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Introducing the circular economy in road infrastructure development. Challenges and dilemmas in designing circular roads.

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Abstract

The throwaway culture has for years been the hallmark of our economic system. We produce, use and throw away what is left as waste. A circular economy assumes that materials are part of a closed system of subsequent loops, where the output of one loop is the input of the next loop. Ideally, resources are used over and over again without becoming waste. Currently, there is a growing political and societal pressure to reduce the use of basic materials and to prevent creating waste. For example, Dutch government decided in 2016 that the whole Dutch economy - including road construction - should be circular in 2050! The road construction industry is infamous for its' major use of energy resources and materials. Road constructions are usually constructed for a 50 to 100 years' lifetime and are then supposed to be written off as waste. Under the above mentioned political and societal pressure also the road infrastructure sector is strongly challenged to become circular. But, how to design and realize a circular road for multiple lifecycles? The paper will discuss this question by mirroring theory about circular design to the first circular designed highway viaduct in The Netherlands. The aim is to understand circular design in highway development and to explore general design principles.

Keywords: Circular Economy, Circular Design. Road Infrastructure, Construction Industry

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1. Introduction

Scarcity of raw resources constitutes major challenges in this 21st century. Not just for environmental reasons, but also for economic and strategic reasons. Consumption and use of natural resources has generally followed a linear approach. Materials are sourced, used and finally disposed of as waste. The (perceived) abundance of cheap natural resources has enabled this approach to endure. However, as resources become harder and more expensive to access and the discussion about the effects of climate change increases, it is becoming ever more critical to find alternative means of sourcing and using materials. A circular economy aims to keep products, components, and materials at their highest utility and value at all times. As a result, economic value is retained and created and negative environmental effects are reduced.

Currently, there is a growing political and societal pressure to reduce the use of fossil, critical and not-sustainable resources and to prevent creating waste. In 2015 the European Committee commissioned an action plan to trigger a transition to a circular economy (EU, 2014; 2015). In line, Dutch government decided in 2016 that the whole Dutch economy - including road construction - should be circular in 2050! This transition is stimulated by making current production chains more efficient, by replacing fossil, critical and not-sustainably produced commodities by sustainable, renewable and widely available raw materials and by developing new production methods (RLI, 2015; Ministry of Infrastructure & Environment, 2016).

The road construction sector is infamous for its' major use of energy resources and materials - like concrete, earthwork, asphalt and steel - necessary for construction and maintenance. The sector is also known for its' linear - project oriented - approach. Road constructions are usually designed and constructed for a 50 to 100 years' lifetime and are then supposed to be written off as waste. Although literature is not consistent in exact numbers of use of materials some indications are given. The construction industry accounts for 50% of global steel production and consumes more than 3bn tons of raw materials a year. According to the US Green Building Counsel and US Environmental Protection Agency websites, about 10% of these materials are only used for the construction phase and deposited as waste afterwards. The construction industry is responsible for more than 40% of the produced (weight) amount of waste in Europe, as compared to municipal waste of only about 12% (Pepe, 2015). Moreover, literature allocates 25-40% of energy consumption and 40% of CO_2 emission to this industry (CE Delft, 2015; WEF, 2016; US Green Building Counsel website). It is estimated that the production of cement alone is responsible for 5% of the worlds' total CO_2-emission (Damtoft et al., 2008; see also Kleiwerks.org). The mentioned figures comprise the whole construction industry such as buildings as well as infrastructure including transportation, telecommunications, energy and water. They give an idea of the potential gain of a circular economy. More detailed figures of road construction are, unfortunately, lacking in literature.

Under the afore mentioned political and societal pressure also the road construction sector is strongly challenged to become circular. However, the focus in the day-to-day practice within the sector is still often limited to reduction of energy consumption and carbon emissions (Pomponi & Moncaster, 2016), while overlooking excessive resource consumption (Rees, 2009). Most of the focus of emission reduction tends to be on the manufacturing of materials or components, not on the design of structures (Murray et al., 2017).

What does the circular economy really mean for the road construction sector? And how to design and realize a circular road for multiple material lifecycles? This paper will discuss these questions by exploring literature and supplementing it with lessons learned from the practice of the first circular designed highway viaduct in The Netherlands. This paper aims to understand circular design in road planning, construction and use and to derive general design principles. In the next two chapters we first elaborate on the principles of the circular economy based on recent literature and elaborate on basic design principles. Next we describe the results of the circular designed viaduct and compare the results with the studied literature and discuss lessons learned.

2. The concept of circular economy

Greyson (2007) claims that Kenneth Boulding (1966) was the originator of the term 'circular economy' when he wrote: "Man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy" (p. 7-8). Whoever is the founding father, the term 'circular economy' has been linked with a range of meanings and associations by different authors, but what they generally have in common is the concept of a cyclical closed-loop system (Ness & Xing, 2017). Recent momentum has been catalyzed by the Ellen MacArthur Foundation (EMF), the international think-tank that is commonly recognized as being an authoritative source for circular concepts. The EMF defines the circular economy (CE) as "an economic and industrial system that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times..." (EMF, 2014). In this definition the concept of the CE is related to the importance of circular design. Less ambitious and without specifically mentioning the relationship to circular design, the European Commission defined CE as an economy "where the value of products, materials and resources is maintained in the economy *for as long as possible*, and the generation of waste is minimized" (EU, 2015).

The circular economy concept has emerged as a way to obtain more value from resources while reducing material throughput. The concept builds on earlier sustainability concepts such as 'people-planet-profit', 'cradle-to-cradle' (McDonough & Braungart, 2002; Bakker et al., 2010), 'multi-value creation' and 'responsible entrepreneurship' (Van Buren et al., 2016; Geissdörfer et al., 2017). CE is a closed-loop concept where the output of one lifecycle is used as resource for a next lifecycle and so on (Stahel, 2010). Or, as Yuan et al. (2006, p. 5) state: "the core of the circular economy is the circular (closed) flow of materials and the use of raw materials and energy through multiple phases". CE focuses on closing the entire supply and demand chain of raw materials and waste over the entire economic system. However, according to Gregson et al. (2015), a perfect closed-loop system does not reflect reality. Products always lose value through use, damage, wear, but also economic aging or the rise of better alternatives. The challenge is to keep resources in the loop for as long as possible with minimal loss of quality (Braungart et al., 2007). A further basis of CE is the link to the 'economic system' (EMF, 2013; Geissdörfer et al., 2017; Lewandowski, 2016; Bocken et al., 2016). From an economic (and business) point of view, it is important to reuse products and materials with as much value as possible, or, if possible, add value (Stindt & Sahamie, 2014). As this economic benefit can very well coincide with social and environmental value creation, the concept of CE was embraced as a very attractive and new sustainable economic principal both by public authorities as private companies.

In order to achieve a circular economy, a transition must take place from a linear to a circular process approach (Ghisellini et al., 2016). The World Economic Forum (WEF, 2016) proposes a systematic approach for this transition following three lines. First and for all, reorganize and streamline materials flows. Second, set up reverse and collaborative networks for products along the incumbent value chain (comparable to the idea of a 'materials bank' proposed by Braungart et al., 2007). Third, create innovative business models on the demand side to accommodate the growing trend towards collaborative use of physical assets (the 'sharing economy', Stahel, 2001 or 'material banks', Braungart et al., 2007) or on the supply side by for example performance and service packages ('products as service carriers', Stahel, 2010; 'resource stewardship', Hill, 2014; Lieder & Rashid, 2016).

In literature the transition is usually described through three steps or types as originally developed by Lifset and Graedel (2001, see also Stahel, 2016). The first type is the linear economy, which has a take-make-waste character. Manufacturers are assumed to have an infinite stock of raw materials, which are processed into products, sold, consumed and then waste will develop. The second type is a linear economy with feedback loops as a quasi-cycle. There is an awareness of the scarcity of commodities and sustainability. Therefore, cascading of primary commodities, repair and maintenance, reuse, rebuilding and recycling is incorporated as much as possible in production and use of products. As a consequence, a limited amount of waste is produced after the end of the life cycle of products. The final type is the circular economy. In the circular economy there is an ideal multi-cyclic material flow. All raw materials stay within the system and there is no waste disposal. Only energy is required to maintain these raw materials in the system. Circularity is incorporated in the economic system, for example by delivering performance as services through rent, lease and share business models (Wells & Seitz, 2005; Stahel, 2010).

Figure 1 schematically shows the three described transition steps or types to a circular economy. In theory the types are demarcated. However, in practice, differences will be gradual and be a combination of all types.

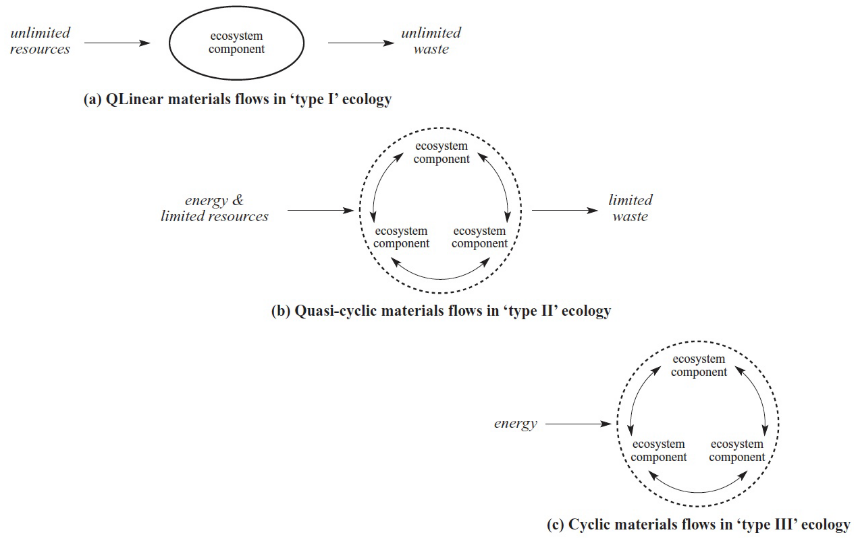

Figure 1. Transition steps to a circular economy (based on Lifset & Graedel, 2001)

In literature a distinction is made between various strategies for circularity (Potting et al., 2016). Different strategies (often referred to as the '9 Rs') are listed in Table 1.

Table 1. Strategies of circularity (based on Potting et al., 2016)

Strategies of Circularity		
Smart production and use	Ro Refuse	Preventing use of resources by changing functions or delivering functions through radical different resources
	R1 Rethink	Intensify use of resources for products by sharing or multi-functional use
	R2 Reduce	Efficient production and use by using less raw materials and resources
Extending the life of products and components	R3 Reuse	Reuse of products for the same function by another user
	R4 Repair	Repair and maintenance of broken products for use in current function
	R5 Refurbish	Refurbish and modernize old product
	R6 Remanufacture	Use of parts of discarded product in new product with the same function
	R7 Repurpose	Use of discarded products or component in new product with different function
Useful use of materials	R8 Recycle	Processing material to the same (high-grade) or lesser (low-grade) quality
	R9 Recover	Incineration of residual materials with energy recovery

3. Principles of circular design

Central in the concept of CE is the cyclic flow of materials through subsequent life-cycles of products. Life-cycles follow each other and bring about an evolution that can continue indefinitely in a circular economy (closed-loop). The characteristics of a life-cycle are predominantly determined in the design phase. Therefore, different strategies of circularity should be considered and anchored in this phase (Table 1). The design should take into account all the phases in the current life-cycle, but also the following life-cycles. Based on Arup (2016) the life-cycle of a (road)construction project can be phased in an initiation and planning phase, a design and conditioning phase, a sourcing phase, construction, operation and renewal and a disassembly phase.

Designing involves developing a coherent system of components that jointly perform an intended function (Arup, 2016). A road must provide availability and safety to road users in an environmentally acceptable manner. Designing is making choices for that system from an overall view of all the relevant phases for the functioning of that system. Additionally, a circular design asks for choices from circular strategies across multiple life-cycles. This chapter reviews recent literature on design principles regarding these choices in the different phases of a project life-cycle (summarized in Table 2).

3.1. Initiation and Planning Phase

The key of CE is the life-cycle. But what exactly is the life-cycle of a road system? Currently, civil engineering structures are developed for a lifespan of 50 to 100 years. Actually, however, most road constructions are reconstructed every 25 to 30 years. Asphalt typically has to be renewed every 7 to 15 years depending on the quality of the asphalt and the intensity of use. Installations for traffic management have a usual lifespan of 10 to 20 years and ICT 5 to 10 years. Moreover, traffic management is very dynamic due to new developments such as smart mobility. So, different parts of the system have different technical and/or economic lifespans. The essence of a circular design is to decompose the road system in essential functional components (modules) and design each component or module from its own life-cycle sequence while keeping the system coherent (Webster, 2013; Stahel, 2001). Essential is not to design on a preset linear lifespan requirement (i.e. 100 years for concrete), but on the real (economic) lifespan of the components as part of a sequence of life-cycles (Braungart et al., 2007). The economic lifespan, however, is uncertain and strongly related to the (dynamic) environment of the road system. Therefore, the system needs to be adaptive, i.e. that it can be adapted to external or internal influences while keeping its function. A modular design makes a system more adaptive if modules can be disassembled, changed or replaced during the life-cycle (Geldermans & Jacobson, 2015; Geldermans, 2016).

3.2. Design and Conditioning Phase

Because there is little certainty about future life-cycles, an important aspect of a circular design, is the prevention of locked-in situations (WEF, 2016). This arises when a choice in the design has irreversible non-circular consequences for the system. For example, the choice of mixing of material streams or coupling of components making it impossible to use the material or components in the same quality for a second life-cycle.

Much of the discussion of the CE is couched in terms of material flows, and to recycle materials that constitute these flows (Bocken et al., 2016). In a recycling process the original materials are reclaimed to be reused in a next or other life-cycle. Recycling has been a significant part of sustainable practice for many years, and it is fundamental to the circular economy (George et al., 2015; WEF, 2016; Murray et al., 2017). After all, the more materials that can be recovered, the smaller the chance of a locked-in situation for a next life-cycle. It is not necessary in circular design for every raw material to be reused for exactly the same application, as long as it remains within the economic system in the long term. However, according to Stahel and Reday-Mulvey (1981) reuse and remanufacture conserve more value than recycling, because most recycling is down cycling, with reduced quality and value (Braungart et al., 2007; Gregson et al., 2015).

Most of the circular design principles mentioned in literature consist of lifespan extension within the life-cycle. According to Gregson et al. (2015, p. 223) longevity stimulates maintaining or even improving value, quality, and performance. However, this principle should be balanced with the afore mentioned principle of designing for an economic lifespan (Kohler & Yang, 2007). Lifespan extension can be realized through a design aimed at easy maintenance, making repair more attractive than replacement. In addition, a design consisting of replicable modules can lead to easier maintenance and is more adaptive.

A road system design always takes place in a physical and social context. The challenge is to make the most of the given situation. The use of local available materials (for example soil and construction modules) reduces transport and energy consumption. Specific partnership agreements have to be made with local authorities to reuse materials or components locally in a next life-cycle (Daly, 2015). With regard to this, Naustdalslid (2014) warns that an excessive focus on materials and their optimization in a project design may underestimate the key role of stakeholder involvement to implement CE successfully.

3.3. Sourcing Phase

Minimal use of primary commodities is at the heart of the circular ambition of the Dutch government (Ministry of Infrastructure & Environment, 2016). The assumption is that using less materials leads to less use of raw materials and causes less waste and environmental effects. However, zero use seems not feasible with current technology (Gregson et al., 2015). By consistently designing from the principle of low material use (low material design) the use of primary commodities is at least minimized. Moreover, using less material also may lead to less waste and environmental effects. Additionally, by using maximum recycled raw materials as resources, less basic raw materials are required.

Renewable raw materials (bio-based) are often referred to as alternatives to primary and secondary raw materials (O'Brien et al., 2011). Bio-based raw materials are degradable and renewable by nature itself. In addition, it is a form of storage of CO_2.

Essential for the conscious handling and reuse of materials, many years after they are initially used, is the availability of data. By linking data to materials and material flows the design of a life-cycle can be optimized and subsequent life-cycles can be coupled. An example of this is the so called 'materials passport' (BAMB, 2020). A materials passport gives the designer of the present and next life-cycles information about the composition of the materials used in the design, its origin, supply and environmental performance. The idea is to allow information to travel with the product itself through time. The development of the materials passport is still in its infancy. A promising development is the BIM (Building Information Model) design tool, which already contains an extensive database of materials. The greatest challenge is possibly how to store and keep such information traceable and accessible so that it can be usefully employed after the life-cycle, 50 to 100 years later.

3.4. Construction Phase

When connecting various materials or components together, currently, hardly any account is taken of the possibility of taking these apart at a later date and reusing them for building elsewhere or in a next life-cycle (Royal HaskoningDHV, 2016). It is important to mix as little raw material streams together and keep interacting components demountable by designing for recycling and deconstruction or disassembly (Densley Tingley & Davison, 2011; Carpenter et al., 2013; Bakker et al., 2014). Mixing and kitting material streams together make recyclability later on much more difficult. A solution for deconstruction might be modular (prefab) construction with 'smart' demountable connections (see case circular viaduct as described in the next chapter). Mainly the 'ease' of deconstruction is of great importance for a circular design. With enough energy, after all, everything can be broken apart.

Much of the focus in circular design, both in literature and practice, is about material use for the final product. According to Bossink and Brouwers (1996) about 1-10% of the construction materials, measured by weight of the purchased materials, leave the building site as waste from temporary structures. Moreover, the building process is responsible for a lot of energy consumption for transport, machinery use etcetera.

3.5. Operation and Renewal Phase

In the operation phase no real circular design choices have to be made. Repair and refurbishment is considered to be part of the renewal phase. However, in the operation phase energy is consumed to keep the road operational. Especially traffic management, lightning and special structures such as tunnels or bridges are major energy consumers. From a circular perspective the design should be made such that operation uses as little energy as possible, for example by using energy-efficient technologies (Peeling et al., 2016) or self-generation (Dzhusupova et al., 2012). Rijkswaterstaat, for example, has the ambition to make her infrastructure networks energy neutral in 2030.

Important in CE is that the value of materials and components is maintained. At the end of the life-cycle, they can then be reused for subsequent life-cycles or alternate life-cycles. Depreciation is supposed to be minimal in CE as the various used materials and components are the resources of the future. Therefore, during the operational phase, loss of value should be minimized as much as possible by maintaining the road in as high a state of functionality as possible. The basis for this is a design aimed at simple and effective maintenance and management, focusing on value retention over replacement (Bakker et al., 2014).

3.6. Disassembly Phase

When the road structure can be completely disassembled, it is possible to give a new destination to the used materials and components. Most important, according to literature, are the principles of design for recycle and design for deconstruction. In order to actually reuse at high quality, it is important to take into account the application of materials, components or modules in a next or other life-cycle. This can be direct use or after some adaptation. Design for recycling is needed to ensure that the supply of residue from one life-cycle meets the demand for future life-cycles. Matching supply and demand within a life-cycle and over different life-cycles is fundamentally in the closed-loop approach of CE (Chertow, 2007; Ghiselini et al., 2016).
This phase faces similar challenges as the construction phase regarding energy consumption and material use for temporary constructions needed for disassembly.

Table 2. Principles for circular design as mentioned in literature

Phase	Design Principle	Strategy
Initiation & Planning	Design for economic lifespan rather than preset lifespan requirement	Rethink
	Make the road system adaptive (modular design)	Reuse, Repurpose
Design & Conditioning	Design for multiple life-cycles and minimize potential locked-in	
	Design for recycle	Recycle
	Design for lifetime extension within the first life-cycle	Repair, Refurbish
	Design for easy maintenance and management	Repair
	Design standardized reusable modules (modular design)	Reuse, Repurpose
	Use the physical and social environment of the road system	
Sourcing	Design for material-poor constructions	Reduce
	Design for maximum use of recycled raw materials	Recycle
	Maximum utilization of raw materials or components from a previous life-cycle	Reuse
	Design for employability of renewable raw materials (bio-based)	
	Develop a 'materials passport' linked to materials and material flows	Recycle
Construction	Design for recycling i.e. prevent un-recyclable mixing and kitting	Recycle
	Design for deconstruction of components (modules)	Reuse, Repurpose
Operation	Reduce energy consumption and energy needed should be self-generated	
Renewal	Design aimed at simple and effective maintenance and management, focusing on value retention over replacement	Repair, Refurbish
Disassembly	Match supply and demand within a life-cycle and over different life-cycles	Refuse, Rethink

4. Case circular design of a highway viaduct

In 2016 Van Hattum & Blankevoort (VHB, part of the Volker-Wessels holding) took the initiative to make a circular design of a highway viaduct. The ambition was to finish the design in 2017 and to build the viaduct in 2018 as part of the N18 project, a new 23 km highway in the eastern part of The Netherlands. The circular design was performed parallel to a regular designed viaduct. The circular design team was helped by an expert team consisting of specialists of Spanbeton (prefab-concrete producer), SGS Nederland (materials), SBR-CUR (knowledge institute) and Rijkswaterstaat. The design of the circular viaduct was originally a commercial initiative ("to become the most sustainable construction firm in The Netherlands"), however, strongly supported by Rijkswaterstaat. The interchange of knowledge between the two teams working on a real-life case stimulated finding solutions for encountered dilemmas in the circular design. Initially the design focussed on the following design principles: multiple use of resources and functions i.e. optimal use of resources per function, maximum use of 'healthy' raw materials and elimination of 'unhealthy' raw materials, uncoupling of life-cycles to enable high value use of resources in next life-cycles, introduction of a materials passport, and design for deconstruction and reassembly. However, during the design process the design focussed, besides design for recycle, on the modular composition of the viaduct (see Figure 2) especially a demountable bridge deck, because that part seemed to be best upscalable with the available knowledge. Unfortunately, the circular design of the viaduct will not be realized in the N18 project due to time risks. Currently, VHB and Rijkswaterstaat are considering to realize the modular viaduct elsewhere.

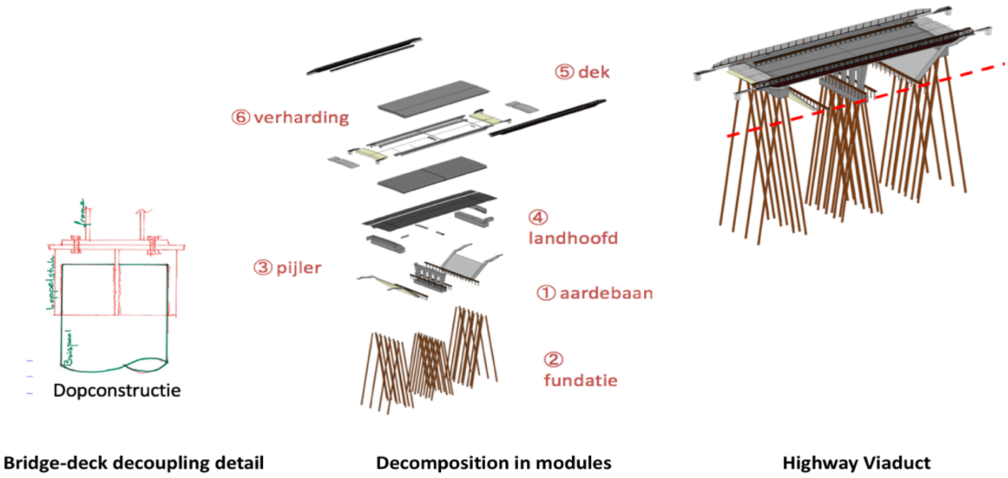

Figure 2: Modular decomposition of the viaduct and bridge-deck connection detail (pictures courtesy of VHB, 2017)

From the case design the following practical lessons were derived:

- Involve the supply chain parties right from the beginning of the design. This includes parties not only involved in the first life-cycle, but also those assumed to be possibly involved in future life-cycles;
- Design in co-creation. Co-creation stimulates parties and leads to innovative ideas by combining knowledge;
- Involve the client in an early stage and assure that he or she is willing to incorporate (parts of) the circular design in the realization of the project;
- Include a high-level sponsor in the project to facilitate potential conflicts with laws and regulations;
- Focus the design on a few deliberately selected design principles;
- Design with the materials that are now available and applicable. Do not make an advance on future technological developments;
- Organize a CE-community of market parties, public authorities and knowledge institutes related to the circular design (a 'living lab'). Offer a perspective to learn, but also a perspective on possible market share.

5. Discussion and conclusions

Apparent from the literature exploration is that there is abundant general literature on CE and product design. The literature on design of road infrastructure is, apart from recycling, rather scarce. Moreover, it focusses merely on (technical) design principles rather than business aspects essential for economic embedding of CE and social aspects like the sharing economy. The studied case confirms this focus. This fits the technical-rational approach of the sector. However, it is questionable whether this will lead to a self-standing circular economy without constant stimulation by the government.

The main design principles mentioned in literature are raw material or resource reduction, recycling and modular design. These principles are, however, mostly used as distinguished design principles and hardly integrated. Moreover, CE is strongly intertwined with objectives for CO_2-reduction and reduction of energy consumption both in construction and operation. In most designs these three elements of sustainability are treated separately. It would be good to integrate these elements in circular design.

Modular design is an upcoming principle in road infrastructure design. However, both literature and the described case focus on the technical aspects of creating modules. The idea of a closed-loop suggests reuse of modules in next or parallel life-cycles. The design should 'guarantee' this reuse, for example by specific public or commercial reuse-agreements or through models of resource stewardships or ownerships. The potential for reuse can be maximized by standardization of modules. However, nor in literature, nor in the case, standardization is mentioned as important aspect of CE.

Apparent form the case is the importance of support and willingness from the involved organizations and the client. Current institutions like laws and regulations are still mostly based on a linear approach. To implement

CE, current constraints will have to be challenged. Co-creation and collaboration in the supply and demand chain are indispensable for this challenge.

Literature and the case show that a transition to circular design, let alone a circular economy, in road infrastructure has just started. That is positive, however, it is also striking. When the objective is to be circular in 2050, given an economic life-cycle of 25-30 years for constructions and a planning period of 3-5 years, all designs that are currently made should already be circular! This being not the case, leaves a huge challenge for the road construction sector.

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