's BIM (ID# 15, 19). Moreover, the respondent mentioned that there are no standardized BIM guidelines, which hampers interoperability (ID# 15). While managers do receive an overview and timeline of which construction elements need maintenance, they rarely use BIM for management operations. As a result, the management history is not digitally recorded or lost by the time the construction reaches its EoL.

The vast majority of EoL constructions do not have digital construction information available, which makes it difficult to utilize their full potential value, and generally results in demolition. At the EoL stage, constructions are visually inspected for dangerous materials (such as asbestos) and salvageable parts. One respondent mentioned that with a material passport system, this information would already be available, saving time and money (ID# 14). Another respondent elaborated that due to budget and time constraints, buildings are usually demolished as quickly as possible, meaning no selective demolition takes place (ID# 11). Also, demolition is generally the only option since EoL constructions are not designed with deconstruction in mind. At this stage, demolition concrete is recorded in the national Electronic Waste Declaration Information and Communication (EWDIC) system, which is a waste monitoring/management tool of the Dutch government. This information is not available to private companies since it contains market-sensitive information such as the origin, intermediaries, processor, processing method, and final destination of a waste flow. While extensive, this system does not register quality.

The recycler accepts concrete that passes a visual quality assessment, which mainly focuses on the presence of contaminants (wood, plastic, etc.) (ID# 13). After processing, the product, such as concrete granules of a specific size, receives a quality certificate, usually containing the ECI. The product's ECI is calculated using a standardized LCA and is stored in the NED. Companies are required to update the ECI information periodically. However, this means that while a batch of concrete can be certified according to a general standard, batch-specific information, such as the exact type and quantity of pollution, is not recorded. For concrete returning to the sector, only the product certificate is digitally recorded. All other information about the concrete (composition, strength class, etc.) does not accompany the material through the chain. If the original information regarding composition etc. would be available, an additional quality assessment would be required to account for the possible contamination from the demolition process. Currently, concrete quality is (only) visually assessed but not independently verified. To tackle this problem, the TU Delft has developed a spectroscopy-based quality assessment machine, which provides automated, independent quality certification for the sourcing phase (Di Maio et al. 2012). This system provides immediate local quality assessment, in contrast to the current method, which manually assesses the quality in a certified laboratory. By adding a quality component to concrete rubble, recyclers no longer depend on visual inspection methods. The next step would be to make this information available to the chain.

Since respondents mentioned that an information system for concrete should integrate well with existing practices, one respondent suggested a decentralized system that connects to the various existing databases to store and retrieve the information instead of creating a new centralized registration system (ID# 24). This way, it is a matter of communication, rather than registration. Currently, the information which is generated by the different sectors is stored in various private and public databases. Since the information requested by the other sectors is generally produced elsewhere in the chain, the current challenge is not generating more information, but storing it where others can access it. For example, while the composition of concrete is one of the most requested types of information, it is not passed on beyond the concrete production sector because the builder usually has no interest in the exact composition; the concrete should fulfill construction criteria, such as a specific load-bearing capacity. If the builder does not receive the composition, it does not pass through the chain. All interviewed concrete producers agreed they could share the composition of their concrete (ID# 1, 17, 18). The composition could be recorded in the concrete's 'birth certificate' that accompanies the material throughout its life-cycle. This 'birth certificate' could remain stored in a concrete producer's database, which would be accessible to other actors in the chain. An essential requirement is a normalized format to store this information (ID# 23). Current efforts by Platform CB'23, an organization that includes the Dutch normalization institute, are geared towards generating a standardized material passport system format across the construction industry (Platform CB'23 2019).

In conclusion, a sector-wide approach for the normalization, sharing, and security of information is required. The focus of the approach should be on information logistics and access, rather than information registration. However, for the transition from the EoL to the sourcing phase, additional quality information registration is required. If the producers of information are made responsible for its generation and registration, the system could integrate better within the existing infrastructure, and cost less, since most of the information is already recorded, but not shared. The right information could be retrieved from all the various databases using the unique material passport serial number. Similar to the NED, different access levels allow for sensitive information to only be available to the ones with the right credentials. Of course, such a decentralized system will still require investment in terms of time, labor, and money, but might be more adaptable and cost-effective than an entirely new information platform. Essential to its success, however, is the cooperation by all actors in the chain, which should be stimulated through cooperation, policy, and innovative business models.

## 5.3 SRQ 2 results

*"What are the strengths and weaknesses of an RFID-based material passport for storing information in concrete aggregates on a lab-scale?"*

This section presents the results of the laboratory experiments, as described in section 4.2.

I. This experiment assessed the various reading ranges of the RFID tag when encompassed in different materials. The test revealed distinct patterns per material (Figure 7). The RFID tags showed much higher readability along the 0°-180° axis than the 90°-270° axis. This shape corresponds to previous observations by Bheemireddy (2018, unpublished) and is a result of the directionality of the RFID antenna (Appendix L). The maximum reading range was found with a gravel of 8-16 mm (≈ 56 cm), the minimum with water (≈ 3 cm). The overall best-conducting material was sand 0.25-0.50 mm (≈ 36 cm average). Out of the substances tested, the baseline (open-air) scenario had the second-lowest overall readability.

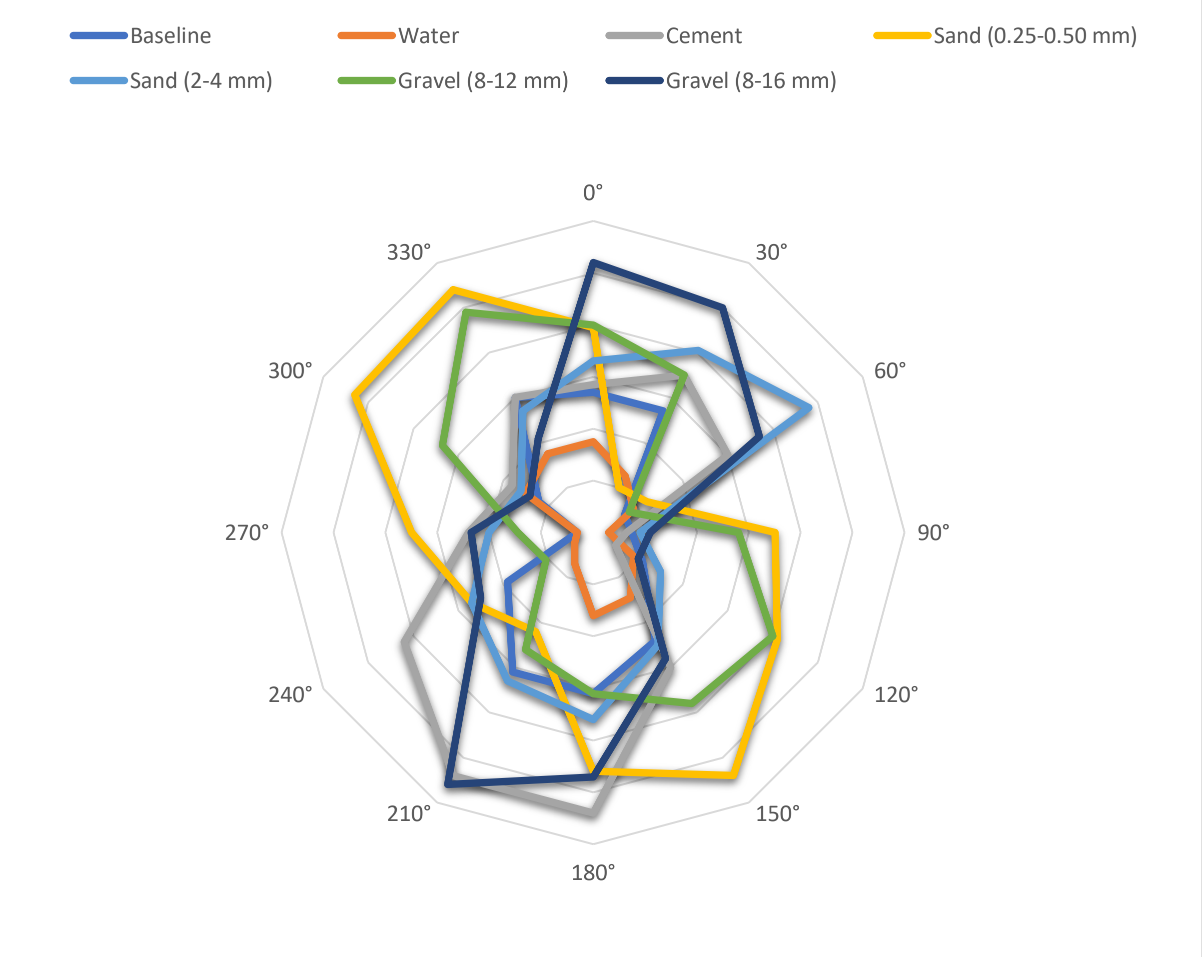


**Figure 7:** Radar chart depicting the maximum reading distances of the RFID tag through various substances. It excludes the 6 cm radius of the material and 3mm of the plastic cylinder. The distances of the radar chart are in 10 cm increments.

II. As a result of dropping group ‘3’ (15 RFID tags) with 12.5 kg of coarse aggregates from a height of 2.5 m, two tags became unreadable; tag 3-1-5 broke within five repetitions, 3-3-5 between five and ten repetitions. Two others got severely chipped (3-1-2 and 3-1-3).

III. During the tumbling with a dry concrete mix for 90-120 seconds, one tag broke (3-1-2). This tag had already been chipped in test II. One additional tag (3-2-4) became difficult to read. None of the group ‘2’ tags showed severe signs of visible wear or reduced readability.

IV. After submersion in water for 60 minutes, all of the tags remained readable. The water did not appear to have any effect on readability.

V. During the mixing of concrete for the three group ’1’ rectangular prisms, 3 RFID tags were placed inside the wet mixture and tumbled for 20 minutes. Although three rectangular prisms were cast, two tags were found in the same prism, leaving one prism with one tag, and the other empty. Due to the random mixing, the sides of the rectangular prisms were seemingly not aligned with the RFID antenna, resulting in short reading ranges (<3 cm) under standard angles. Although higher reading ranges could sometimes be observed by moving the reader out of the perpendicular angles with the sample, these data were not recorded to maintain the repeatability of the methods. This rectangular prism group was the only group to showcase a net negative reading range through time.

The samples in which the tags were placed manually showed different results. Readability increased over time amongst all group cube averages (Table 4). Although group ‘3’ had the highest average increase, the reading distance was generally meager (<7.5 cm). The control group had the overall highest average reading distance, followed by group ‘2’ and ‘3’. This is expected to be a result of the decrease in water content of the concrete samples since water blocks the RFID signal (Figure 7)

Due to the asymmetrical shape of the rectangular prism (10x10x40 cm), sides three and four had a concrete thickness of 20 cm, whereas all other sides had a thickness of 5 cm, which is reflected in the reading ranges of these sides, which are overall lower than sides one, two, five, and six (Table 5). After 28 days, the prisms with rebar had the highest overall reading range, and the highest reading ranges for sides three and four, followed by group ‘2’, the control group ‘0’, group ‘1’ random, and finally, group ‘3’. None of the sides of the group ‘3’ prism were readable.

**Table 4:** Average maximum reading distance (in cm) per RFID tag group and percentage change through time. Each numbered group consisted of three samples.

| | '0' Cube | | | '2' Cube | | | '3' Cube | | |
|---|---|---|---|---|---|---|---|---|---|
| | Day 3 | Day 28 | % change | Day 3 | Day 28 | % change | Day 3 | Day 28 | % change |
| Side 1 | 19.3 | 30.3 | 57% | 19.3 | 34.3 | 78% | 1.7 | 7.3 | 340% |
| Side 2 | 11.0 | 20.5 | 86% | 13.7 | 23.3 | 71% | 0.0 | 0.0 | 0% |
| Side 3 | 22.5 | 38.2 | 70% | 9.8 | 18.5 | 88% | 0.0 | 1.0 | N.A. |
| Side 4 | 18.7 | 50.0 | 168% | 13.5 | 20.0 | 48% | 1.0 | 2.0 | 100% |
| Side 5 | 17.2 | 21.7 | 26% | 19.3 | 30.3 | 57% | 0.0 | 0.0 | 0% |
| Side 6 | 18.0 | 32.0 | 78% | 18.7 | 26.3 | 41% | 3.3 | 4.7 | 40% |
| Total | 17.8 | 32.1 | 81% | 15.7 | 25.5 | 64% | 1.0 | 2.5 | 96% |

**Table 5***:* Average maximum reading distance (in cm) per RFID tag group and percentage change through time. There were only duplicates for group ‘1’ (both rebar and random), the other group does not depict averages but values of single samples.

| | '0' prism | | | '1' prism rebar | | | '1' prism random | | | '2' prism | | | '3' prism | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Day 3 | Day 28 | % change | Day 3 | Day 28 | % change | Day 3 | Day 28 | % change | Day 3 | Day 28 | % change | Day 3 | Day 28 | % change |
| Side 1 | 6.0 | 9.0 | 50% | 22.0 | 35.0 | 59% | 0.0 | 0.3 | N.A. | 21.0 | 35.5 | 69% | 0.0 | 0.0 | 0% |
| Side 2 | 12.0 | 17.0 | 42% | 16.0 | 26.7 | 67% | 2.3 | 0.8 | -64% | 18.0 | 32.0 | 78% | 0.0 | 0.0 | 0% |
| Side 3 | 0.0 | 12.0 | N.A. | 5.0 | 6.2 | 23% | 1.3 | 1.0 | -25% | 0.0 | 0.0 | 0% | 0.0 | 0.0 | 0% |
| Side 4 | 0.0 | 19.5 | N.A. | 0.0 | 5.0 | N.A. | 1.0 | 1.0 | 0% | 0.0 | 0.0 | 0% | 0.0 | 0.0 | 0% |
| Side 5 | 8.0 | 16.0 | 100% | 7.0 | 29.8 | 326% | 1.2 | 1.0 | -14% | 20.0 | 28.0 | 40% | 0.0 | 0.0 | 0% |
| Side 6 | 6.0 | 15.0 | 150% | 14.5 | 27.7 | 91% | 0.0 | 0.0 | 0% | 21.0 | 27.0 | 29% | 0.0 | 0.0 | 0% |
| Total | 5.3 | 14.8 | 85% | 10.8 | 21.7 | 113% | 1.0 | 0.7 | -21% | 13.3 | 20.4 | 36% | 0.0 | 0.0 | 0% |

## 5.4 SRQ 2 discussion

The RFID technology has promising potential use as a material passport (Iacovidou et al. 2018). The RFID-based system tested in this experiment showed opportunities for real-world applications in terms of ease of use and relatively low cost in comparison with active RFID tags. While useful for low-exposure uses, more research should be conducted to develop tags that withstand the exposure to the external forces in the concrete handling and production process.

The dropping of the tags (test 2) resulted in physical damage and appeared to affect the overall readability of the tags (Table 4, 5). Although exposure to water and short exposure to the dry concrete mixing process did not appear to have significant impact on overall performance, exposing tags to 2.5-meter droppings with coarse aggregate (group ‘3’) and placement in a mixer for twenty minutes in a wet concrete mix (group ‘1’ random) appeared to drastically affect reading performance.

The readability of the tags seemed to reduce with increasing material thickness. The short sides of the rectangular prism (5 cm concrete) remained readable, while the long sides (20 cm concrete) generally had lower reading ranges or no signal at all. If applied in real-world constructions, this could cause readability issues if the tag ends up encased by concrete >20 cm. However, considering the tags are passive, meaning the power of the reader determines their signal strength, a stronger reader could provide better readability performance but might give up the portability and ease of use of a handheld reader. Also, the undesired performance of the RFID tags when exposed to outside forces might prove problematic during the recycling phase of concrete, which will likely destroy them. In addition, the tags were placed in small samples and were not exposed to the pressure they might receive when embedded in an actual construction.

## 5.5 SRQ 3 results

"*What are the main opportunities and barriers for the diffusion of an integrated RFID-based material passport system, and which niche strategy could be adopted to optimize diffusion?*

Based on the twelve factors formulated by Ortt et al. (2013b), an analysis of the RFID-based IMPS will be performed, after which the most appropriate niche strategy is formulated.

Factor 1: *The new high-tech product*. While the Madaster has proved the functionality of a BIM-based material passport system, the current RFID-based passport cannot provide the necessary functionality to support the information system. In short, while the technological principles of the technology are understood, the functionality is insufficient, which means that large-scale diffusion is not yet possible.

Factor 2: *The production system*. The physical production of the material passport system and RFID tags is not considered a problem as it already takes place on an industrial scale. Adjustments in the production process should be made to make the tags more resilient against external forces, but this is unlikely to require radically new production processes. Therefore, the production system is considered to be up to scale.

Factor 3: *Complementary products and services.* The services needed for the functioning of this system still require development; the use of RFID tags in industrial concrete applications has started only in the last several years. Also, the use of techniques to bring back concrete to its aggregates is still in development, although in a mature stage. The crushing techniques that take place before the use of the ADR are well-established. However, the unavailability of the appropriate RFID technology for its application means that large-scale diffusion is not yet possible.

Factor 4: *Suppliers*. The suppliers of knowledge regarding material passport systems are present in the Netherlands (Madaster, f.e.), and RFID tags are a universal product. Therefore, the supply of these products is not expected to be a problem.

Factor 5: *Customers*. As a launching customer, the government is already involved with the use of a material passport system, as evidenced by the Platform CB '23 project. The government is already using digital information systems for asset/resource management. Recently, they have started exploring the possibility of using RFID tags in concrete. Besides the government, the results of SRQ 1 show that the majority of the concrete chain is interested in a material passport system. However, unlike the government, not all actors are willing to pay additional costs for its implementation, which should hopefully change once economies of scale lower costs, or when regulations make its use mandatory.

Factor 6: *Institutional aspects.* The rules and regulates regarding the use of material passport systems and RFID technology are currently still in development. Both the government and contractors need to get used to these new technologies and their integration into existing frameworks. This ties into the grander challenge of transitioning to a CE, of which this system is a part. However, organizations such as Platform CB '23 aim to tackle these challenges by connecting organizations with circular ambitions, and developing national agreements for circular construction by 2023. It connects organizations such as the Dutch normalization institute, industry members, Madaster, and the national government.

Factor 7: *Knowledge of technology*. The knowledge of technology regarding information systems is present, although continued innovation takes place. Meaning that there is enough knowledge to “develop, produce, replicate, and control the technical principles of a product” (Ortt et al. 2013b, p. 4). However, knowledge regarding the use of passive RFID tags in concrete is currently underdeveloped and merits more research, especially when used for concrete aggregates.

Factor 8: *Natural resources and labor.* The resources required for both the information system and RFID tags are not considered critical, which should not be considered a challenge to large-scale diffusion. The potential environmental impact of the IMPS will be discussed at the end of this chapter. Since the Netherlands is a knowledge economy, enough knowledge is available for the labor required for the development of an integrated RFID-based material passport system.

Factor 9: *Knowledge of application.* The knowledge regarding the application of material passport systems and RFID technology is considered to be understood since both technologies are currently applied in practical applications.

Factor 10: *Socio-cultural aspects.* There do not appear to be significant socio-cultural hindrances regarding the use of information systems or RFID technology. Of course, a change will result in resistance from the status quo, but this seems to be different from deeply embedded socio-cultural norms. In general, there seems to be a consensus regarding the use of an integrated material passport system.

Factor 11: *Macro-economic aspects.* According to a report by the European Commission (2019), the economy is expected to grow in 2019 but slightly decline in 2020. However, this does not indicate an economic recession. Moreover, the national budget until 2024 shows an increase in spending on infrastructure, and the circular economy (Infrastructuurfonds 2019). Therefore, funding for these type of technologies is expected to remain available in the (near) future.

Factor 12: *Accidents or events*. No accidents in terms of material passport systems or RFID have taken place. On the contrary, an information system could prevent accidents from happening by indicating when it is time for refurbishment or replacement of construction components. Also, if a specific construction fails, it will be easy to find other at-risk constructions with the same construction type. The future location of potentially hazardous materials could also be facilitated if this information is recorded in an information system. Asbestos, f.e., was a widely used insulation material that turned out to be highly dangerous. Because it is unclear where and how it was applied, buildings still have to undergo an asbestos check before being demolished.

## 5.6 SRQ 3 discussion

By analyzing the factors of the framework by Ortt et al. (2013b), the main bottlenecks are (a part of) the new high-tech niche-innovation itself, the complementary products and services, institutional aspects, and knowledge of the technology. Based on this, a niche strategy should focus on technology and knowledge development. An appropriate niche-strategy would be the *Demo, experiment, and develop* strategy in which the technology is first used in pilot and demonstration projects to show the public the potential of the technology. Meanwhile, this serves as input for the continued research on the subject. This ties into the *Educate* niche strategy, which aims at sharing knowledge to others in the value-chain to for knowledge development. A niche strategy that already seems to be applied in terms of the integrated material passport system is the *lead user* strategy, in which early adopters help to co-develop and experiment with the product.

## 5.7 Chapter conclusion and limitations

In conclusion, the development and communication of knowledge are considered the most crucial factors for developing an IMPS in the Netherlands. Developments should focus on gathering lead users, research institutes, and investors, in a 'coalition of the willing,' for experimentation with (decentralized) information systems, and RFID technology. Regarding the MPS, a sector-wide approach for the normalization, sharing, and security of information is required. The focus of the approach should be on information logistics and access, rather than information registration. However, for the transition from the EoL to the sourcing phase, additional quality information registration is required. Although the RFID-based system tested in this experiment showed opportunities for real-world applications in terms of ease of use and low cost, its performance is currently undesired in terms of resistance to external forces.

Once the technologies reach a certain level of maturation, the only potential barrier appears to be *institutional aspects*. However, current efforts are already being made to adjust these rules and regulations to fit the development of a CE in the Netherlands. Although not mentioned as an essential factor by Ortt et al. (2013b), the existing economic incentive structure of the regime remains a substantial barrier, requiring innovative business models.

### Environmental and economic considerations

The development of niche innovations requires a balance between the operational- and embodied environmental costs and benefits. The digitalization of information is supported by devices that require minerals for production, and electrical energy for operation. These reflect the embodied impacts and operational impacts, respectively. In the case of the MPS, this will likely not drastically change energy consumption. The challenge is the communication between these systems, not the lack of hardware. Nonetheless, the demand for additional data storage and processing capabilities will require electricity, which should be sourced renewably.

The diffusion of the IMPS, on the other hand, requires RFID tags. Since the operational energy of passive RFID tags is zero, the embodied energy determines the environmental performance. Because the exact composition and weight of the tags for this experiment are unknown, information regarding RFID material composition and environmental impact derived from the literature (RAND 2012). RFID tags usually contain metals (gold, silver, copper, aluminium, and nickel), and silicon, depending on their type. The most substantial environmental impacts are from the precious metals, which account for 37-81% of the total environmental impact (for an aluminium- and silver-based chip, respectively). Overall, the lowest environmental footprint comes from aluminium-based chips.

A case calculation for the Amsterdam Metropolitan Area (AMA) is made to put the material use of the IMPS into perspective. In 2018, an estimated 525 kilotons of waste concrete was crushed in the AMA (Gemeente Amsterdam 2020, unpublished). If a density of 2400 kg/m$^3$ of concrete is assumed (The Engineering Toolbox 2019), a volume of roughly 218,875 m$^3$ was crushed. Assuming this remains in the concrete cycle (100% recycling using ADR and HAS technologies), and one RFID tag per m$^3$ of concrete is added, a total of 218,875 tags are required. Although the RFID tag for this thesis is smaller (5x5x3mm) than the reference tag (30x30x1mm) (RAND 2012), it is assumed that both contain similar materials. However, the values of the reference tag are proportionally divided based on the difference in volume between the tags (factor 1:10). For this calculation, all tags are assumed to be aluminium-based, since it is the most common type of tag (RAND 2012). The results are presented in Table 6.

**Table 6:** Material composition of RFID tag and material requirements for the AMA

| | Reference tag Mass [mg] | Assumption RFID tag Mass [mg] | For AMA Mass [mg] | For AMA Mass [g] |
|---|---|---|---|---|
| Silicon | 0.1 | 0.01 | 2189 | 2.19 |
| Gold | 0.01 | 0.001 | 219 | 0.22 |
| Nickel | 0.01 | 0.001 | 219 | 0.22 |
| Aluminium | 8.3 | 0.83 | 181666 | 181.67 |

In terms of the metal requirements for RFID tags for all the waste concrete treated in the AMA, a total of 184.29 grams is required. The material's impact is estimated at 7 kg $CO_2$ (RAND 2012). Even if the actual RFID tag and the reference tag had the same material requirements, the impact is considered small. However, this calculation does not take the production, distribution, and use of the RFID tags into account. When applied in concrete, the tags will not be able to be salvaged, since they will most likely be destroyed and mixed in the recycling process, meaning their resources will be lost. More research into the balance between environmental costs and benefits is required to make an accurate assessment of the environmental implications of an IMPS in the Netherlands. Regarding the development of technology, increased use will make it cheaper, and more (resource) efficient (Bose and Yan 2011). Therefore, standardization and experimentation are required (Thomas 2008).

Besides the environmental impact, the economic aspect of this technology should be considered. The economic costs of the spectroscopy-based quality assessment method, including RFID tags, will be estimated. Because the operational costs of the RFID-based system are unknown, this assessment only considers capital costs. The spectroscopy machine currently costs € 120,000, and the RFID tags cost € 0.50 apiece. It is assumed that the machine completely depreciates in 24 months, meaning a depreciation of € 5000 per month. The ADR processes 80 tons per hour x 8 hours a day x 20 days per month = 12800 tons per month. It is assumed that only the coarse and fine aggregate (≈ 60% of the mixture) will be mixed with the RFID tags, resulting in 7680 tons of SRM. Considering € 5000 per month and 7680 tons per month, the total costs are roughly € 0.65 per ton. Considering that one RFID tag will be applied per $m^3$ of concrete (weighing 2400 $kg/m^3$), the costs of RFID per ton is € 0.21. The total capital cost is € 0.65/ton + € 0.21/ton = € 0.86/ton. Although this estimate does not include operational costs, it demonstrates that the capital costs are less than € 1/ton, which is important for the adaptation of the technology.

## Limitations

The goal of this thesis is to provide insights in terms of the concrete chain's transition to a CE. While generalizations regarding the entire concrete chain are made, these are based on the answers from a small group of interviewees, and may therefore not be generalizable. Moreover, the distribution of respondents per sector in the chain was uneven (Appendix A), potentially leading to more discrepancies. In terms of the laboratory tests, due to the small sample sizes, limited exposure time, and non-realistic environments, the RFID technology should be tested in more realistic scenarios.

In order to effectively develop and diffuse an IMPS in the Netherlands, cross-disciplinary cooperation is required. Due to the size and complexity of the concrete chain, it is essential to receive input from its actors to understand their ambitions and motivations. Unfortunately, the overall response rate for this thesis is 11%. One sector had a single respondent, who thereby became the voice of their entire sector. Because the information from local actors was used to portray a national picture, the generalization might result in unrepresentative conclusions. Lastly, the interview data might contain subjective (un)conscious biases.

Regarding the RFID tag tests, the laboratory setting did not accurately reflect realistic application environments. Due to the small samples, no definitive conclusions about their performance in larger concrete structures could be drawn. In addition, the performance of the RFID tags was measured during several weeks, a fraction of its expected use.

If the Netherlands decides to develop and diffuse an IMPS, more research in terms of actor evaluations, perception of the technology, potential value models, policy, and regulations, should be conducted. This research served as an exploratory study on the topic and only scratched the surface. Before such a system is implemented, the performance of RFID technology should improve, requiring additional financial and time resources. To prevent additional value and environmental loss, more research regarding the environmental costs and benefits, and the appropriate business models for this technology should be explored.

# 6. Future outlook

Based on the previously described status-quo, this chapter shifts its gaze towards the future. The future outlook of the RFID-based IMPS discusses trends on the landscape, regime, and niche level.

## 6.1 Landscape

The global presence and impact of humanity's activities are so profound that global collaborative actions are required to maintain a balance between our natural environments (the biosphere) and man-made environments (the technosphere). In the construction sector, which consumes 40% of primary global energy utilization, the majority (80%) is operational energy, the minority (20%) embodied energy (Huang et al. 2018). Therefore, operational energy receives the most attention in sustainability debates. However, due to the rise of zero-energy construction technologies, operational energy may become negligible, meaning that embodied energy will increasingly affect sustainability performance (Rovers 2015). While high embodied energy materials, such as cement and steel, can be used in such a future, their value maintenance in the technosphere should be ensured by extending their functional life beyond the current average.

International agreements are required to ensure the effective management of embodied energy. Although collaborations such as the Paris Agreement exist, the vast majority of the pledging countries still have insufficient policies for actualizing the required changes (ClimateActionTracker 2019). However, the recently published EU Green Deal calls for increased $CO_2$ reduction, especially for polluting industries, such as the cement industry (Slooten 2019). It requires examining current laws and regulations. Shaping effective policy requires data, which is generally collected for its use in models, virtual simplifications of reality that help us understand our world. For example, to manage embodied energy, we must know how it 'behaves' in the technosphere; we want to know the 'what, where, when, who and why.' Due to the lack of an enforcing global organization, the responsibility for policy development lies with regional authorities and individual states. In the EU, the development of models for understanding the movement of embodied energy, and determining the required policy for mitigating climate change is taking place (REPAiR 2019). In the Netherlands, the demand for such systems is also developing, as evidenced by the pilot case study of the Amsterdam Metropolitan Area (Gemeente Amsterdam 2020, unpublished).

Historically speaking, we live in the information revolution. Although we see value in producing digital information to model the technosphere, we do not (yet) know what should be collected, how it should be stored, shared, updated, and used. Therefore, current EU projects focus on the standardization of all these processes (BAMB 2019), while others aim to provide information to policymakers on various spatial scales (REPAiR 2019). Regardless of the focus, it is clear that the EU is exploring the potential of digital solutions for climate change mitigation.

## 6.2 Regime

In the Netherlands, the socio-technical regime is bustling with activities, the wheels of the circular economy have been set in motion, and different forces are searching, thinking, inventing, collaborating, and competing. As mentioned in the previous section, the demand for information to model the technosphere is increasing, fueled by the urgency of the climate crisis. Therefore, an evolution of the Dutch information infrastructure is taking place in both the private and public sectors (ID# 16, 24). Although the Madaster has successfully applied material passport systems for utility constructions for several years, their use in the infrastructure sector remains novel (Mol et al. 2019). Moreover, the use of material passport systems remains limited to specific markets and user preferences and has not yet anchored itself into mandatory policies or construction regulations. However, driven to develop a circular economy by 2050, the Dutch government is actively exploring the potential of this technology, as evidenced in the CE transition agenda for the construction industry (Rijksoverheid 2018). Platform CB '23 is currently looking into the normalization of the information types, formats, and structure for material passports in the construction sector (Platform CB'23 2019). Platform CB '23 aims to connect organizations with circular ambitions and develop national agreements for circular construction by 2023. It connects organizations such as the Dutch normalization institute, industry members, Madaster, and the national government. Although research is still ongoing and no definitive measures have been released, these developments provide clear indications of the utilization of these systems in the near future, also on a European level (ID# 23).

Simultaneously, several trends are developing in the concrete chain. The following paragraphs discuss the future outlook concerning the demand and supply of concrete in the Netherlands. As mentioned previously, 95% of the waste concrete is used for road construction. According to the 2019 Dutch national infrastructure budget (Infrastructuurfonds 2019), the increase in budget for the realization of main roads occurs gradually, to reach a 95% increase in 2021. Until 2024, a stabilization will take place, which is around 30% higher than the current budget. Also, the budget for exploration and actualization of main road constructions continually increases from 123 million in 2019 to 1085 million in 2024, a 781% increase. Regarding maintenance, the budget declines steadily until 2024, where it will reach a 26% decrease to the current budget. However, the budget for replacement will increase to 278% of the current budget in 2023. Due to intensive infrastructure development in the '60s, and a lifespan of several decades, it is expected that more waste concrete will become available in the coming years due to replacement. While the maintenance phase generally does not demand new concrete waste (ID# 21), the construction of new roads indicates a certain future demand for waste concrete if no alternative methods for road-base construction are implemented. The increased construction and demolition provides an excellent opportunity for the testing and implementation of technological niches, such as the IMPS.

While the demand for concrete waste is expected to increase, the supply appears to be decreasing (ID# 4, 8, 13). It is unclear whether this assessment includes the expected liberation of concrete waste from the 1960's infrastructure; the interviewees did not mention it. Perhaps the next years will see an increase in concrete waste supply. Nonetheless, interviewees mentioned a noticeable decrease in the supply of urban concrete waste, perhaps as a result of repurposing, i.e., from office to residential space, and the past choice for other construction materials. This coincides with trends in municipalities to use construction value-maximization models for decision-making in every step of the lifecycle (Berger et al. 2019). Nonetheless, Cascade (2018), the primary aggregate branch organization, calculated the supply gap of concrete waste to be 80%, meaning that only 20% of the demand for concrete aggregates can be fulfilled by waste concrete. This gap has recycling companies looking across the border to import concrete waste. While the use of concrete granules as a replacement of coarse aggregates can be considered circular, transport distance is essential in determining the ECI of concrete. As a result, the integration of imported goods into the LCA calculation behind the ECI is receiving more attention (ID# 22).

The digitalization of information regarding critical infrastructure is also placing more emphasis on cybersecurity as a means of national security. A member of the Dutch government mentioned that the information about resources would be used to understand the future demand and supply of materials, such as concrete, for strategic national material policy (ID# 24). In addition, the national government intends to develop policy around the ECI of materials by adding a circularity indicator which is developed by Platform CB'23. Material passports will supply the necessary information. The collection of data itself is not circular; it is about the decision that it informs (ID# 23). The national government intends to act as a launching customer and develop complementary rules and regulations.

## 6.3 Niche

On the niche level, technological advancements are (co-)developed by universities, private actors, and government organizations. These advancements are aimed to maximize value in a CE by providing insight into the complexity of the technosphere (Figure 1). The technosphere can be seen as an interconnected system of material/energy flows and stocks. By collecting data and modeling the technosphere, our ability to interact and coordinate activities increases. Governments require this to govern healthy, abundant, and fair living environments for their citizens and natural ecosystems. In terms of business, the optimal distribution and use of resources can be facilitated by creating platforms for business trade and matchmaking. The following paragraphs discuss several unique technological niches that apply to the material-, digital-, and material/digital levels.

On the material level, the vision of concrete in the CE is that of an adaptable and versatile material, which maintains its highest value through multiple lifecycles. Constructions can be made according to modular design principles, which make them adaptable for a changing world (Rios et al. 2015). However, concrete components will eventually reach their functional EoL. Concrete needs to return to its primary aggregates to be reintroduced into the concrete chain. The ADR and HAS, and similar technologies, can 'revert' concrete back into its coarse, fine, and ultra-fine fractions, allowing on-site concrete aggregate reuse. These technologies ensure local, cost-effective value creation, and are moving out of the pilot-scale to industrial-sized applications (Lotfi et al. 2017b), ID# 17).

However, due to the energy required to dehydrate the reacted cement, only the unreacted cement can be used in new constructions to avoid additional emissions. This means that the recovered cement can only partially replace the cement demand for new construction. Therefore, biogenic alternatives for calcium carbonate (the most polluting element in cement production), are being developed. One option is to use the $CaCO_3$-rich shells from mussels/oysters, as a replacement for limestone. These will be farmed for human consumption while providing essential resources and habitats for aquatic biodiversity (ID# 6). The biogenic sourcing of carbon-rich materials is essential for the Dutch concrete sector to achieve its climate goals (Industry partners and Government 2018).

On the digital level, the use of data to model the flows and stocks of our society are taking place (Geofluxus 2019; ID# 24). Municipal and national governments are currently assessing the adaptability of their digital infrastructure to meet the future needs for data storage and communications (ID# 22, 24). Simultaneously, advancements in cross-disciplinary data analysis allow for the spatial mapping of the technosphere's flows (Geofluxus 2019). On the other hand, the Madaster is recording the materials in new constructions, thereby collecting information on the current building stock. However, the vast majority of the current construction stock remains unrecorded, which is why there is an increasing number of projects dedicated to mapping these stocks (Metabolic 2017). Combining such databases will allow for more accurate representations of the technosphere's dynamics.

The registration, communication, and implementation of digital information for decision-making remain a challenge. Models are only as good as their data, which means that data registration, collection, and communication should receive the primary focus. In other words, the digital representation of our physical world is only as good as the translation into digital data. Due to the various competing interests amongst actors in the concrete chain, data registration should be done according to an objective, or at least co-created, view of reality (Leising et al. 2018; ID# 4). Therefore, in the case of concrete, the TU Delft is developing an automated data quality assessment and monitoring system for concrete waste. The RFID technology has shown the potential as a connector between the physical and digital world, although the tags used in this thesis are not yet ready for applications in concrete aggregates. However, the government has shown increasing interest in this technology for storing and communicating information embedded in modular concrete structures (Consolis 2019). It is expected that future developments will focus on sensor technology, automated processing, and digitalization of existing information.

# 7. Conclusion

Using Geels' framework for understanding socio-technical transitions (2019), this thesis considered the development and diffusion of an integrated RFID-based material passport system for concrete in the Netherlands. The attitudes of actors in the concrete chain and the performance of RFID technology was considered essential to the developments of such a system. A mixed-methods approach was used to assess both factors.

In short, the ambition and need to develop information systems for a circular economy is shared by the public and private sector (Rijksoverheid 2018; Mol et al. 2019), and is confirmed by the research results; the majority of respondents (79%) think it is important to receive more information from the concrete chain, especially information regarding the concrete's composition, and environmental performance. Moreover, 85% of the respondents were interested in an information system for concrete that provides them with this information. Their motivations align partly with the literature, which states that information is crucial for maintaining value in a circular economy (Iacovidou and Purnell 2016). However, the development of such systems requires changes in economic incentives, policy, and technological performance.

In that regard, respondents mentioned that the use of the system should not require (much) additional work, preferably integrate with existing systems for information exchange, and be objective. Information systems are only as useful as their data, which means that data registration, collection, and communication should receive the primary focus. In other words, the digital representation of our physical world is only as good as the translation into digital data. Due to the various competing interests amongst actors in the concrete chain, data registration should be done objectively, or at least stem from a co-created, view of reality (Leising et al. 2018).  In the concrete chain, the most fundamental challenge is not data registration, but communication and cooperation. On the information level, data quality assurance for rubble concrete and concrete aggregates is vital for closing the information and material loop. While the majority (32%) agreed that the construction's owner should be responsible for the registration and communication of information, others pointed towards the national government (28%), the concrete sector (16%), or chain cooperation (12%). Similar to the findings of Bukvić (2018), actors in the concrete chain generally consider the responsibility for change to lie outside their scope. As mentioned by one construction company, change in the construction sector will not happen by itself; it will change as a result of laws and regulations, or due to market demand (ID# 15).

While rules and regulations are being drafted (Platform CB'23 Leidraad 2019), market demand is stimulated by national and municipal governments, which are exploring the use of innovative procurement contracts to signal the construction industry that circular design and construction, including the use of material passport systems, is becoming a requirement. Several municipalities are cooperating with concrete producers to configure a sustainable local concrete chain (ID# 6,19, 22, 28). The concrete mixing plant is considered the economic unit of a concrete chain; the customers and producers of concrete are all within a 30-50 km range. While national agreements, such as the concrete agreement, are essential for the entire value-chain, this should be translated to the local concrete chain. The entire lifecycle of concrete is firmly regionally dependent.

Besides agreements and regulations, innovative business models are required. Concrete mixing plants are owned by international concrete production companies, whose business models rely on the sale of cement and concrete (ID# 25). In order to facilitate change, the right business case needs to be developed for companies with a significant market presence (ID# 20). As mentioned by Geels (2011), these companies are at an advantage in comparison with niche-innovations due to their established practices, networks, and knowledge. Due to this ‘lock-in’ of practices, large companies are unlikely to be the initiators of change, which creates path dependency. However, if these companies support sustainable innovation, they can be essential accelerators for the adoption of new practices.

Innovative ownership/business models, such as *concrete as a service,* could change the aforementioned incentive structure. Although attractive on paper, one prefabricated concrete producer challenges the idea because the return of concrete products consumes additional time and money (ID# 17). It is considered easier to break the old concrete and order new products. In particular, such a business model increases the need for logistics, quality inspection, cleaning, and redistribution. Considering these actions currently require manual labor, the costs are higher than for the automated production process. In response, one municipal government actor mentioned that if there is enough return of standardized prefabricated products, the cleaning process can be automated too (ID# 6). However, this requires a particular volume to be cost-effective.

Lastly, the performance of the tested RFID tags and reader were currently considered insufficient as a physical material passport for concrete, requiring increased technological development before their large-scale application. Nonetheless, the use of RFID technology as a material passport provides an opportunity that merits exploration.

In conclusion, there is a growing demand for an IMPS, but there are challenges in terms of economic incentive structures, chain cooperation, rules and regulations, logistics, and technology. As mentioned by Geels (2019), such new technological innovations are generally more expensive because they have not suffered through the growing pains yet, meaning there are no economies of scale or a history of improvements. Therefore, the advised strategy is to demonstrate, experiment, (co-)develop, and share knowledge about these innovations (Ortt et al. 2013b). Although new technological innovations allow us to close the concrete loop further, the majority of secondary materials exits the cycle to road construction activities. While it has value as a road-base, its application currently prohibits its re-introduction into the concrete chain. However, current demand for concrete outweighs all secondary concrete supply (Cascade 2018). Taking the national infrastructure budget into account, construction activities will increase in the next five years, meaning the Netherlands will require virgin concrete resources for the next five years minimum (Ministry of Infrastructure and Water Management 2019). Nonetheless, governments and businesses are taking steps to develop a circular concrete chain.

# 8. References

Akanbi, L.A., L.O. Oyedele, O.O. Akinade, A.O. Ajayi, M. Davila Delgado, M. Bilal, and S.A. Bello. 2018. Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resources, Conservation and Recycling* 129(October 2017): 175–186. http://dx.doi.org/10.1016/j.resconrec.2017.10.026.

Akinade, O.O., L.O. Oyedele, K. Omoteso, S.O. Ajayi, M. Bilal, H.A. Owolabi, H.A. Alaka, L. Ayris, and J. Henry Looney. 2017. BIM-based deconstruction tool: Towards essential functionalities. *International Journal of Sustainable Built Environment* 6(1): 260–271. http://dx.doi.org/10.1016/j.ijsbe.2017.01.002.

BAMB 2019. *Materials Passports - BAMB*. [online] BAMB. Available at: https://www.bamb2020.eu/topics/materials-passports/ [Accessed 16 Dec. 2019].

Berger, I., M. Kerkstra, and C. Luijten. 2019. *Bouwwaardemodel waardevernietiging*.

Bheemireddy, R. 2018. RFID Tests in Gravel and Concrete , unpublished

Bodemrichtlijn 2019. *Bodemassen en slakken | Bodemrichtlijn*. [online] Bodemrichtlijn.nl. Available at: https://www.bodemrichtlijn.nl/Bibliotheek/bouwstoffen-en-afvalstoffen/bodemassen-en-slakken [Accessed 16 Dec. 2019].

Bose, I. and S. Yan. 2011. Potencial da RFID em projetos verdes (IEEE Explore): estudos de casos. *IT Professional* 13: 41–47. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5708283&tag=1%5Cnhttp://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5708283.

Brito, J. De and R. Silva. 2016. Current status on the use of recycled aggregates in concrete: Where do we go from here? *RILEM Technical Letters* 1: 1.

Bukvić, U. 2018. Change towards a Circular Economy: eliminating inertia in supply chains: A concrete case of stony materials supply chain in the Netherlands. Technical University Delft. https://repository.tudelft.nl/islandora/object/uuid%3Afd728d8a-a391-4f6d-af1b-558228bdfc7e?collection=education.

Caniëls, M.C.J. and H.A. Romijn. 2008. Strategic niche management: Towards a policy tool for sustainable development. *Technology Analysis and Strategic Management* 20(2): 245–266.

Cardullo, M. 2003. *Genesis of the Versatile RFID Tag - 2003-04-21 - Page 1 - RFID Journal*. [online] Rfidjournal.com. Available at: https://www.rfidjournal.com/articles/view?392 [Accessed 16 Dec. 2019].

Cascade. 2018. terugblik(06): 2018–2021.

Climate Action Tracker 2019. *Home | Climate Action Tracker*. [online] Climateactiontracker.org. Available at: https://climateactiontracker.org/ [Accessed 16 Dec. 2019].

Collectors. 2019. *Construction and demolition waste (CDW) » Collectors*. [online] Available at: https://www.collectors2020.eu/the-project/scope/construction-demolition-waste-cdw/ [Accessed 16 Dec. 2019].

Consolis. 2019. *First circular viaduct in the Netherlands - Consolis*. [online] Available at: https://www.consolis.com/first-circular-viaduct-in-the-netherlands/ [Accessed 16 Dec. 2019].

Deloitte. 2014. Construction and Demolition Waste Management in The Netherlands. http://www.newmoa.org/solidwaste/CDReport2006DataFinalJune302009.pdf.

Di Maio, F. 2018. Keynote lecture at the Seramco Conference

Di Maio, F., M. Peter, R. Somi, S. Serranti, G. Bonifazi, I. Chimica, M. Ambiente, S. Università, V.N. Burganos, and E. Skouras. 2012. Cement and Clean Aggregates from CDW : The C2CA Project Delft University of Technology Fernando Cucchietti Mariano Vázquez: 1–12.

EC Europa (2019). *Construction and demolition waste - Environment - European Commission*. [online] Available at: https://ec.europa.eu/environment/waste/construction_demolition.htm [Accessed 16 Dec. 2019].

EEA. 2015. *European environment — state and outlook 2015: Assessment of global megatrends*. *European Environment*. http://www.eea.europa.eu/soer-2015/global/action-download-pdf/at_download/file.

Ehrenfeld, J.R. 1997. Industrial ecology: A framework for product and process design. *Journal of Cleaner Production* 5(1–2): 87–95.

Erkman, S. 1997. Ecology : an historical view. *Journal of Cleaner Production* 5(1): 1–10.

European Commission. 2019. *The Netherlands*.

Eurostat. 2019. *Eurostat - Tables, Graphs and Maps Interface (TGM) table*. [online] Ec.europa.eu. Available at: https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&plugin=1&pcode=cei_wm040&language=en [Accessed 16 Dec. 2019].

Gagg, C.R. 2014. Cement and concrete as an engineering material: An historic appraisal and case study analysis. *Engineering Failure Analysis* 40: 114–140. http://dx.doi.org/10.1016/j.engfailanal.2014.02.004.

Gálvez-Martos, J.L., D. Styles, H. Schoenberger, and B. Zeschmar-Lahl. 2018. Construction and demolition waste best management practice in Europe. *Resources, Conservation and Recycling* 136(May): 166–178. https://doi.org/10.1016/j.resconrec.2018.04.016.

Gemeente Amsterdam. 2020. Startmonitor Circulaire Economie. Unpublished.

Geels, F.W. 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions* 1(1): 24–40. http://dx.doi.org/10.1016/j.eist.2011.02.002.

Geels, F.W. 2019. Socio-technical transitions to sustainability: a review of criticisms and elaborations of the Multi-Level Perspective. *Current Opinion in Environmental Sustainability*. https://doi.org/10.1016/j.cosust.2019.06.009.

Geofluxus. 2019. *geoFluxus* | *Welcome*. [online] Geofluxus.bk.tudelft.nl. Available at: https://geofluxus.bk.tudelft.nl [Accessed 16 Dec. 2019].

Ghisellini, P., C. Cialani, and S. Ulgiati. 2016. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production* 114: 11–32. http://dx.doi.org/10.1016/j.jclepro.2015.09.007.

Ghisellini, P., M. Ripa, and S. Ulgiati. 2018. Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. *Journal of Cleaner Production* 178: 618–643. http://dx.doi.org/10.1016/j.jclepro.2017.11.207.

Haas, W., F. Krausmann, D. Wiedenhofer, and M. Heinz. 2015. How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European union and the world in 2005. *Journal of Industrial Ecology* 19(5): 765–777.

Hermans, L. and T. van der Lei. 2012. *Actorenanalyses Methoden voor een Succesvol Beleid of Project*.

Hoogma, R., R. Kemp, J. Schot, and B. Truffer. 2005. *Experimenting for sustainable transport: The approach of strategic niche management*. *Experimenting for Sustainable Transport: The Approach of Strategic Niche Management*.

Hradil, P., A. Talja, M. Wahlstr, S. Huuhka, J. Lahdensivu, and J. Pikkuvirta. 2014. *Re-use of structural elements Environmentally effi Re-use of structural elements Environmentally effi*. http://www.vtt.fi/publications/index.jsp.

Hu, M., E. van der Voet, and G. Huppes. 2010. Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing. *Journal of Industrial Ecology* 14(3): 440–456.

Huang, L., G. Krigsvoll, F. Johansen, Y. Liu, and X. Zhang. 2018. Carbon emission of global construction sector. *Renewable and Sustainable Energy Reviews* 81(November 2016): 1906–1916. https://doi.org/10.1016/j.rser.2017.06.001.

Iacovidou, E. and P. Purnell. 2016. Mining the physical infrastructure: Opportunities, barriers and interventions in promoting structural components reuse. *Science of the Total Environment* 557–558: 791–807. http://dx.doi.org/10.1016/j.scitotenv.2016.03.098.

Iacovidou, E., P. Purnell, and M.K. Lim. 2018. The use of smart technologies in enabling construction components reuse: A viable method or a problem creating solution? *Journal of Environmental Management* 216: 214–223. http://dx.doi.org/10.1016/j.jenvman.2017.04.093.

IEA. 2018. *Cement technology roadmap plots path to cutting CO2 emissions 24% by 2050 - News - IEA*. [online] IEA. Available at: https://www.iea.org/news/cement-technology-roadmap-plots-path-to-cutting-co2-emissions-24-by-2050 [Accessed 16 Dec. 2019].

Industry partners and Government. 2018. *Betonakkoord*.

Infrastructuurfonds. 2019. Rijksbegroting 2020.

Köhler, J., F.W. Geels, F. Kern, J. Markard, E. Onsongo, A. Wieczorek, F. Alkemade, et al. 2019. An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions* 31(December 2018): 1–32. https://doi.org/10.1016/j.eist.2019.01.004.

Korhonen, J., A. Honkasalo, and J. Seppälä. 2018. Circular Economy: The Concept and its Limitations. *Ecological Economics* 143: 37–46. https://doi.org/10.1016/j.ecolecon.2017.06.041.

Leising, E., J. Quist, and N. Bocken. 2018. Circular Economy in the building sector : Three cases and a collaboration tool. *Journal of Cleaner Production* 176: 976–989. https://doi.org/10.1016/j.jclepro.2017.12.010.

Lotfi, S., J. Deja, P. Rem, R. Mróz, E. Van Roekel, and H. Van Der Stelt. 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. and P. Rem. 2016. Recycling of End of Life Concrete Fines into Hardened Cement and Clean Sand. *Journal of Environmental Protection* 07(06): 934–950. http://www.scirp.org/journal/doi.aspx?DOI=10.4236/jep.2016.76083.

Lotfi, S., P. Rem, J. Deja, and R. Mróz. 2017a. An experimental study on the relation between input variables and output quality of a new concrete recycling process. *Construction and Building Materials* 137: 128–140. http://dx.doi.org/10.1016/j.conbuildmat.2017.01.085.

Lotfi, S., P. Rem, F. Di Maio, A. Teklay, M. Hu, E. Van Roekel, and H. Van Der Stelt. 2017b. Closing the loop of EOL concrete(June): 83–91.

Madaster. 2019. *Home :: Madaster*. [online] Madaster.com. Available at: https://www.madaster.com/en [Accessed 16 Dec. 2019].

Maio, F. Di, P. Rem, L. Somi, S. Serranti, G. Bonifazi, M. Hu, V. Burganos, E. Skouras, F. Cucchietti, and M. Vazquez. 2012. Cement and Clean Aggregates from CDW : The C2CA Project Delft University of Technology Fernando Cucchietti Mariano Vázquez: 1–12.

Majrouhi Sardroud, J. 2012. Influence of RFID technology on automated management of construction materials and components. *Scientia Iranica* 19(3): 381–392.

Maljers, D. and J. Stafleu. 2010. Uitbreiding van het delfstoffeninformatie systeem voor het NCP.

Maljers, D., J. Stafleu, A. Wiersma, P. Kiden, and P. Frantsen. 2010. De ontwikkeling van een delfstoffeninformatiesysteem voor het NCP: resultaten van een pilotstudie.

Marzouk, M., E.M. Abdelkader, and K. Al-Gahtani. 2017. Building information modeling-based model for calculating direct and indirect emissions in construction projects. *Journal of Cleaner Production* 152: 351–363. http://dx.doi.org/10.1016/j.jclepro.2017.03.138.

McNeill, J. 2001. *Something new under the sun*. New York [u.a.]: Norton.

Metabolic 2017. *Prospecting the Urban Mines of Amsterdam*. [online] Metabolic. Available at: https://www.metabolic.nl/projects/prospecting-the-urban-mines-of-amsterdam-puma/ [Accessed 16 Dec. 2019].

Ministry of Infrastructure and Water Management. 2012. Green Deal Bodemas: 1–9.

Ministry of Infrastructure and Water Management. 2017. Richtlijnen Ontwerp Kunstwerken 1.4(April): 1–255. https://staticresources.rijkswaterstaat.nl/binaries/RTD1001_ROK1.4_BijlageA_april2017_tcm21-108742.pdf.

Mol, K., W. Besier, and E. van Eiijk. 2019. *Position paper – nut en noodzaak materialenpaspoorten Infra sector*.

Ng, S.T., J.M.W. Wong, S. Skitmore, and A. Veronika. 2012. Carbon dioxide reduction in the building life cycle: a critical review. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability* 165(4): 281–292. http://www.icevirtuallibrary.com/doi/10.1680/ensu.11.00005.

Ortt, J.R., D. J. Langley, and N. Pals. 2013a. Ten Niche Strategies To Commercialize New High-Tech Productstle. *IEEE International Technology Management Conference & 19th ICE Conference*.

Ortt, J.R., D. Langley, and N. Pals. 2013b. Ten Niche Strategies To Commercialize New High-Tech Products. http://www.rug.nl/research/portal/publications/ten-niche-strategies-to-commercialize-new-hightech-products(757bad2c-9dc8-44a0-92ca-0857f77dcbc1)/export.html.

Ortt, J.R., C.M. Shah, and M.A. Zegveld. 2012. Commercializing Breakthrough Technologies: Scenarios and Strategies: 207–221.

Ortt, R. 2012. Market creation for radically new technologies: A literature review on the role of market niches. *2012 18th International Conference on Engineering, Technology and Innovation, ICE 2012 - Conference Proceedings*.

Platform CB’23 Leidraad. 2019. Paspoorten voor de bouw: 1–44.

RAND. 2012. Smart trash: Study on RFID tags and the recycling industry.

REPAiR. 2019. *home - REPAiR Project*. [online] REPAiR Project. Available at: http://h2020repair.eu/ [Accessed 16 Dec. 2019].

Rijksoverheid. 2016. Nederland circulair in 2050. *Het Ministerie van Infrastructuur En Milieu En Het Ministerie van Economische Zaken, Mede Namens Het Ministerie van Buitenlandse Zaken En*

*Het Ministerie van Binnenlandse Zaken En Koninkrijksrelaties.*: 1–72. https://bouwenuitvoering.nl/duurzaam/nederland-circulair-2050/.

Rijksoverheid. 2017. *Grondstoffenakkoord*.

Rijksoverheid. 2018. Circulaire Bouweconomie: 38. http://www.debouwagenda.com/actueel/downloads+en+brochures/handlerdownloadfiles.ashx?idnv=955001.

Rijkswaterstaat. 2019. *DuboCalc | Rijkswaterstaat*. [online] Rijkswaterstaat.nl. Available at: https://www.rijkswaterstaat.nl/zakelijk/zakendoen-met-rijkswaterstaat/inkoopbeleid/duurzaam-inkopen/duurzaamheid-bij-contracten-en-aanbestedingen/dubocalc/index.aspx [Accessed 16 Dec. 2019].

Rios, F.C., W.K. Chong, and D. Grau. 2015. Design for Disassembly and Deconstruction - Challenges and Opportunities. *Procedia Engineering* 118(December): 1296–1304. http://dx.doi.org/10.1016/j.proeng.2015.08.485.

Rockström, J., W. Steffen, K. Noone, Å. Persson, F.S. Chapin, E. Lambin, T.M. Lenton, et al. 2009. Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society* 14(2).

Rovers, R. 2015. Zero-energy and beyond: A paradigm shift in assessment. *Buildings* 5(1): 1–13.

Schot, J. and F.W. Geels. 2008. Strategic niche management and sustainable innovation journeys: Theory, findings, research agenda, and policy. *Technology Analysis and Strategic Management* 20(5): 537–554.

SIKB. 2019. *IBC-werken - SIKB*. [online] Sikb.nl. Available at: https://www.sikb.nl/bodembescherming/ibc-werken [Accessed 16 Dec. 2019].

Slooten, B. 2019. *'Green deal': Timmermans wil haast maken in strijd tegen klimaatverandering*. [online] Nos.nl. Available at: https://nos.nl/artikel/2314229-green-deal-timmermans-wil-haast-maken-in-strijd-tegen-klimaatverandering.html [Accessed 16 Dec. 2019].

The Engineering Toolbox 2019. *Concrete - Properties*. [online] Engineeringtoolbox.com. Available at: https://www.engineeringtoolbox.com/concrete-properties-d_1223.html [Accessed 16 Dec. 2019].

Thomas, V.M. 2008. Environmental implications of RFID. *IEEE International Symposium on Electronics and the Environment*: 15–19.

United Nations Environment Program. 2014. UNEP GEAS Sand 2012(March): 1–15.

Wang, L.C. 2008. Enhancing construction quality inspection and management using RFID technology. *Automation in Construction* 17(4): 467–479.

# 9. Appendices

## Appendix A: Thesis research information sheet

### Informatieblad scriptieonderzoek

*Onderzoekstitel*: “Stakeholder perceptions and requirements of an information system for the lifecycle of concrete”

*Onderzoeker* Kozmo Meister (k.r.meister@student.tudelft.nl, +31 641508152)

*Supervisors*: Francesco Di Maio (f.di.maio@tudelft.nl), Mingming Hu (hu@cml.leidenuniv.nl)

*Onderzoeksdoel:* Het onderzoeken van de percepties, verwachtingen, en eisen aan een informatiesysteem voor beton door belanghebbenden in de Nederlandse betonketen. Dit onderzoek vindt plaats als onderdeel van de master Industriële Ecologie aan de TU Delft en Universiteit Leiden.

*Voordelen van deelname aan het onderzoek:* Deelnemers aan het onderzoek zullen inzicht krijgen in de percepties van anderen belanghebbenden in de Nederlandse betonketen. Deze informatie kan worden gebruikt om samenwerking binnen de keten te verbeteren.

*Risico’s van deelname aan het onderzoek*: Er zijn geen fysieke, juridische, of financiële risico’s met betrekking tot deelname aan dit onderzoek.

*Gebruik van data:* De data verzameld tijdens dit onderzoek zal enkel worden gebruikt voor het onderzoek van Kozmo Meister, tenzij anders aangegeven door de deelnemer op het toestemmingsformulier (zie toestemmingsformulier). Het verzamelen en opslaan van data valt onder de Europese General Data Protection Regulation (GDPR), en wordt overzien foor het Human Research Ethics Committee van de TU Delft. De interviewdata en het originele transcript zullen worden opgeslagen op een beveiligde server van het TU Delft netwerk waartoe enkel de onderzoeker en de supervisors toegang hebben. De deelnemer zal zelf op het toestemmingsformulier aangeven hoe de geanonimiseerde data mag worden gebruikt, voor verder onderzoek op het gebied van informatiesystemen in de betonsector gebied, bijvoorbeeld.

*Dataopslag:* De gangbare opslagtijd van onderzoeksdata is 10 jaar. Op het toestemmingsformulier kan de deelnemer zelf aangeven of, en hoe deze data mag worden gebruikt voor andere doeleinden.

*Intrekkingsprocedure:* Deelname aan dit onderzoek is volledig vrijwillig. De deelnemer kan zich zonder consequenties op ieder moment uit het onderzoek terugtrekken. De informatie die tot dan toe is verzameld zal niet worden gebruikt.

Voor vragen, opmerkingen, klachten, of voor het terugtrekken uit de studie, neem contact op met de onderzoeker:

Kozmo Meister (k.r.meister@student.tudelft.nl, +31 641508152)

# Appendix B: Informed consent form (Dutch)

## Toestemmingsverklaring scriptieonderzoek

| ***Vink aan wat van toepassing is*** | **Ja** | **Nee** |
|---|---|---|
| **Deelnemen aan het onderzoek** | | |
| Ik heb het informatieblad (gedateerd 05-04-2019) gelezen en begrepen, of het is aan mij voorgelezen. Ik heb mijn vragen wat betreft de studie kunnen stellen, en deze zijn voldoende beantwoord. | ☐ | ☐ |
| Ik neem vrijwillig deel aan dit onderzoek. Ik begrijp dat ik niet verplicht ben antwoord te geven op vragen, en dat ik mij op ieder moment, zonder consequenties, kan terugtrekken uit het onderzoek zonder daarvoor een reden te geven. | ☐ | ☐ |
| Ik begrijp dat er tijdens het onderzoek audio opnamen worden gemaakt, ik geef hiervoor mijn toestemming. | ☐ | ☐ |
| Ik begrijp dat de informatie die ik verschaf voor het onderzoek gebruikt zal worden voor het scriptieonderzoek van Kozmo Meister als onderdeel van de opleiding Industrial Ecology. | ☐ | ☐ |
| **Gebruik van de informatie in dit onderzoek** | | |
| Ik begrijp dat persoonlijke informatie (informatie die mij kan identificeren zoals naam of werkgever) niet met anderen buiten het studieteam (Kozmo Meister en supervisors) wordt gedeeld. Deze informatie wordt opgeslagen op de beveiligde server van de TU Delft. | ☐ | ☐ |
| Ik geef de onderzoeker toestemming om (delen van) het transcript anoniem te citeren in de onderzoeksresultaten. | ☐ | ☐ |
| Ik geef de onderzoeker toestemming om mijn naam te gebruiken voor het citeren van (delen van) het transcript in de onderzoeksresultaten. | ☐ | ☐ |
| **Toekomstig gebruik and hergebruik van informatie door derden** | | |
| Ik geef toestemming om de interviewopname en het originele transcript op te slaan op een beveiligde database (alleen toegankelijk voor Kozmo Meister & supervisors) voor de gebruikelijke tijd van onderzoeksdata (10 jaar). | ☐ | ☐ |
| Ik geef toestemming het geanonimiseerde transcript vrij te geven als *open access* data voor gebruik in toekomstig onderzoek en educatie op het gebied van grondstoffenmanagement in de DANS-EASY database. | ☐ | ☐ |

Ik geef toestemming het geanonimiseerde transcript op te slaan in de 4TU database (database van de 4 Nederlandse TU's) voor gebruik in toekomstig onderzoek en educatie op het gebied van grondstoffenmanagement. ☐ ☐

**Handtekeningen**

______________________ ______________________ ________

Naam deelnemer Handtekening Datum

_________________________ _______________________ ________

Naam onderzoeker Handtekening Datum

Voor vragen, opmerkingen, etc. contacteer:

Kozmo Meister (k.r.meister@student.tudelft.nl, +31 641508152)

## Appendix C: Interview questions

*Vragenlijst voor interview scriptieonderzoek materiaalpaspoorten beton Kozmo Meister*

0. Kunt u de activiteiten van uw organisatie in het kort samenvatten?

1. Kunt u een ruwe schets maken van de betonketen, en aangeven waar uw organisatie zich in deze keten bevindt?

2(a). Vinden er in uw organisatie processen plaats gerelateerd aan het recyclen en/of hergebruiken van beton?

2(b). Zo ja, wat voor processen gerelateerd aan het recyclen en/of hergebruiken van beton worden nu door uw bedrijf toegepast?

3. Wat is volgens u de grootste uitdaging m.b.t het circulair maken van beton?

4(a). Tot welke hoogte denkt u dat het belangrijk is om meer informatie vanuit de betonketen te ontvangen voor het succes van uw organisatie?

4(b). Indien belangrijk, wat voor informatie zou u vanuit andere delen van de betonketen willen ontvangen?

4(c). Welke informatie betreft de activiteiten van uw organisatie denkt u dat anderen in de keten van belang vinden?

5. Is het voor uw organisatie interessant om de specifieke eigenschappen van beton (en de bestanddelen daarvan) te kennen gedurende de gehele levenscyclus?

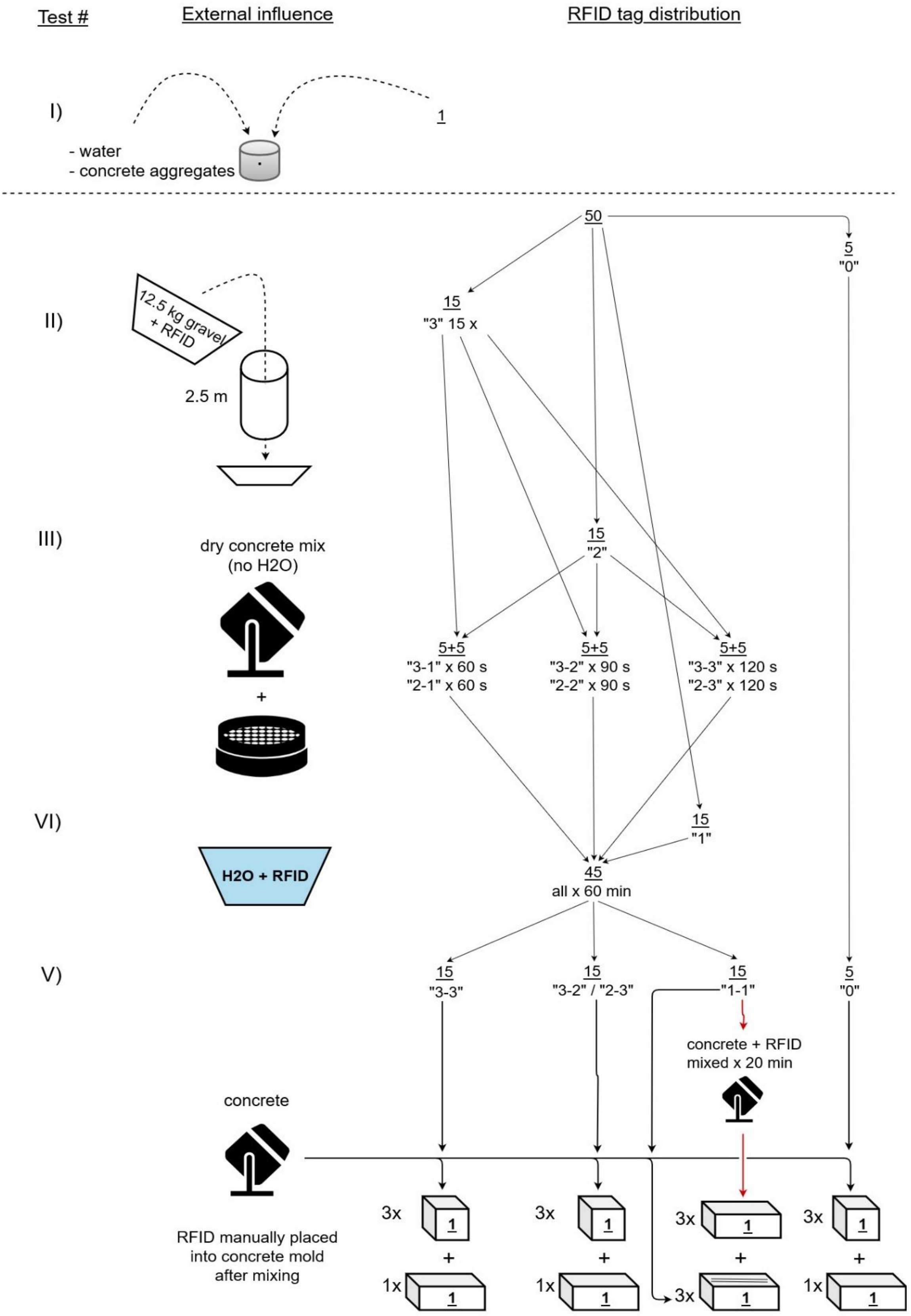
6. Denkt u dat informatie wat betreft de specifieke eigenschappen van beton (en de bestanddelen daarvan) relevant is voor het nakomen van de toekomstige Nederlandse wet- en regelgeving volgend uit de Nederlandse visie op circulaire economie en duurzaamheid?

7. Zou u geïnteresseerd zijn in een informatiesysteem dat de eigenschappen (en daarbij de kwaliteit van het betonproduct en de bestanddelen) gedurende de hele levenscyclus beschikbaar stelt?

8. Wie zou de verantwoordelijkheid moeten dragen voor het opzetten en bijhouden van een dergelijk informatiesysteem?

9. Wat zijn volgens u de uitdagingen en kansen voor een dergelijk systeem in de Nederlandse betonketen?

# Appendix D: Laboratory experiment flow chart



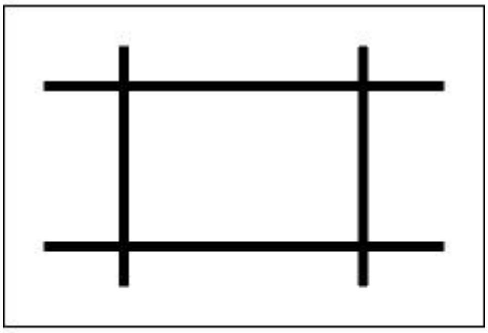
# Appendix E: Specifications of the samples' concrete mix

| **Cubes** | | |
|---|---|---|
| Piece(s) | 12 | margin |
| Volume (cm3) | 3375 | 1.1 |
| | *Mass (kg)* | *Mass (kg)* |
| Cement (CEM 1) | 10.52 | 11.58 |
| 0.125-0.250 mm | 3.19 | 3.51 |
| 0.250-0.500 mm | 10.38 | 11.42 |
| 0.250-1 mm | 10.38 | 11.42 |
| 0.250-2 mm | 6.38 | 7.02 |
| 2—4 mm | 3.98 | 4.38 |
| 4—8 mm | 15.96 | 17.56 |
| 8—16 mm | 29.52 | 32.47 |
| Water | | 6.95 |
| Total | 90.32 | 106.30 |

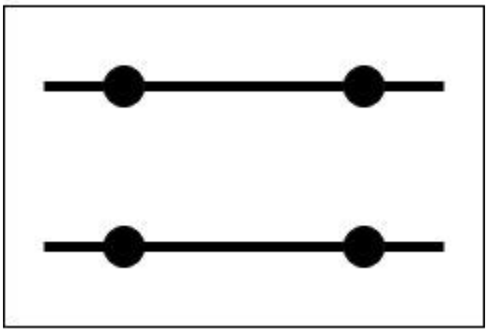
| **Rectangular prisms** | | |
|---|---|---|
| Piece(s) | 9 | margin |
| Volume (cm3) | 4000 | 1.1 |
| | *Mass (kg)* | *Mass (kg)* |
| | 9.35 | 10.29 |
| | 2.84 | 3.12 |
| | 9.23 | 10.15 |
| | 9.23 | 10.15 |
| | 5.67 | 6.24 |
| | 3.54 | 3.90 |
| | 14.19 | 15.61 |
| | 26.24 | 28.86 |
| | | 7.20 |
| Total | 80.29 | 95.52 |

# Appendix F: Orientation of rebar in the concrete sample

Top view



Side view



## Appendix G: Overview of answers category 1 (question # 0, 1, 2)

| | Answers question 1 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Respondent ID # | GOV | DEV | PAP | CP | CON | DEM | REC | NGO | INFO | ACA |
| 1 | | | | ■ | | | | | | |
| 2 | | | | | | ■ | ■ | | | |
| 3 | ■ | | | | | | | | | |
| 4 | | | | | | | ■ | | | |
| 5 | | | | | ■ | | | | | |
| 6 | ■ | | | | | | | | | |
| 7 | | | ■ | | | | | | | |
| 8 | | | | | | | ■ | | | |
| 9 | | | | | | | | ■ | | |
| 10 | | | ■ | | | | | | | |
| 11 | | | | | | ■ | | | | |
| 12 | | | | | | | ■ | | | |
| 13 | | | | | | | ■ | | | |
| 14 | | | | | | ■ | | | | |
| 15 | | | | | ■ | | | | | |
| 16 | | | | | | | | | ■ | |
| 17 | | | | ■ | | | | | | |
| 18 | | | ■ | ■ | | | ■ | | | |
| 19 | ■ | | | | | | | | | |
| 20 | | | | | | ■ | ■ | | | |
| 21 | | | | ■ | | | | | | |
| 22 | ■ | | | | | | | | | |
| 23 | | | | | | | | ■ | | |
| 24 | ■ | | | | | | | | | |
| 25 | | | | | | | | | | ■ |
| 26 | | | | | ■ | | | | | |
| 27 | | | | | | ■ | ■ | | | |
| 28 | ■ | | | | | | | | | |
| 29 | | | | ■ | | | | | | |
| 30 | | | | ■ | ■ | ■ | ■ | | | |
| 31 | | | | ■ | | | | | | |
| 32 | | | | ■ | | | ■ | | | |
| 33 | | | | ■ | | | | | | |
| 34 | | ■ | | | | | | | | |

| **Answers question 2a** | **ACA** | **CON** | **CP** | **DEM** | **DEV** | **GOV (Mun)** | **GOV (Nat)** | **INFO** | **NGO** | **PAP** | **REC** | **Grand Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NA | 1 |  | 1 |  |  |  |  | 1 |  | 1 | 1 | 5 |
| No |  | 1 |  |  | 1 | 1 |  |  |  | 1 |  | 4 |
| Yes |  | 2 | 7 | 3 |  | 4 | 1 |  | 2 |  | 6 | 25 |
| **Grand Total** | **1** | **3** | **8** | **3** | **1** | **5** | **1** | **1** | **2** | **2** | **7** | **34** |

| **Answers question 2b** | **ACA** | **CON** | **CP** | **DEM** | **DEV** | **GOV (Mun)** | **GOV (Nat)** | **INFO** | **NGO** | **PAP** | **REC** | **Grand Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | 1 |  |  |  |  | 1 | 2 |
| Contractually demand reuse of concrete |  |  |  |  |  | 4 | 1 |  |  |  |  | 5 |
| Development of recycling innovation |  |  |  | 1 |  |  |  |  |  |  |  | 1 |
| Facilitating cooperation in the concrete chain |  |  |  |  |  |  |  |  | 1 |  |  | 1 |
| Facilitating standardization and normalization regarding concrete reuse |  |  |  |  |  |  |  |  | 1 |  |  | 1 |
| Modular construction |  | 1 |  |  |  |  |  |  |  |  |  | 1 |
| Production and use of concrete granules |  |  | 2 |  |  |  |  |  |  |  | 1 | 3 |
| Production of concrete granules |  |  |  |  |  |  |  |  |  |  | 3 | 3 |
| Production of concrete granules and secondary concrete aggregates |  |  |  |  |  |  |  |  |  |  | 2 | 2 |
| Research into the replacement of limestone in concrete |  |  | 1 |  |  |  |  |  |  |  |  | 1 |
| Selective demolition |  |  |  | 2 |  |  |  |  |  |  |  | 2 |
| Use of concrete granules and secondary concrete aggregates |  |  | 1 |  |  |  |  |  |  |  |  | 1 |
| Use of secondary granules in concrete |  | 1 | 3 |  |  |  |  |  |  |  |  | 4 |
| (blank) |  |  |  |  |  |  |  |  |  |  |  |  |
| **Grand Total** |  | **2** | **7** | **3** |  | **5** | **1** |  | **2** |  | **7** | **27** |

## Appendix H: Overview of answers category 2 (question # 7)

| **Answer question 7** | **ACA** | **CON** | **CP** | **DEM** | **DEV** | **GOV** | **INFO** | **NGO** | **PAP** | **REC** | **Grand Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No | | | 2 | | 1 | | | | 1 | | 4 |
| Yes | | 2 | 6 | 2 | | 5 | 1 | 1 | 1 | 5 | 23 |
| **Grand Total** | | **2** | **8** | **2** | **1** | **5** | **1** | **1** | **2** | **5** | **27** |

| **Motivation question 7** | **ACA** | **CON** | **CP** | **DEM** | **DEV** | **GOV** | **INFO** | **NGO** | **PAP** | **REC** | **Grand Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| But yes for the development of such a system | | | | | | | | 1 | | | 1 |
| For asset management | | | | | | 1 | | | | | 1 |
| For monitoring purposes | | | | | | 1 | | | | | 1 |
| For quality control | | | 2 | | | | | 1 | | 2 | 5 |
| For the selective use of materials | | | | | | | | | | 1 | 1 |
| If there is a demand | | | | | | 1 | | | | 1 | 2 |
| It facilitates deconstruction; saves time and money | | | | 1 | | | | | | | 1 |
| It's a prerequisite for high quality reuse | | | 1 | | | | | | | | 1 |
| That's for the contractor | | | | | 1 | | | | | | 1 |
| **Grand Total** | | | **3** | **1** | **1** | **3** | | **2** | | **4** | **14** |

## Appendix I: Overview of answers category 3 (question # 4, 5, 6)

| Answers question 4a | ACA | CON | CP | DEM | DEV | GOV | INFO | NGO | PAP | REC | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| - | 1 |  | 1 |  |  |  |  | 1 |  | 2 | 5 |
| Important |  | 3 | 6 | 2 |  | 6 | 1 | 1 |  | 4 | 23 |
| Not important |  |  |  |  | 1 |  |  |  | 2 |  | 3 |
| Not important necessarily |  |  | 1 |  |  |  |  |  |  |  | 1 |
| Not important, unless demanded by the concrete producers |  |  |  |  |  |  |  |  |  | 1 | 1 |
| Not sure |  |  |  | 1 |  |  |  |  |  |  | 1 |
| **Grand Total** | **1** | **3** | **8** | **3** | **1** | **6** | **1** | **2** | **2** | **7** | **34** |

| Answers question 4b | ACA | CON | CP | DEM | DEV | GOV | INFO | NGO | PAP | REC | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 |  | 2 |  | 1 |  |  | 1 | 1 | 3 | 9 |
| Availability of waste concrete |  |  | 1 |  |  |  |  |  |  |  | 1 |
| Be involved in the design process |  |  | 1 |  |  |  |  |  |  |  | 1 |
| BIM |  |  |  |  |  |  | 1 |  |  |  | 1 |
| Characteristics |  | 1 |  |  |  |  |  |  |  |  | 1 |
| Composition |  | 1 | 1 |  |  | 2 |  |  | 1 | 2 | 7 |
| ECI |  |  |  |  |  | 1 |  |  |  |  | 1 |
| Insight into stocks |  |  | 1 |  |  |  |  |  |  |  | 1 |
| Not sure |  |  |  | 1 |  |  |  |  |  |  | 1 |
| Quality, composition, ECI, social sustainability |  |  |  |  |  | 1 |  |  |  |  | 1 |
| Tenders and award criteria |  |  |  |  |  | 1 |  |  |  |  | 1 |
| The market's experience regarding rules and regulations |  |  |  |  |  |  |  | 1 |  |  | 1 |
| The quality of waste concrete |  |  | 1 |  |  |  |  |  |  |  | 1 |
| The requirements for recycling |  |  |  | 1 |  |  |  |  |  |  | 1 |
| Use of WIA or other materials which limit high-quality reuse |  |  |  | 1 |  |  |  |  |  | 1 | 2 |
| What type of innovations occur within the concrete chain |  | 1 | 1 |  |  |  |  |  |  |  | 2 |
| Which materials are present in a construction |  |  |  |  |  | 1 |  |  |  | 1 | 2 |
| **Grand Total** | **1** | **3** | **8** | **3** | **1** | **6** | **1** | **2** | **2** | **7** | **34** |

| Answers question 4c | ACA | CON | CP | DEM | DEV | GOV | INFO | NGO | PAP | REC | (blank) | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| |  | 2 | 2 |  |  |  |  |  |  | 2 |  | 6 |
| - |  |  |  |  |  |  |  | 1 |  |  |  | 1 |
| Certificates of concrete granules |  |  |  | 1 |  |  |  |  |  |  |  | 1 |
| Circularity of the construction's materials |  |  |  |  |  |  | 1 |  |  |  |  | 1 |
| Composition |  | 1 | 2 |  |  | 2 |  |  |  |  |  | 5 |
| Concrete granule quality |  |  |  |  |  |  |  |  |  | 1 |  | 1 |
| Deconstruction manual |  | 1 |  |  |  |  |  |  |  |  |  | 1 |
| ECI |  |  | 1 |  |  |  | 1 |  | 2 |  |  | 4 |
| Entry requirements for waste concrete recycling |  |  |  |  |  |  |  |  |  | 1 |  | 1 |
| LCA of the concrete aggregates |  |  |  |  |  |  |  |  | 2 |  |  | 2 |
| Level of sustainable operation |  |  |  |  | 1 |  |  |  |  |  |  | 1 |
| Procurement requirements |  |  |  |  |  | 1 |  |  |  |  |  | 1 |
| Product sheets |  |  |  |  |  |  |  |  |  | 1 |  | 1 |
| Quality secondary concrete |  |  |  |  |  |  |  |  |  | 1 |  | 1 |
| Quantities of concrete used |  | 1 |  |  |  |  |  |  |  |  |  | 1 |
| Quantity of recycled concrete granules in concrete products |  |  |  |  |  |  |  |  |  | 1 |  | 1 |
| Technological know-how |  |  | 1 |  |  |  |  |  |  |  |  | 1 |
| Tenders and award criteria |  |  |  |  |  | 1 |  |  |  |  |  | 1 |
| The construction's maintenance needs |  |  |  |  |  | 1 |  |  |  |  |  | 1 |
| The relevance of making prenormative agreements |  |  |  |  |  |  |  | 1 |  |  |  | 1 |
| Type of concrete materials in a construction |  | 1 |  |  |  |  |  |  |  |  |  | 1 |
| Type of concrete, composition, BIM |  |  | 1 |  |  |  |  |  |  |  |  | 1 |
| Use of additives |  |  |  |  |  | 1 |  |  |  |  |  | 1 |
| **Grand Total** |  | **6** | **7** | **1** | **1** | **6** | **2** | **2** | **4** | **7** |  | **36** |

| **Answers question 5** | **ACA** | **CON** | **CP** | **DEM** | **DEV** | **GOV** | **INFO** | **NGO** | **PAP** | **REC** | **Grand Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No | | 1 | 2 | | 1 | 2 | | 1 | 2 | 1 | 10 |
| Not yet | | | | 1 | | | | | | | 1 |
| Yes | | 2 | 4 | 2 | | 3 | 1 | | | 2 | 14 |
| **Grand Total** | | **3** | **6** | **3** | **1** | **5** | **1** | **1** | **2** | **3** | **25** |

| **Answers question 6** | **ACA** | **CON** | **CP** | **DEM** | **DEV** | **GOV** | **INFO** | **NGO** | **PAP** | **REC** | **Grand Total** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No | | | | 1 | | | | | | 1 | 2 |
| Yes | | 1 | 2 | | | 4 | | | 1 | | 8 |
| Yes, but unsure how | | | | | | | | | | 1 | 1 |
| Yes, for quality assessment of constructions | | | 1 | | | | | | | | 1 |
| Yes, such systems facilitate the circular transition | | | | | | | | 1 | | | 1 |
| Yes, to ensure the quality of concrete | | | 1 | | | | | | | | 1 |
| Yes, to know which materials are easy to reuse | | | 1 | | | | | | | | 1 |
| **Grand Total** | | **1** | **5** | **1** | | **4** | | **1** | **1** | **2** | **15** |

## Appendix J: Overview of answers category 4 (question # 8)

| Answers question 8 | ACA | CON | CP | DEM | DEV | GOV | INFO | NGO | PAP | REC | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Client | | | 1 | 1 | | 2 | | 1 | 1 | | 6 |
| Concrete industry | | | | | | | | | | 1 | 1 |
| Concrete producers | | | | | 1 | 1 | | | | | 2 |
| Cooperation concrete producers | | | 1 | | | | | | | | 1 |
| Everyone in the chain | | | 1 | | | | | | | 2 | 3 |
| Manager | | | | | | 1 | | | | | 1 |
| National government | | 2 | 2 | 2 | | | | | | | 6 |
| National government, Madaster, combination of both | | | | | | | | | 1 | | 1 |
| Owner | | | | | | 1 | | 1 | | | 2 |
| Recyclers | | | 1 | | | | | | | | 1 |
| T.B.D. new public organization | | | | | | | | | | 1 | 1 |
| **Grand Total** | | **2** | **6** | **3** | **1** | **5** | | **2** | **2** | **4** | **25** |

## Appendix K: Overview of answers category 5 (question # 3, 9)

| Answers question 3 | ACA | CON | CP | DEM | DEV | INFO | NGO | PAP | REC | (blank) | GOV | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2 | | | | | | | 2 | | | 4 |
| A missing indicator for circularity | | | 1 | | | | | | | | | 1 |
| Altering unsustainable incentive structures in construction | 1 | | | | | | | | | | 1 | 2 |
| Applying circular design | | | | | | | | | | | 1 | 1 |
| Circularity should also be sustainable | | | 1 | | | | | | | | | 1 |
| Circularity should be sustainable | | | | | | | | 1 | | | | 1 |
| Developing a profitable business case for secondary concrete | | | | | | | | | 1 | | | 1 |
| Developing rules and regulations regarding (the use of) secondary concrete aggregates | | | 1 | | | | 1 | | 2 | | | 4 |
| Ensuring 100% circularity in the concrete chain | | | | | | | | | | | 1 | 1 |
| Ensuring a government push towards making the concrete chain sustainable | | | | | | | | | 1 | | | 1 |
| Ensuring a stable availability of affordable high quality recycled concrete | | | 4 | | 1 | | 1 | | 1 | | | 7 |
| Ensuring cooperation between actors | | | | | | | | | | | 1 | 1 |
| Ensuring high-quality use of secondary concrete | | | | 1 | | | | | | | | 1 |
| Ensuring profitable incentive structures for circular operations | | 1 | | 1 | | | | | | | | 2 |
| Ensuring reuse of prefabricated concrete elements | | 1 | | | | | | | | | | 1 |
| Ensuring the quality of concrete made with secondary materials | | | | | | | | 1 | | | | 1 |
| Finding alternative binders for cement | | | | | | | | | | | 1 | 1 |
| Maintaining the quality of concrete by avoiding the use of WIA | | | | | | | | 1 | 1 | | | 2 |
| Producing secondary aggregates | | | | | | | | | 1 | | | 1 |
| Retrieving and reusing cement from waste concrete | | | 1 | 1 | | | | | | | | 2 |
| Reusing the fine fraction (0-4mm) | | | 1 | | | | | 1 | | | | 2 |
| The disclosure of information regarding (the environmental performance of) concrete | | 1 | | | | | | | | 1 | 1 | 3 |
| Prevention, modular design | | | | | | | | | | | 1 | 1 |
| **Grand Total** | **1** | **5** | **9** | **3** | **1** | | **2** | **4** | **9** | **1** | **7** | **42** |

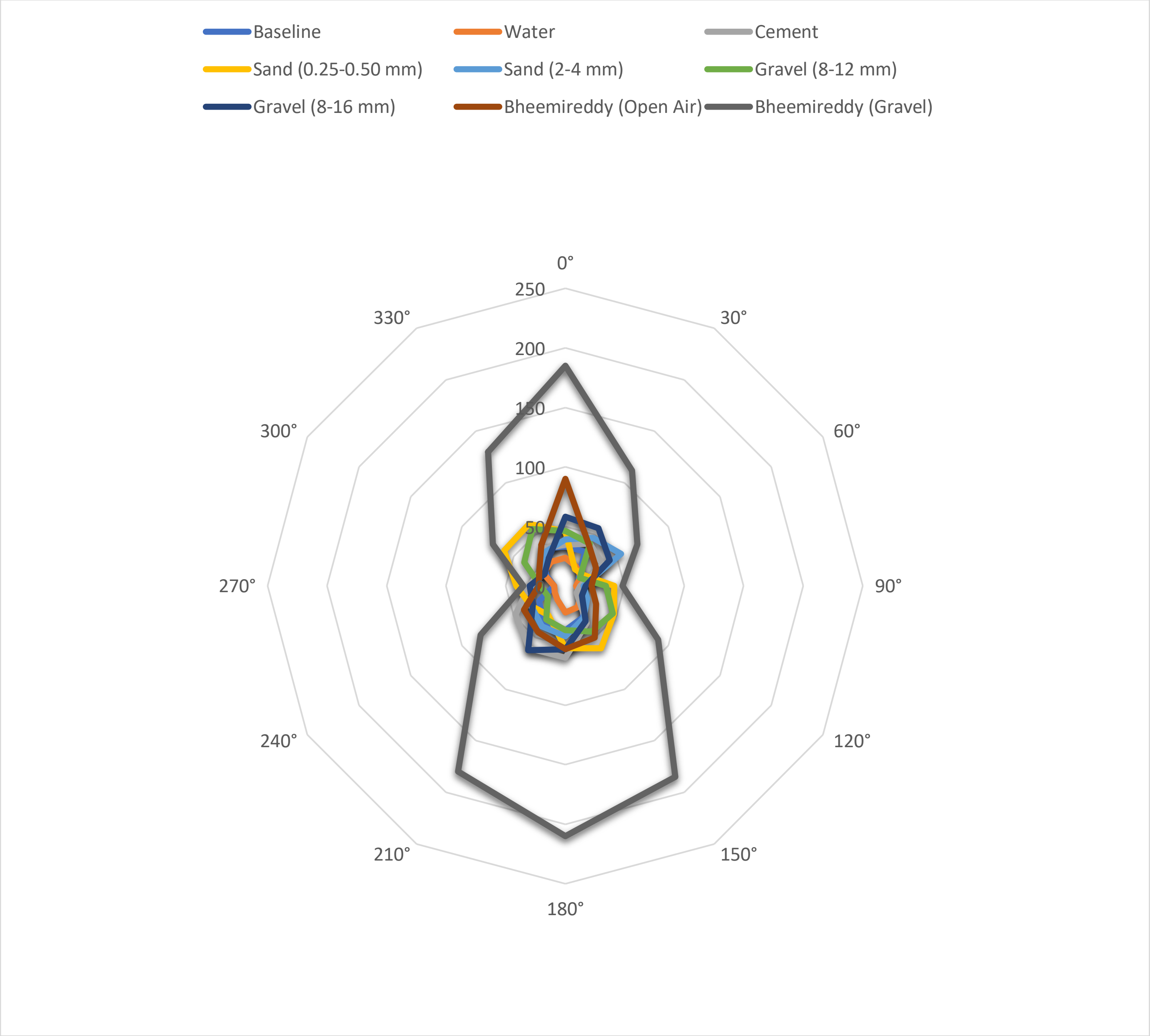
| Answers question 9 | ACA | CON | CP | DEM | DEV | GOV | INFO | NGO | PAP | REC | (blank) | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Clear agreements and rules | | | 1 | | | | | | | | | 1 |
| Concrete is not built for deconstruction | | | | | | | | | | 1 | | 1 |
| Connect to current information exchange | | | | | | 1 | | | | | | 1 |
| Cooperation in the chain | | | | | | 1 | | | | | 1 | 2 |
| Cooperation in the chain; ensuring that everybody's on board | | | | | | | | | | 1 | | 1 |
| Cooperation in the chain; working together on one goal | | | | | | | | | | 1 | | 1 |
| Cooperation, adding information on the current building stock | 1 | | | | | | | | | | | 1 |
| Creating uniformity | | | | | | | | 1 | | | | 1 |
| Data validation | | | | | | 1 | | | | | | 1 |
| Developing stimulating rules and regulations, don't wait on the industry to change by itself | | | | 1 | | | | | | | | 1 |
| Digitalization and recording information | | | 1 | | | | | | | | | 1 |
| Ensuring an objective platform | | | | | | | | | 1 | | | 1 |
| Entry of information that might devaluate the material | | | | | | | | | | 1 | | 1 |
| insight into the quantity and quality of secondary materials | | | 1 | | | | | | | | | 1 |
| Maintaining and managing the information system | | | 1 | | | | | | | | | 1 |
| Maintaining the information in the user phase | | 1 | | | | | | | | | | 1 |

*Due to its size, the table continues on the next page*

*Answers to question 9, continued*

| | ACA | CON | CP | DEM | DEV | GOV | INFO | NGO | PAP | REC | (blank) | Grand Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Making sure the contractors are on board | | | | | | | | | 1 | | | 1 |
| More insight into the composition of concrete | | | 1 | | | | | | | | | 1 |
| More up-to-date rules and regulations | | | | | | | | | | | 1 | 1 |
| No additional systems and work | | 1 | | | | | | | | | | 1 |
| O: Better reuse of (clean) materials | | | | | | | | | 1 | | | 1 |
| O: Digitalisation | | | 1 | | | | | | | | | 1 |
| O: Exchanging experiences | | | | | | | | | | | 1 | 1 |
| Rethinking of the construction process | | | | | | | | | | 1 | | 1 |
| Rules and regulations; move towards biobased concrete | | | 1 | | | | | | | | | 1 |
| Setting up a system which you might only use in several decades | | | | | | | | | | 1 | | 1 |
| Should we invest in a system which might be outdated in 20 years? | | | | | | 1 | | | | | | 1 |
| The client will have to want to pay for circularity | | | | 1 | | | | | | | | 1 |
| The separation and storage of waste concrete | | | | 1 | | | | | | | | 1 |
| What is the contribution of a material passport | | | | | | | | | | 1 | | 1 |
| Which information should be on the passports | | | | | | | | 1 | | | | 1 |
| Which information will be recorded? | | 1 | | | | | | | | | | 1 |
| (blank) | | | | | | | | | | | | |
| **Grand Total** | **1** | **3** | **7** | **3** | | **4** | | **2** | **3** | **7** | **3** | **33** |

# Appendix L: Comparison of SRQ 2 results compared to Bheemireddy's results



Maximum reading distances of the RFID tag through various substances. It includes the 6 cm radius of the material, and 3mm of the plastic cylinder. The distances of the radar chart are in 50 cm increments.