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A systemic perspective on transition barriers to a circular infrastructure sector

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ABSTRACT

Due to the large use of resources and waste generation, the transition to a circular economy (CE) has become a major sustainability-related topic in construction. Intentions to achieve circularity are shared widely, but developments are slow in practice. This study identifies systemic barriers to the circularity transition from a social-technical systemic perspective. We used the Mission-oriented Innovation System (MIS) framework to provide insights into the problems and potential solutions underlying the circularity mission, the structure of the system and the system dynamics. Based on the analysis of a wide range of policy documents and twenty in-depth interviews with stakeholders in the Dutch infrastructure sector, three vicious cycles were identified that form persistent barriers to the transition: (1) the CE contestation cycle given the contested nature of the circularity mission; (2) the knowledge diffusion cycle given the need to adopt and diffuse knowledge; and (3) the innovation cycle when it comes to procuring and upscaling circular innovations. These barriers all relate to processual, organizational and institutional challenges rather than to technological ones. This indicates that construction managers, policymakers and researchers in the field of infrastructure circularity should shift their focus from specific circular solutions to creating appropriate conditions for changing current and introducing novel processes that facilitate circular ways of doing things.

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Introduction

Due to the large use of resources and waste generation in construction, the transition to a circular economy (CE) has become a major sustainability-related topic (Benachio *et al.* 2020, Joensuu *et al.* 2020). Unfortunately, in practice, developments lag the widely shared intentions and strategies for achieving circularity. This is despite the growing body of literature on CE in the built environment (Mhatre *et al.* 2021). Much of this literature targets specific strategies, technological solutions or frameworks that should be applied, such as novel design or reuse strategies (Charef *et al.* 2021). Further, the majority of the CE literature focuses on the private rather than public sectors, such as infrastructure, and this has major implications for implementation (Klein *et al.* 2022). However, becoming circular as an industry requires not only new technologies but also socio-technical changes, including context-specific reconsideration of relationships, institutions and practices (Singh *et al.* 2021). As such, socio-technical change towards an inherently more sustainable system is needed, a process which is referred to as a sustainability transition (Köhler *et al.* 2019). Despite this general recognition, the barriers to introducing these changes in practice just seem to be too high within the current industry for a smooth transition to take place.

When considering systemic change, most construction and project management scholars look at specific actors, projects, institutions, indicators, tools, mechanisms or practices rather than the sector at large. Gluch and Svensson (2018), for instance, explained changing practices as requiring intertwined multilevel actions by practitioners. Toppinen *et al.* (2019) took a more systemic view to sector change but focussed on a specific (technological) solution. Salmi *et al.* (2022) considered the wider sustainability transition in construction by focusing on the role of municipalities within the wide landscape of actors. In a similar vein, Ninan *et al.*

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(2022) adopted a systemic view to understand the role of narratives as temporal discourses to guide and shape innovation. While Leiringer *et al.* (2022) addressed the systemic level, leaving room for many solutions for becoming circular, their scope was unfortunately limited to the role of assessment methods. And although individual solutions and strategies are important ingredients for a successful transition, understanding these is not enough to inform policymakers on the actual barriers to comprehensive system change. We therefore aim to identify the root causes of a smooth transition towards a circular economy at the industry level, referred to as systemic barriers.

From a policy perspective, socio-technical transitions are increasingly directed towards shared societal challenges synthesized in missions (Schot and Steinmueller 2018). Such missions are formulated in sectoral, national or even supra-national agreements on, for example, climate change, socioeconomic inequality or insecurity (Mazzucato 2018). These missions can be found on supra-national levels, such as the United Nation's Sustainable Development Goals (SDGs), but also on national and regional levels, and even within organizations. They often include open-ended discourses and shared long-term goals (Kuhlmann and Rip 2018, Janssen *et al.* 2021). Mission-oriented innovation policies are considered instrumental in shifting transitions towards a desired direction (Schot and Steinmueller 2018), since such policies "[provide] directionality in supporting the process towards converging problem-solution constellations" (Wanzenböck *et al.* 2020, p. 475).

The purpose of this paper is to reveal the systemic barriers to transitioning towards a circular economy in the infrastructure sector by analysing a construction sector in transition and seeking an understanding of the circularity transition in construction that goes beyond single changes and solutions. Specifically, we study the Dutch infrastructure sector, which is considered a frontrunner in CE policy (Giorgi *et al.* 2022), to contribute to knowledge building on this topic in the field of construction management.

To address the co-evolutionary and non-linear dynamics that are inherent in transitions (Köhler *et al.* 2019), we employ the Mission-oriented Innovation System (MIS) framework (Wesseling and Meijerhof n.d., Hekkert *et al.* 2020). This framework takes a systemic and directional view on transitions, rather than looking at specific solutions or practical problems that negatively influence the pace and direction of transformative processes (Wieczorek and Hekkert 2012). We aim to determine how mission-oriented innovation policies can accelerate specific mission achievements, since clarity is needed on the structure and dynamics of the socio-technical system including its actors and activities in which the transition takes place (Hekkert *et al.* 2007).

The remainder of this paper is structured as follows. First, the general transition concepts are introduced to inform the subsequent MIS framework that we use to study the transition. This is followed by a discussion of the research approach and the empirical results. The paper continues with a discussion of the barriers and their implications, before drawing conclusions and providing recommendations.

Understanding and studying transformations of socio-technical systems

Transitions are generally understood as transformations of socio-technical systems (Grin *et al.* 2010). Such systems, which can be delineated, possibly spatially or sectorally, consist of many elements that co-evolve and change the system. This shift is propelled through an interplay that involves many actors and institutions (Geels 2004). Transitions embody a transformation or replacement of socio-technical regimes. These regimes refer to a "semi-coherent set of rules that orient and coordinate the activities of the [actor] groups that reproduce the various elements of [the system]" (Geels 2011, p. 27). Change processes are generally assumed to be contested, inherently uncertain and multi-decade in duration (Köhler *et al.* 2019). In addition, societal challenges and specific missions, such as the quest for a CE, add a normative and directional component to this change, often approached from a public policy perspective (e.g. Janssen *et al.* 2021). Beyond trying to fix market failures, governments increasingly intervene to direct change in a societally desirable direction – i.e. a mission (Mazzucato *et al.* 2020).

When studying a transition, it is generally assumed that the socio-technical structures exist in an independent but layered way and are not directly observable (Geels 2022). Therefore, although mediated by individuals, knowledge can only be captured by studying socio-institutional causal mechanisms through a wide range of potential frameworks and methods. To reveal systemic barriers to the transition towards a CE in the Dutch infrastructure sector, it is therefore helpful to adopt an analytical framework that enables us to link observable developments in the sector to explanatory mechanisms.

We use the concept of Innovation Systems as explained by Carlsson *et al.* (2002) to describe the constellation of components, relationships and attributes involved in the development of innovation. Depending on the scope of the change or innovation, and the boundaries placed around the system, conceptualizations vary and can be in the form of National Innovation Systems, Sectoral Innovation Systems or Technological Innovation Systems (TIS) (Souzanchi Kashani and Roshani 2019). Traditionally, these Innovation Systems have been aimed at helping policymakers stimulate innovativeness for economic growth in a particular context.

Over the past decade, especially the TIS concept has developed into a framework for policy making, addressing sustainability transitions around the development of specific (sets of) technologies embedded in socio-technical systems (Köhler *et al.* 2019). In particular, the system functions approach has become a key feature in explaining the development, diffusion and utilization of changes and innovations (Bergek 2019). The rationale for these system functions is that the lack of a positive presence and alignment of functions is indicative of system weaknesses and reveal opportunities for policy improvement and intervention (Hekkert and Negro 2009). Examples of such empirical studies in the construction industry include the sustainability transition of sustainable concrete in the Netherlands (Wesseling and Van der Vooren 2017) and the introduction of wood in multi-storage buildings in Finland (Toivonen *et al.* 2021).

Grounded in the TIS framework as well as responding to the call to shift innovation policy from economic growth towards stimulating innovation towards a specific societal mission (Kattel and Mazzucato 2018, Kuhlmann and Rip 2018), Hekkert et al. (2020) proposed the Mission-oriented Innovation System (MIS) framework. Here, the MIS places the mission, such as the development of a circular economy or a zero-carbon society, at the centre of the system analysis.

The mission-oriented innovation systems (MIS) framework

The Mission-oriented Innovation System (MIS) framework, defined as "the network of agents and set of institutions that contribute to the development and diffusion of innovative solutions with the aim to define, pursue and complete a societal mission" (Hekkert *et al.* 2020, p. 77), facilitates the analysis of innovation and change-delineated systems with respect to predefined missions. Eventually, the structure and functioning of the predefined MIS provide the insights needed to determine the barriers to effective mission attainment.

The MIS framework consists of four major parts that need to be determined (Wesseling and Meijerhof n.d.). The first part is the problem-solution space. This concerns the definition of, and dynamics between, the societal challenges that the mission aims to address (e.g. climate change) and the potential solutions to address these challenges (e.g. wind energy). It focuses on the level of convergence between the framings of the societal problems underlying the mission and the variety and prioritization of solution pathways (Wanzenböck *et al.* 2020).

The second part is concerned with the composition and rules of the system. This includes the system elements, their relationships, and the boundaries of the MIS. These can be derived from a description of the involved actors, networks and institutions that give the system its particular and unique characteristics. As such, this provides the boundary conditions for the workings of the system. Moreover, an analysis of the structure addresses the presence and structure of one or more *mission arenas* within the wider MIS. These are defined by Wesseling and Meijerhof (n.d., p. 6) as "[spaces of] actors that are engaged in the highly political and often heavily contested process of mission governance." Depending on the mission, arenas can be industry networks, collections of front-runners or formal working groups that aim to direct the mission.

The third part consists of the innovation-enabling or innovation-preventing activities and processes within the system in terms of the mission. This system functioning is determined based on theory-derived but empirically-validated key system functions (Bergek 2019). Largely based on TIS conceptualizations and empirical case studies (Bergek *et al.* 2008, Hekkert and Negro 2009), the MIS functions are defined as abstract categories of (clusters of) activities and sub-processes of the overall innovation processes that provide insights into the dynamics and potential patterns of change and innovation with respect to the development of the innovation system (Hekkert *et al.* 2007). Although the extent to which the system functions need to be present or aligned depends on the particular system studied, they have explanatory power with respect to transformational failures and play a crucial role in identifying systemic barriers (Raven and Walrave 2020). In addition, the performance of functions can be causal. For example, a lack of legitimacy for a specific

Table 1. List of MIS functions (adapted from Wesseling and Meijerhof n.d.).

Code	Function	Description
F1	Entrepreneurial activities	Activities, initiatives, experiments, pilot projects, market introductions and novel business models regarding (clusters of) novel solutions related to the mission.
F2	Knowledge development	Creating knowledge on the problems and solutions "by research" and "by doing", including forecast studies, laboratory work, field studies, working groups and strategic studies.
F3	Knowledge diffusion	Dissemination and adoption of knowledge regarding the problems and solutions through media, stakeholder meetings, knowledge networks, governance structures, publications and interaction.
F4a	Problem directionality	Formulation and guidance of the societal problem(s) with respect to the mission and their priority and interaction with respect to other societal problems and missions.
F4b	Solution directionality	The efforts made to provide direction towards the mission goals in terms of (clusters of and coordination between) potential solutions and their priorities.
F4c	Reflexive governance	Monitoring, evaluation, active learning, impact assessment, securing knowledge and anticipation of progress to provide input for guidance and governance with respect to the mission attainment.
F5	Market creation and destabilization	Creation of conditions such that innovative solutions can develop and compete with existing practices through, for example, creating "arenas", pricing mechanisms, as well as phasing out and destabilizing undesirable markets with respect to the mission.
F6	Resource (re-)allocation	Mobilization of financial, human and material resources to enable other system functions and withdrawal of resources that support unwanted activities with respect to the mission.
F7	Creation and withdrawal of legitimacy	Creating and eliminating legitimacy and social acceptance for the solutions and problems respectively and in favour of the mission through raising awareness, stakeholder engagement, lobbying, standardization, championing etc.

mission (e.g. increasing biodiversity) might lead to a lack of resources (e.g. no subsidy schemes), which might lead to a lack of entrepreneurial activities (e.g. only a few pilot projects). The resulting list of MIS functions adapted from Wesseling and Meijerhof (n.d.) is shown in Table 1.

The knowledge of the problems and solutions that the MIS addresses, the structural characteristics of the MIS, and the activities and developments that take place in the MIS that influence mission attainment provide an understanding of the MIS. Together, these three parts enable the identification of barriers (the fourth part) by revealing causes of, and causalities between, the underperforming or misaligned functions based on the events and activities that are linked to the functions. The resulting causal chains can result in vicious and virtuous cycles (Suurs 2009). These causalities provide insights into the locked-in dynamics that are valuable in determining interventions that can remove barriers and guide and stimulate a transition – in our case the transition to a circular infrastructure sector.

Research approach

In this section, we first introduce the case study of the transition towards a circular infrastructure sector in the Netherlands. Second, the data sources and collection methods are discussed and, third, we explain how these data were analysed.

Case selection, characteristics and boundaries

We apply the MIS framework to the Dutch infrastructure sector since this is considered a frontrunner in CE policy (Giorgi *et al.* 2022). For this research, boundaries were placed around Dutch infrastructure works commissioned by public bodies only. These include road infrastructure, railway infrastructure and waterways, and all supportive assets, such as bridges, dams, sluices and tunnels. Energy infrastructure, telecommunication infrastructure and the cable and pipe subsectors were not part of this analysis.

Infrastructure sectors have several typical characteristics that affect which data can be collected and how. First, it is a public sector with a highly politicized context. This means that the assets are generally purchased, owned and financed by public organizations (Dominguez *et al.* 2009). Further, client-contractor relations are subject to public procurement law, which puts strict rules on contracting in order to guarantee transparency and a level playing field (Volker 2010). Here, the government, as a client, has considerable power in setting the terms for specific projects and in deploying specific governance instruments (Hueskes *et al.* 2017). Nevertheless, infrastructure is designed, commissioned and maintained through a rather fixed system of actors and institutions (Lienert *et al.* 2013). Second, infrastructure assets are highly unique, resource intensive, and usually have multi-year lead times and multi-decade lifespans. This leads to challenges in planning, management and governance. Moreover, it is difficult to measure CE benefits in the infrastructure sector due to these long asset lifespans and lack of clarity as to what circularity is in this context (Coenen *et al.* 2021a). Third, infrastructure works are usually executed as multi-actor public-private projects with strict predefined goals and task specifications, time/budget constraints and interdependent team and actor relations (Harty 2005). In these projects, participants traditionally have conflicting interests (Olander and Landin 2008). Overall, the reputation of the sector is a conservative and risk-averse one, sustained by the small profit margins.

Data collection

For the case study, we collected data from multiple sources to reveal insights into the first three components of the MIS framework. In terms of the problem-solution analysis, we studied the range of problems and solutions as reflected by the mission. These were collected from policy documents and then complemented and validated by interviews. For the structural analysis, we established an overview of the sector in terms of actors and institutions. Here too, policy documents served as the primary data source. In addition, the academic literature was used to understand the particularities of the sector and interviews were then carried out to complement and validate the findings. To identify the presence and relationships between the MIS functions (Table 1), we needed to understand the developments in the sector as experienced by practitioners. Here, we carried out in-depth interviews rather than study policy documents as the primary source on the basis that such documents tend to reflect what used to happen or ought to happen rather than what currently happens in practice.

Thirteen policy documents were studied to define the mission, mission arenas and predefined boundaries of the Dutch infrastructure sector (see Appendix A). This set contained documents produced between 2015 and 2021 by central and regional governments and industry networks that specifically addressed CE goals, measures and strategies for infrastructure. These documents were collected through an internet search. Here, we primarily made use of the formal website of the "circular construction economy" that was launched by the Dutch Government.

The interviewees were selected using a purposive sampling strategy (Campbell *et al.* 2020), aiming to include a variety of perspectives on the transition and the different actor types as categorized by Kuhlmann and Arnold (2001). These categories included demand (public clients), industrial system (contractors and suppliers), intermediary organizations (network organizations, advisories and thematic experts), education and research (public and private research organizations), resource infrastructure (financers) and political system (policymakers). The results from the analysis of the policy documents were used to specify the interview questions that were largely deduced from the system functions of the MIS framework (Table 1) and to tailor these to the infrastructure context.

In total, twenty people were interviewed in two sets of interviews. First, we conducted ten in-depth semi-structured interviews of approximately ninety minutes each. The identified MIS functions were used as a basis to acquire a general overview of the performance and dynamics of the MIS in practice. These interviews helped to generate a systemic view by tracing developments in an explorative way. In line with the interpretive genre in interview studies (Langley and Meziani 2020), we focused on differing perspectives and backgrounds of the interviewees. Hence, this first set of interviews produced an overview of the unclarities, ambiguities and contested subjects. The second set of interviews was executed following a more structured approach that focused on clarifying specific unclarities. Saturation was reached after ten of these structured interviews (see Appendix B for the full anonymized list). These were transcribed verbatim, resulting in twenty documents of 7,000–13,000 words each.

Data analysis

We analysed the policy documents to create a narrative on the development of CE since 2015, and to determine the problem and solution spaces and their interaction. Statements from the interviews were used to complement and validate this narrative. Furthermore, the documents were analysed on the actor and actor group level to establish an overview of the mission arenas and structural barriers to the transition. In addition, we analysed professional and scientific literature to create a comprehensive overview of the system, including specifics of the infrastructure sector that affect developments towards mission attainment, such as its project-based nature, dependence on procurement law and long asset lifespans.

The Atlas.ti software tool was used to link the interview data to system functions (Table 1). For example, when an interviewee mentioned the financing of a circular pilot, it was labelled under function 6 (resource mobilization) and when an interviewee explained the consequences of the procurement process for the ability to develop circular solutions it was placed under function 5 (market formation). Next, all the comments regarding a particular function were summarized for each interviewee. We inserted these quotes in a large matrix with the interviewees on one axis and the MIS functions on the other, followed by a cross-interviewee analysis for each function, in which each referral to another function or structural characteristic was noted separately. This was first done for the first ten interviews and later complemented with the latter ten. Finally, we summarized the functions in qualitative terms based on the matrix to draw conclusions on their performance.

By studying the functional relationships mentioned by interviewees and by searching for explanations for under-performing functions in the interview transcripts and policy documents, causal links between functional and structural elements that hamper the transition were identified. These were assembled in an elaborate causal diagram in which specific reasons were linked to specific functional and structural elements. The resulting diagram was discussed with professionals from the infrastructure agency. Based on this validation with practice, elements with similar causations were clustered to simplify the diagram. This enabled the identification of three vicious cycles that can be understood as looping chains of cumulative causation (Suurs 2009) that we labelled: (1) the CE contestation cycle; (2) the knowledge diffusion cycle; and (3) the innovation cycle.

First we discuss the problem-solution analysis, structural analysis and functional analysis from the MIS framework, followed by describing the barriers and vicious cycles that were identified within the Dutch infrastructure sector. The results related to the first three framework components are described in the “results and analysis” section, and the final systemic barriers in the fourth part are discussed in the “analysis of the barriers towards a circular industry” section.

Results and analysis

Problem-solution analysis

The Dutch government set a mission to be fully circular in 2050, but it is experiencing difficulties in the implementation of circular innovations and practices for achieving this mission (Hanemaaijer *et al.* 2020). Since 2014, CE gained traction as a holistic means to reduce environmental impact and sustain a healthy economy. It ever since became one of the dominant concepts in the field of environmental sustainability (Goyal *et al.* 2021). Generally, the interpretation of the CE definition is linked to closing resource loops in order to minimize resource depletion and waste creation in all industries (Kirchherr *et al.* 2017). Nevertheless, the focus on technological solutions and economic gains, rather than the resulting environmental impact also has been one of its main criticisms (Corvellec *et al.* 2022). While it gained popularity, the diversity of interpretations also increased, leading to CE being an essentially contested concept (Blomsma and Brennan 2017, Korhonen *et al.* 2018). The differing interpretations are not only limited to the pluralistic perspectives of scholars, but also include varying meanings in particular geographic, sectoral, technological and socio-economic contexts (Calisto Friant *et al.* 2020), and has changed through time.

Nevertheless, many public organizations have incorporated circularity in strategies and policies. Here, circularity has often become a goal in itself with its own time-bound targets in terms of waste reduction, reduction of virgin material uses and reduction of carbon emissions. Despite being presented as a mission in itself, in many documents CE had been introduced as a means to address societal challenges on all governance levels, not just resource scarcity and waste generation, but also wider issues, such as carbon emissions and loss of biodiversity. In the next sections, the mission development and current problem-solution space is discussed in greater depth.

The origins and goals of the CE mission in Dutch infrastructure

For the Dutch infrastructure sector, according to a policy officer, “the step towards formal CE policy was taken rather radically.” It was connected to previous and parallel missions and agreements. Largely grounded in the national strategy *Nederland circulair in 2050* [The Netherlands circular in 2050], the Resource Agreement stated that the infrastructure sector should procure 100% circularly in 2023, reduce its use of virgin resources by 50% in 2030, *work circularly* while reducing its CO_2 emissions by 49% in 2030 and *be fully circular* in 2050. The resulting transition agendas published in 2018 formed the starting point for the formal sectoral transition.

Substantiation and execution of the national mission for infrastructure was from 2018 onward, aside from their own initiatives, largely delegated to Rijkswaterstaat [Dutch Directorate-General for Public Works and Water Management]. The goals and strategies were adopted in agreements by other public bodies such as municipalities, provinces and waterboards too. Substantiation and operationalization of the strategies differed between these decentral government bodies and appear to have been poorly aligned and coordinated. The Unie van Waterschappen [national waterboard platform] was an exception. As one representative mentioned, "we, as 21 waterboards, find it essential to exude a shared ambition"; a view that differs from the more politicized and individualistic disposition of municipalities and provinces.

Problem space

Despite the clear goals in policy documents, interviews revealed contestation about the problem space in practice. This contestation centred around the societal challenges that the mission addressed, to what extent there was consensus on these challenges, and how the mission related to other missions and challenges – particularly with respect to *sustainability*. In addition, some interviewees presented a definition of CE in terms of solutions, or even in terms of measurement criteria, rather than in terms of problems. Although considering CE as a goal might increase the actionability of the concept, it runs the risk of developing solutions that address no essential problems. Also, there appeared to be no consensus on potential feasibility. Moreover, the meaning of CE seems to be an evolving construct and the question is how useful it is to capture such fluid concept in a fixed conceptualization. As one interviewee put it, "if we keep adapting the definition of what a 100% CE means, we will eventually get there, but if we stubbornly hold on to the current definition, we won't."

Several interviewees stressed the importance of distinguishing *circular economy in general* from *circular construction* or *circular infrastructure*. The former interpretation relates to reforming society at large towards a closed-loop system, whereas the latter is aimed at more concrete resource-related issues in the construction process, often addressing specific issues of resource depletion. Most interviewees who did not distinguish between the two seemed to have interpreted circularity as the latter. Nevertheless, the operationalization of both interpretations through circular solutions was strongly subjected to contestation.

Solution space

Specific solutions were barely and only specified in the policy reports in abstract terms. However, when analysing the interviewees' interpretations of the solution space, operationalizations of CE solution pathways appeared on three levels (Table 2). First, there was the level for actual, often technological, solutions, such as modular design or bio-based materials. Second, there was the level of circularity design, construction and operation strategies. This includes the waste hierarchy, in which various *Rs* are defined to be circular to a certain extent (e.g. Potting *et al*. 2017). This waste hierarchy could also be found in several policy documents. Third, there were solution directions aimed at the conditions necessary for a circular system, such as data strategies, measurement tools or procurement strategies to facilitate circular decision-making during asset lifecycles. The overall Dutch strategy in infrastructure seems to be focusing on this third level, particularly with respect to procurement as a tool to stimulate circular alternatives.

Solutions on the third level appear to be rapidly converging as there are, at least on paper, numerous networking activities. However, solutions for the first two levels are still highly contested throughout the sector. The first level is still divergent, indicated by the high level of experimentation and low level of uniformity, which, according to some interviewees, fits the current early phase of the transition. In line with several other respondents, a public manager observed that "rather than a sustainability issue, CE is an asset management issue." In a similar vein, several interviewees stressed that the circularity transition is an organizational challenge, rather than an innovation challenge.

Specific solutions are generally developed by market parties to address public tenders. These solutions are eventually determined by the public clients who either develop, purchase or collaborate on certain solutions. As such, the public clients' procurement power strengthens the top-down ability to steer the formal problem direction. This resonates with Jones (2018) who urged for an intelligent combination of top-down steering and bottom-up action in relation to a widely-interpreted sustainable built environment. However, an interviewee also pointed out that, "often, not only the [circular] solution, but also the [level of] circularity ambition is procured", indicating a lack of central (top-down) steering and coordination from a client's perspective. This is problematic because by only addressing that "something circular" is desired and not the degree and boundaries of the

Table 2. Circular solutions in the infrastructure sector exist on three levels.

Level of solution	Description and examples
1. Technological solutions	Circular solutions in terms of material use, design strategies or other technological changes or innovations. Well-known examples are bio-based materials and modular design.
2. Solutions as abstract strategies	Circular solutions in terms of conceptual strategies and principles, e.g. refuse, reuse and recycle. The most prominently applied way is the waste hierarchy, which is often operationalized in the R-ladder (varying from 3 to 10 Rs).
3. Solutions on conditions for circularity	Circular solutions in terms of conditions for facilitating the first two categories, often aimed at processual, institutional and organizational changes. Well-known examples are circular data management strategies and circular business models.

conceptualization, it is nearly impossible to compare and reward particular circular ideas within conventional procurement processes.

Problem-solution interaction

The problem interpretation of the interviewees in terms of solutions indicates that the directions and interpretations of the solutions result, not only from the problem interpretation, but also that the operationalization and direction of the problem is influenced by the solution. Similarly, the question as to whether CE is a goal in itself, or a means, has blurred over time, especially in project contexts. A consultant even explained that because of problem and solution contestation "I try to avoid terms like circularity and sustainability and instead talk about the underlying problems and how we can solve them." This is in line with the findings on the innovation trajectory of the Circular Viaduct in which the first reusable and modular viaduct was developed (Coenen, *et al.* 2021b). This case affected the Dutch understanding of CE as a concept in terms of circular design principles.

Structural analysis

Structure of the Dutch infrastructure MIS

The barriers for a circular infrastructure sector depend on the structure of the studied system and its context. Dutch infrastructure works rely on the involvement of various public bodies which are coordinated from various ministries and regional governments. Furthermore, the sector encompasses multiple subsectors, both horizontally (e.g. waterways, roads, railways) and vertically down the supply chain (e.g. bridge elements, concrete production) and has no clearly delineated boundaries. Both because of the distinctive governance bodies and the many separate subsectors, the Dutch infrastructure sector is generally considered fragmented by nature. In addition, the actors are highly interdependent, given the regional nature of the construction market and small size of the Netherlands. While the clients guide the direction with their purchasing power, eventually, the market parties introduce innovations. This results in tense and opposing relations and values across the whole sector (Kuitert *et al.* 2019).

The Dutch infrastructure sector consisted in 2019 of over 1100 contractors, where only 34 companies have over 100 employees (EIB 2021). The demand side of the sector involves only a few large public clients (national and regional bodies) but a few hundred smaller ones (mostly municipalities). In addition to the clients and contractors, the sector comprises a large number and variety of, e.g. suppliers, consultancy and engineering firms, knowledge institutions and financers, as well as societal pressure groups and lobby groups that influence the direction and pace of transition in the sector and are generally considered to have a lot of power. Nevertheless, there is considerable variation in the intensity and impact of the actors involved in the transition process and circularity at large. Within the many subsectors, by far the most turnover was generated from road construction, followed at some distance by the concrete civil engineering structures (EIB 2021).

Next to these actor constellations, the Dutch infrastructure sector has some specific features that potentially affect the CE transition. First, from a political perspective, the past decades have been dominated by a neoliberal system in which the New Public Management has become a central governance paradigm (Kuitert 2021). Here, the market has been becoming more dominant in determining direction at the cost of top-down public steering in which responsibilities have been strongly shifted towards market parties (known as "markt, tenzij" [market, unless]). Strengthened by in the breach of confidence resulting from the "Bouwfraude" [major collusion scheme of market parties in the 1990s and early 2000s], the main task of the government has become to offer the conditions for the market to exploit its full competitive potential while risks are also allocated to the market. Due to the fierce competition between the market parties, the profit margins are generally low, while the stakes and risks taken are high. However, in the past few years, the public-private relations are slowly shifting towards more collaborative ones, partly as a

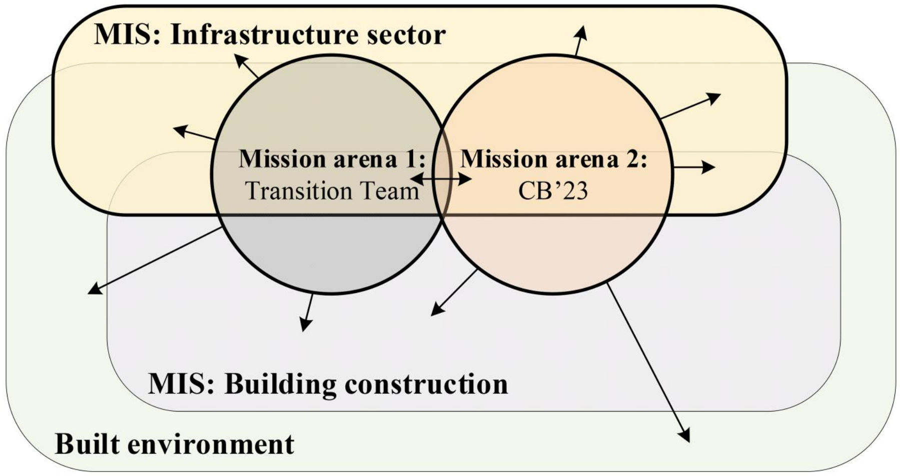

Figure 1. Schematic outlines of the MIS and two major mission arenas.

response to the structural time and budget overruns in the sector.

Second, the Dutch infrastructure sector is challenged by an enormous cumulation of deterred maintenance of infrastructure assets in combination with a large amount of post-World War II assets that are nearing their technical end-of-life. This results in a huge task of renovation and replacement of infrastructure assets across all tiers of government in the next few decades (Bleijenberg 2021). Currently, both the available budget and capacity are considered tight.

Third, the overall infrastructure is compared to other countries considered of exceptionally high quality in terms of, e.g. connectivity, efficiency and reliability of roads, waterways and railways (World Economic Forum 2019). This has consequences for the standards to which circular alternatives should comply.

Mission arenas

We found that, because the mission was both centrally governed and several platforms and networks exist in which the mission directions are developed, two interrelated mission arenas exist (Figure 1): (1) Transition Team Circular Building Economy (hereinafter referred to as "Transition Team"); and (2) platform Circular Building '23 (hereinafter referred to as "CB'23"). Both mission arenas concern both the infrastructure sector and the building construction sector, which largely shape the built environment. Although both subsectors are addressed the overall goals and strategies, for example, in the *Transition agenda circular construction economy*, their operationalization is discussed in separate strategies and policies.

The Transition Team (Mission arena 1) forms a rather formalized arena. It was established in 2018 by the Dutch Ministry of Economic affairs and Climate (EZK) and Ministry of Infrastructure and Water Management (IenW) to shape and steer the implementation programme towards circular construction in line with the *Transition Agenda*. It consisted of 16 individuals who represent ministries, other government bodies, universities, market organizations and financers, including their relations with other sectoral actors, both from building construction and infrastructure.

CB'23 (Mission arena 2) is a platform established in 2017 by Rijkswaterstaat, the Dutch Public Real Estate Agency and the Dutch Normalization Institute with the goal to establish a shared basis for circular construction aimed at both building construction and infrastructure. In contrast to the Transition Team, CB'23 is aimed at sector-wide participation and encourages all interested actors to join. The result is a heterogeneous platform of over one hundred participants from almost as many organizations contributing to several thematic working groups. The output consists of widely supported and publicly available guidelines to encourage circularity in construction. Active alignment exists between arena 1 and arena 2 with several individuals who participate in both the Transition Team and the board of CB'23. As a result, there is no single place where the direction of the transition towards CE is governed. Instead, there is an interconnected and dynamic collection of actors who operate in varying arenas.

Apart from these central mission arenas that aim to direct the transition at large, specific arenas exist that aim at specific parts of the transition, such as the agreements for specific material groups such as concrete [Betonakkoord] and steel [Bouwakkoord staal]. These are not separately studied but merely considered as context for the sectoral arenas.

Functional analysis

The performance of the MIS functions (Table 1) are summarized in Table 3. Based on these functions, the dynamics in the sector are explained in greater depth in the next sections.

Entrepreneurial activities and experiments for circular solutions (F1)

The entrepreneurial activities and experiments for circular solutions are increasingly visible in practice. CE appears as a topic in almost all organizations and is covered in virtually all business strategies. This goes hand in hand with an increasing societal awareness concerned about squander and waste. Yet, several interviewees stressed that most individuals and infrastructure projects did neither actively address circularity nor circular innovation. A foremost reason mentioned was that circularity is generally not an indicator to measure the performance of projects or individuals. Furthermore, the degree to which circularity is implemented differs markedly between organizations but is, generally, low. The reasons mentioned for the low proactivity towards circular solutions in market organizations were small profit margins, overcapacity in sub-sectors and tight and prescriptive procurement procedures.

Given the large dependency of infrastructure works on public clients, the lack of market initiative is largely a result of a circularity-unfriendly procurement practice. As indicated by a contractor, "often you aren't even going to look for novel solutions, because [the clients] request a proven technology." In addition, public clients seem to struggle with handling unsolicited proposals, which hampers circular market initiative. Nevertheless, we found several networking and collaboration initiatives, comprising both market parties and clients, that explore the direction to innovate and to implement circular actions. The result can be seen in the increasing number of pilot projects that address circularity.

Development and diffusion of circularity-enabling knowledge (F2, F3)

The knowledge required to transition is being generated very rapidly by many types of organizations, particularly the larger organizations and academia. According to several interviewees, knowledge on

Table 3. Summary of the results of the functional analysis per function.

Code	Function	Performance
F1	Entrepreneurial activities	Even though the CE theme is widely shared across industry, the actual initiatives in practice are still quite low in number and impact. Moreover, current focus is on pilots and experiments, rather than process and organizational changes.
F2	Knowledge development	Huge steps have been made in the development of circularity knowledge. However, some themes are still underdeveloped, such as distance-to-target knowledge, as well as knowledge on the tactical level.
F3	Knowledge diffusion	Despite a relatively high willingness to share circularity knowledge through showcase examples and network events, access to relevant knowledge is challenging, especially for newcomers. Also, cross-project knowledge diffusion and learning between projects and organizations remains problematic.
F4 F4a	Problem directionality	There are several (policy) initiatives aimed at aligning the CE mission with societal problems, but, nevertheless, the perception of CE is rather contested and highly sector specific. In addition, the relation with other missions, such as sustainability, is perceived divergently.
F4b	Solution directionality	Several solution directions are in a fair stage of development, but there is still a lack of consensus on the priorities between those solutions. This exploration is delegated to the market, rather than being top-down directed. Yet, public clients play a significant role in the solution directionality through their purchasing power.
F4c	Reflexivity	The knowledge infrastructure and distance-to-target knowledge are insufficient for reflexive governance on circularity. However, there are major current developments in these aspects. The circularity strategy is continuously adapting and evolving to new developments and insights on problems and solutions.
F5	Market creation and destabilization	The main instrument to steer markets is the purchasing power of public clients. Also, a lot of effort is being put in experimenting with novel business models, circularity-included procurement, and increasing the minimum CE requirements, but those do still insufficiently apply to conventional projects.
F6	Resource (re)allocation	The allocation of funds for circular initiatives are increasing but insufficient. However, a larger challenge is the lack of capacity in terms of circularity-focused employees and experts to adapt (non-circular) processes and practices.
F7	Creation and withdrawal of legitimacy	Generally, the legitimacy of circularity is high throughout the sector, but its priority is still too low compared to e.g. the energy transition or traditional infrastructure values such as traffic hindrance.

conditions and processes for CE is being driven largely by commissions from ministries and wider networks. Despite the many platforms and networks, individual organizations often develop circular knowledge to increase their competitive advantage, rather than to deliver sectoral or societal benefits. Yet, market parties acknowledge increasingly the benefits of sharing knowledge – particularly given the overall work overload, which reduces the risk of losing competitive advantage. Regardless of the availability of knowledge, access to it for actors new to the topic is considered problematic, especially in terms of the complexity and specificity of CE knowledge. This problem holds true particularly for smaller organizations who do not have the capacity to spend a lot of time on searching for, developing and applying CE knowledge.

The results indicated a major knowledge gap related to distance-to-target knowledge of material and waste flows, material properties and future resource demand. This is knowledge that is required to make circular decisions from the perspective of governance and management, which creates challenges for both the provision of giving a proper perspective to the market and the long-term allocation of funds. The lack of perspective and long-term funding hampers wider market investments in circular operations. Another commonly mentioned gap was the lack of tactical knowledge to enable the implementation and operationality of the strategies, on, for example, supply chains and organizational processes. Nevertheless, there are increasingly developments being initiated by particularly client organizations to develop this type of knowledge.

Alongside the knowledge in practice, we found that scientific knowledge on the topic has experienced a large growth since 2015. As a researcher put it in one of the interviews, "I think that [development of CE knowledge] is rapidly developing in a systematic way, albeit fragmentedly." Although this knowledge is often more fundamental and not necessarily aimed at the infrastructure sector, it gets diffused and adopted in the network through collaborations and network initiatives. Furthermore, circularity seems to become increasingly a topic in civil engineering and construction management education. This helps to diffuse scientific and professional knowledge to both junior employees and experienced professionals.

However, sharing and adopting lessons and knowledge within organizations and between projects appears to remain problematic. A clear coordination of this knowledge development and diffusion throughout the sector seems to be lacking, despite the conceptual alignment between the various initiatives and the mission arenas. Recently, various initiatives have been initiated to overcome this barrier, such as Communities of Practice (CoPs), implementation programmes and client meetings to align circular ideas and strategic agendas. As a consultant confirmed, "[there are] more and more places to showcase good circular examples." This helps to diffuse knowledge and inspire others. Yet, despite the large amount of available circularity knowledge and pilot projects, the diffusion of information, knowledge and lessons learnt was found to be one of the foremost bottlenecks impacting the transition to circular infrastructure.

Directionality of the problem and solution pathways (F4a, F4b)

The problem-solution analysis shows the background of the problem and solution pathways regarding circular construction. But how are these problems and solutions directed and how is this directionality perceived? We found that CE in the infrastructure domain should be understood as *circular construction* aimed primarily at maximizing value per unit resource, reducing the use of virgin materials and reducing waste creation, whether or not to reduce the overall environmental impact. While several interviewees stressed the importance of treating circularity as a separate theme to safeguard governability, most of them argued that circularity must be viewed integrally with other societal problems. These include the goals stated in the formal policies, such as CO_2 emissions and energy use, but also issues like long-term cost reductions and cost efficiency. Despite these differences in interpretation, several interviewees referred to the CB'23 guidelines for a widely supported definition of circular construction which was also adopted by the Transition Team. The Dutch formal problem for infrastructure is nevertheless poorly aligned with the CE goals formulated by the overarching CE strategy report and the monitoring agency (Netherlands Environmental Assessment Agency, PBL).

Notwithstanding the wide debate on and the embrace of circularity, most interviewees stated that the priority of circularity remained too low compared to other themes, such as traffic hindrance, cost efficiency or accessibility to achieve the policy goals for 2030 and 2050. This holds not only true for top-down policy, but also the way in which for instance project managers are assessed on their performance. In this current, early transition stage, the predominant implementation activities are aimed at pilots and experiments to explore circular solutions in infrastructure, rather than at becoming embedded into regular infrastructure projects and practices. Increased by the long lead-times of infrastructure, this has resulted in meagre changes in terms of output results in the short term.

Given the lack and poor coordination of standardization of solutions, it remains unclear what the dominant solution pathways will be. These can range from bio-based materials to increasing reusability to reorganizing asset management. However, several interviewees mentioned that various kinds of infrastructure require different kinds of circular solutions. To illustrate the unclarity on dominant solutions, one civil servant pointed out that: "[…] it is not so much the circular solutions themselves that are under debate, but rather how and to which extent each solution should contribute to solving the problems."

Also, more and more preconditional issues have come to light that are required for the system to become more circular. These include restricting legislation, organizational processes, project approaches and procurement mechanisms. Although rules and legislation were mentioned as instruments to direct the solution space, a policymaker highlighted the balancing act of "trying to move the market in a desired direction, [while allowing] space for their own organizational changes and innovations." This remark reflects the widely shared perception that it should not be the role of the government to choose specific solutions, but rather to provide the conditions for the market to come up with the best solutions. This finding is consistent with the dominant public governance paradigm in the Netherlands as discussed in the structural analysis.

Reflexive governance (F4c)

With respect to the governance of the mission, we found that particularly the large public clients developed several roadmaps, transition pathways and scenario studies to provide longer-term direction to the transition activities and accompanying solutions. These relate to several monitoring and assessment activities, both within the sector and across sectors. At the project, organizational, sectoral and cross-sectoral levels, individual circularity actions and policies are generally assessed and evaluated. Nevertheless, due to the lack of distance-to-target knowledge, it appears difficult to determine the contribution of certain policies or actions and to adapt the coordination and directionality strategies accordingly, especially on an organizational or project level. As one public manager admitted, "we don't know the actual environmental impacts of actions and what is needed to reach the [CE] targets, […] so that makes it very difficult to steer." A big challenge in governing the transition, regardless of the monitoring and evaluation effort, is the long-term planning in infrastructure that is strongly connected to the sector's structure. As long as circularity is not part of these long-term strategies, planning and portfolios, the governance of circularity principles beyond newly built assets remains impossible.

Interviewees also mentioned that it is difficult to learn across projects, even when such projects are specifically labelled circular. This is partly because there is no central knowledge infrastructure in place that facilitates governing, based on lessons learnt in practice. However, next to developing knowledge in general to allow for reflexive governance, a major consequence appears to be the challenging persuasion of politics to systematically allocate funds and build capacity for circularity.

Creation of markets for circular solutions (F5)

Currently, circular market creation appears to be aimed primarily at experiments and pilots for circular alternatives. To create markets for circularity in a regular project setting, the public clients should take a leading role, since, on the one hand, the market is insufficiently organized to do so and, on the other hand, public clients have virtually all the means at hand to steer the transition. As a contractor mentioned, "we are a demand-driven organization and if we do not adhere to the demand, we won't win tenders." Procurement, especially, was mentioned as a major tool to steer CE opportunities and to shift from procuring projects to longer-term collaboration forms that better incorporate the lifecycle principles of CE. Nevertheless, there is a large variety in competencies of public clients to create the conditions for circular markets. Moreover, there is a lack of coordination between them to move the market into circular directions. Next to creating markets with circularity-friendly procurement, several interviewees identified the provision of perspective for future circularity demand as a major bottleneck to market initiative. In that respect, interviewees urge government clients to be prepared to allocate additional funds to create circular markets expecting that, when these markets are in place, costs will be lower than if the current linear way of working would be continued.

An ongoing debate in the domain of circular business models is to what extent these contribute to the overall circularity mission. One dilemma cited was the following. Extending producer or contractor responsibility, e.g. by service contracts, may, on the one hand, result in incentives for resource efficiency, while, on the other hand, it could reduce the control of the client to steer for circularity in the long run, particularly considering the evolving meaning of CE.

Another challenge mentioned was that it depends on the subsector to what extent clients can exert control on circularity requirements. This is strongly linked to the market capacity, reliance of market parties on infrastructure works and the number of contractors. Nevertheless, according to interviewees, new markets should be created, and client organizations should steadily increase thresholds associated with, e.g. recycling rates, CO_2 thresholds or waste quantities. This can include award/punishment mechanisms for material use and waste creation. Still, as one consultant revealed: "The danger with regulations [for increasing thresholds] is that parties take that these as a minimum norm, rather than trying to go beyond it." Hence, a disadvantage of such strategies is that these aim at pushing laggards, rather than stimulating frontrunners and early adopters to go even further. This connects to the dilemma regarding the extent to which public clients are responsible for keeping all market parties on board, as opposed to leaving structural laggards behind.

Our data also indicate several ways of stimulating the market at large. Pricing mechanisms or revision of the tax system from labour to resources were often mentioned. This is in line with structural market barriers beyond the sectoral boundaries (Kirchherr *et al.* 2018). Currently, the government has several subsidy schemes that cover circularity, such as the Small Business Innovation Research (SBIR) programme for circular bridges and grants for replacing fossil fuelled equipment by electric alternatives. Yet, most of these do not seem to have led to many concrete advancements on a sectoral scale. One foremost opportunity to offer conditions for circular alternatives in regular projects would be to replace strict specifications by more functionally specified tenders, which is already happening on an accumulative scale.

Availability and allocation of resources (F6)

Funds in infrastructure are generally public. Hence, they are connected strongly to political decision-making. Most interviewees agreed that there are not enough funds available to finance the changes necessary for circularity – particularly in the long term. Lack of distance-to-target knowledge, including sector-wide material flows and recycling and reuse percentages, were mentioned as important barriers to acquire long-term funds. Next to the mere availability of funds, we found that it is important to link (innovative) construction funds to the maintenance and replacement challenges in the infrastructure sector, especially for public clients. Consequently, it is not only the number of resources, but also the type of activities to which those resources are linked that are needed to effectively stimulate the transition.

The data furthermore suggested that politics should allocate more funds to accompany their increasing targets and ambitions regarding CE – particularly for smaller local governments. As one public manager put it: "When you get an assignment without the requisite means, you should think carefully about the extent to which you are going to execute the assignment." As such, interviewees argue that decision-makers, managers and politicians are insufficiently able to realize that circularity could lead to cost reductions in the long run, especially when, e.g. CO_2 taxes in the future push up the price of virgin materials. However, as another public manager argued: "Despite attention for [CE] might be too low, advocates of safety or other themes probably would probably argue for the same, […] given the overall shortage of resources for infrastructure and particularly its maintenance and operation."

Funding of circularity is often coupled with sustainability in general. As a result, circularity initiatives can often be financed with climate change related funds, e.g. carbon reduction or where the word *climate* is attached. When used for circularity, available resources are often allocated to specific pilot projects and technologies, while for making steps in circularity, resources need to be allocated to structural organizational and operational change. Such investments are still marginal, specifically within market parties. Although it was noted that larger contractors tend to invest increasingly in circularity, the extent is still considered too low and too slow.

Despite the abovementioned lack of financial resources for innovation, the lack of capacity (i.e. employees dedicated to and knowledgeable on the topic) seems to be a pressing challenge too, which is reinforced by the overall labour shortage in the Dutch construction sector. Nevertheless, in line with Gerding et al. (2021), an increasing number of employees in public and market organizations are showing an interest in CE, or are even dedicated to it. Also, CE is increasingly being integrated into educational programmes, which helps to equip future employees with circular knowledge and practices. At the same time, an increasing number of young graduates wants to work only in companies with a clear and progressive vision on environmental issues.

Legitimacy for circular infrastructure (F7)

Overall, there seems to be considerable legitimacy for the circularity theme throughout the Dutch infrastructure sector. This can be explained partly by the clear link to national and supra-national agreements and, also, because of the concept's relation with long-term economic and environmental benefits. Nevertheless, there are other competing themes with higher priority in the Dutch infrastructure sector, such as the energy transition and nitrogen problems that prevent construction projects to start due to the refusal and delay of building permits due to environmental reasons. Their influence can, however big the CE legitimacy, result in limited action. An often-mentioned explanation is that other themes are easier to quantify, measure and compare, particularly in the procurement stage. There is also an increasing societal support and sense of urgency for the circularity theme. This has two benefits. First, individuals project their individual concerns in their daily work and, second, individuals, such as shareholders and civilians, increasingly call for circularity.

Notwithstanding legitimacy on an abstract level, the legitimacy for specific solutions is not as univocal. Interviewees mentioned the considerable debate on the solution directions and the roles that specific pathways can play, for example, bio-based materials and design-for-reuse. Some seemed concerned about the suitability of regulation for circular practices. Others argued that existing legislation offers plenty of space for circular practices and solutions when making use of the "grey area", despite restricting boundaries – particularly regarding ownership.

Most interviewees did not experience any organized anti-circularity lobby, probably because most subsectors see a potential business case in circularity. Nevertheless, a strong lobby can be expected, particularly from the bulk material subsectors. As one consultant stated, "Everyone in the fossil sectors understands by now that this won't continue forever. […] But despite [recent developments], we don't have the sustainable alternatives yet – which they currently exploit." Contrarily, sectors who see an opportunity in circularity principles, such as the wood sector, are actively coupling lobbying activities to the circularity mission.

Analysis of the barriers towards a circular infrastructure industry

By linking the insufficiencies in the functions to specific structural or activity-based causes as discussed in the previous section, three cycles that amount to systemic barriers facing the Dutch infrastructure sector have been identified and visualized in Figure 2. These three major cycles were labelled as: (1) the CE contestation cycle, in which the meaning of circularity is at the centre; (2) the knowledge diffusion cycle, in which the diffusion and adoption of CE-supporting knowledge has a central place; and (3) the innovation cycle, in which innovation, market creation and market initiative are central. The three cycles are explained in detail below.

The first, CE contestation, cycle centres on the observation that both the problem and the solution spaces of CE in infrastructure are contested. That is, there is a divergent understanding of the problem–solution interaction of CE within the Dutch infrastructure sector. This increases the complexity of searching for and developing circular solutions because, particularly in the client–contractor relationships, there is a lack of alignment in understandings of which solutions are the most circular. This contestation of CE, reinforced by the long lead-times and lifespans of infrastructure, leads to difficulties in reflexive monitoring as it is unclear how the benefits of certain activities or solutions can be allocated to the overall CE progress. A lack of clarity as to progress adds to the complexity of governing the CE mission. Given the politicized environment in which infrastructure is positioned within the public sector, a lack of clear contributions from circular solutions to the long-term goals also hampers the long-term funding of the CE mission, particularly for measures where the CE benefits are not directly visible (e.g. on asset prevention or lifespan extension). This results in the slow implementation of CE within organizational processes which, in turn, contributes to a fragmentation of circular initiatives and hence a divergent understanding of CE.

The contestation of the CE concept and resulting low priority given to it also has consequences for the second, knowledge diffusion, cycle. Since there is only very limited straightforward and explicit CE knowledge available to the parties, who also have only a limited capacity to execute projects, it is challenging to apply knowledge in practice. This makes it difficult to implement circular knowledge in organizations. First, a slow implementation of knowledge in organizations leads to a failure to allocate capacity to act in accordance with CE principles. This is reinforced by the low priority given to the CE compared to other themes, such as risk mitigation and traffic continuity, that largely stems from the lack of structural funding. As a result, circular solutions often remain in the pilot project

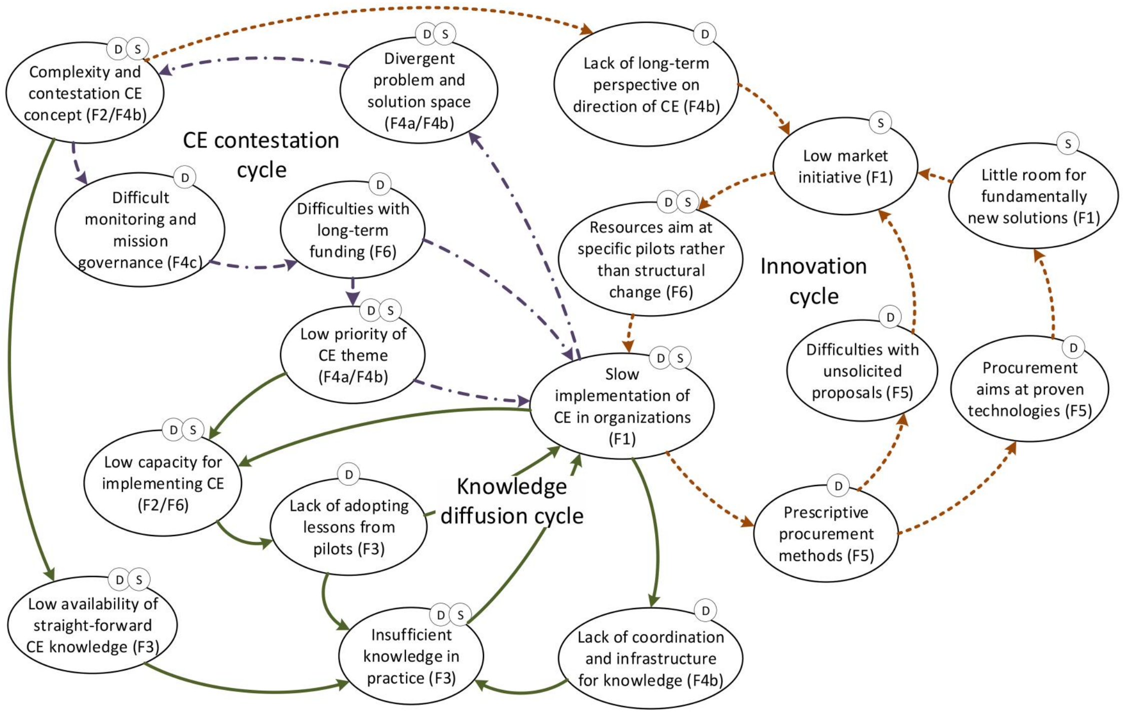

Figure 2. Three causal cycles forming barriers to the transition towards a Dutch circular infrastructure sector. Activities related to the demand side (e.g. clients) are indicated with a "D" and to the supply side (e.g. contractors) with an "S".

stage, with only little attention given to wider applications within more conventional project settings. Second, the very limited implementation of circular knowledge results in a lack of a knowledge infrastructure for circular practices. This leads to the poor availability of knowledge for non-experts which, in turn, results in a slow implementation in organizations.

The third, innovation, cycle predominantly results in a lack of novel circular alternatives. Conventional tenders can be characterized by their use of rather prescriptive procurement methods. This can partly be explained by the strict procurement laws and has the effect that it discourages the introduction of unsolicited and novel proposals by market parties. Further, and sustained by the sector's risk-averse culture, tenders are often aimed at acquiring proven solutions, which leaves little room for novel circular alternatives. This is a particularly important issue for material innovations, which are considered key in the wider transition towards a CE. Together with the lack of a long-term direction for circularity in terms of solutions and goals, due to the contestation of CE, as well as the tight profit margins in the sector, this results in limited initiation and uptake of circular market-led innovations. As a result, clients focus on stimulating market solutions through pilot projects, with little emphasis on implementing more fundamental organizational changes. In turn, this maintains the prescriptive nature of the process of infrastructure procurement by client organizations.

To sum up, three main sets of interrelated cyclic barriers, have been identified that impede the transition towards a circular infrastructure sector in the Netherlands. An issue that affects all three cycles is the contestation of the meaning and operationalization of circularity. Overcoming the self-reinforcing nature of these cycles requires interventions on the systemic level.

Discussion

CE dynamics and barriers in the Dutch infrastructure sector

We have identified three major cycles that hamper the transition to a circular construction industry in the Netherlands: (1) the CE contestation cycle, reflecting the contestation of the circularity mission; (2) the knowledge diffusion cycle, covering the difficulties in knowledge diffusion and adoption in projects and organizations; and (3) the innovation cycle, which addresses difficulties in creating a market for circular innovation. These findings suggest that a greater focus on organizational and institutional aspects is required to facilitate the multidimensional conditions needed for the development, diffusion and adoption of circular solutions. This contrasts with the rather technological focus in current research into achieving circularity in construction and infrastructure (e.g. Munaro *et al.* 2020 and Charef and Lu 2021). Moreover, the systemic nature of the findings points towards deeper causes of unsustainability than the stand-alone solutions or replacements that have been studied in relation to circular practices within public-sector organizations (e.g. Klein *et al.* 2022), especially when pursuing solutions that fundamentally prevent and reduce the use of resources in infrastructure.

Nevertheless, the current focus on experimenting and exploring the subject are consistent with what one might expect – and even encourage – at this current, early stage of the transition (Rotmans and Loorbach 2009). This is likely to also be the case in other European infrastructure industries, given that they all are regarded to be in an early stage of transitioning to a circular economy (Giorgi *et al.* 2022).

Furthermore, several of our findings stand out when considering CE as a mission. The transition towards a circular infrastructure sector is governed in multiple spaces, each with their own specific goals despite being concerned with the same overarching mission, while the formal CE strategy is scattered among several ministries. This increases the complexity and requires other coordination mechanisms to converge the problems and solutions beyond actors being either in or out of a single arena. This point is strengthened by the findings of Çimen (2021), who identified an overall failure to develop CE research that acknowledges the stakeholder complexities in circular practices in the construction industry.

Moreover, we identified a remarkably small number of activities or developments that were aimed at actually removing non-circular system structures or practices, something which is again reflected in other research (e.g. Benachio *et al.* 2020, Mhatre *et al.* 2021). As a consequence, circular solutions seem to have to fit within or be added to the current non-circular system, rather than aiming to replace or restructure the current structure or dynamics of the infrastructure sector fundamentally. However, for a system transformation to take place, circularity must be embedded in the system itself which, by definition, calls for the withdrawal of non-circular practices. This calls for substantially other governance approaches (Stegmaier *et al.* 2014). The large number of recycling and circular design initiatives compared to the limited number of, and difficulties associated with, more impactful systemic resource reduction strategies illustrate this finding (Joensuu *et al.* 2020). The highly institutionalized regime actors that benefit from maintaining the status quo contributes to this (Leiringer *et al.* 2022). Hence, the overall phasing out of hindering practices that is essential for achieving the mission goals is largely lacking.

Managerial and policy implications

Here, we note a few implications of our work that may be relevant to other European infrastructure sectors and beyond. First, our results indicate a highly contested understanding of CE throughout the sector. Highly strategic policy changes at the ministerial level could address the difficulties around the contestation of the CE concept. This connects to a lack of directionality by governments, both as policymakers and as clients, who do little to incentivize market parties to invest and innovate for circularity. Further, central public organizations, such as ministries and their executive agencies, are in a position to organize and coordinate the diffusion and management of knowledge that is necessary to implement circular measures. Since the mission, as a core object, comes with different change and innovation dynamics such as the plurality of potential technological solutions and inherent normative notions, both reflexive governance and coordinated participatory action become ever more important (Ferraro *et al.* 2015).

Moreover, procurement is considered a powerful instrument for clients to further CE developments, not only because clients can act as leading customers, but also because they can, particularly in a pre-contractual stage, direct and organize demand in line with mission-driven procurement strategies (Schotanus 2022). However, procurement power should not be overestimated with respect to the CE transition; the more ambitious circular strategies (e.g. lifespan extension and reduced demand for new assets) can only be realized in a pre-procurement stage, such as in long-term planning and budget allocation, and post-construction phases as applied in asset management and asset removal activities. The focus should therefore be, beyond building more-circular novel assets, on asset management.

In this regard, public client organizations are crucial in organizing processes for circularity in the infrastructure sector, particularly regarding the more fundamental circular solutions, such as reducing the demand for resources and extending lifespans. Vicious cycles can be broken by translating the mission-driven CE strategies into organizational processes that have circular choices as default outcomes. This approach can be initiated from the domains of asset management and knowledge management, yet should also be integrated in data management and portfolio management.

Conclusions

Our MIS-based analysis of the transition towards a circular Dutch infrastructure sector has revealed several causal chains of dynamics related to activities, practices and structures of the sector. In line with findings from previous transition research (e.g. Wesseling and Van der Vooren 2017), many of these causalities appear to be the result of lock-in mechanisms that are difficult to breach. These consist of self-reinforcing cycles related to the configuration of the socio-technical system, which only come to the surface when taking a systemic perspective on the transition. Since these causalities are multidimensional and embedded in the wider system, solving single issues or introducing single innovations or fixes will not suffice.

Studies on the socio-technical system level offer insights into barriers that are conditional on other barriers (Suurs 2009). These insights can contribute to structuring and prioritizing domains of interest for construction management research. In our case, for example, the multiple systemic barriers seemed to relate, at least partly, to the equivocal interpretations of circularity. This has had a large effect on the overall transition towards a circular infrastructure sector in the Netherlands and hence highlights a critical point on which to focus research, policy and management efforts. Only systemic analyses can identify such deep-seated barriers to change.

The findings from our case study enable us to reflect broadly on several levels on the functioning of the infrastructure sector when facing the need to undergo a CE transition, and how one might develop approaches to disrupt the vicious cycles. Given the system interdependencies, one should consider the functioning of the system on the level of the cycles in addressing such barriers. In this respect, construction management research could make significant contributions by considering institutional and organizational aspects in context-specific construction and infrastructure settings.

Future research

This study has several limitations that create opportunities for future research. First, the study focused on a Dutch case, and it is recognized that transitions are highly context dependent. For example, there are several characteristics of the Dutch infrastructure sector, such as the "polder model" in decision-making, that might result in specific transition dynamics that have wider or more limited applications that future studies could identify. Furthermore, the analyses of the structure, dynamics and barriers have been based on policy documents and interviews with practitioners from this particular context who provided their personal argumentations based on individual perceptions of cause and effect. A study based on other data sources on CE-related events, projects and initiatives might reveal deeper insights into the solutions and solution spaces that exist in practice to step beyond the perception of individuals. Apart from new potential findings, this would increase the validity of the findings and the generalizability of the recommendations made.

Second, the *system* we studied is inherently complex. By identifying key causalities, our aim was to simplify this complexity to several key factors and relationships in three major cycles. These simplifications lead naturally to limitations with respect to revealing and explaining causality. Additional research could apply practice research, institutional theory or organizational sciences to find and explain mechanisms behind the causalities in detail and could reveal deeper mechanisms that explain these complexities. This might also lead to more detailed insights into the potential ways of strengthening positive causalities and breaching negative ones, by, e.g., policy interventions. However, rigid government interventions do run the risk of having only a minor or even an adverse effect on the transition in the traditionally highly institutionalized construction context (Leiringer *et al.* 2022).

Finally, the application of the analytical framework used (MIS) has its challenges, because it offers a snapshot of the system barriers at a moment in time, while the transition is an ongoing process. This makes it difficult to determine whether the barriers are present at only a specific point in time and to establish the extent to which they are persistent. Although well-grounded in the empirically well-established TIS functions, the novel MIS functions are not yet thoroughly validated in empirical cases. Doing similar research using other research frameworks, such as the multi-level perspective (MLP; Geels 2004), is needed to increase validity of the findings, possibly revealing new insights on systemic barriers and causalities of mission-driven changes and innovations.

Recommendations for policy and practice

Given the conclusions that highlight three vicious cycles, our work also leads to recommendations for policy and practice. Norms and regulations, both technical and processual, were in our results generally perceived as barriers to change, even when regulations are not legally confining the space for circular practices. Governments could address this by not only ensuring that norms and legislation enable circularity, but rather by ensuring that circular decisions are an integral part of these practices.

Convergence on the societal challenges that the circular solutions aim to address could be stimulated by making the problems and solutions more explicit, both in policy documents as well as in the stated goals and ambitions by clients. This would increase the directionality of governance. Another way to address the lack of univocality and directionality is to strengthen the coordination between CE networking activities to avoid multiple CE operationalizations. Here, ministries and other central government bodies should take a leading role, because of their ability to regulate and allocate resources and their commitment to the CE mission. A shift from the current focus on circular design towards more integral CE solutions is required, decreasing the demand for resources and increasing the lifespans of existing assets. Nevertheless, in situations where both the problem and the solution spaces are divergent, which is the case in Dutch circular infrastructure, it is important to explicitly guide the convergence reflexively from a policy perspective and, above all, take on a learning-by-doing mentality rather than following prescribed policy pathways (Wanzenböck *et al.* 2020).

Furthermore, there is a lack of resources and infrastructure to develop, diffuse, adopt and implement knowledge. Organizational processes aimed at infrastructure for knowledge management regarding circular developments should be established, particularly in and between client organizations. This would not only require putting the knowledge exchange processes in place, but also ensuring the capacity to apply knowledge in conventional project settings, particularly knowledge from pilot projects and exemplary ambitious projects that are characteristic for the sector. Another underlying cause for the problematic knowledge adoption is the lack of incentives, particularly for market parties, to share CE knowledge. Cross-project collaboration, such as programmes and strategic partnerships, which can be launched by public clients, would provide incentives to invest in circular solutions and reduce the competitive advantage of withholding CE knowledge (Håkansson and Ingemansson 2013). In turn, this would increase the propensity for cross-project applications of circular solutions.

The solutions proposed above, particularly the alignment of understandings of a circular future within the sector and developing a long-term perspective, would enable significant market investments. Currently, markets are not incentivized towards CE although assessment methods to include CE in procurement are rapidly improving. Circular innovations are often so radically different that they do not meet the current assessment and procurement criteria. This requires public clients to be more open to solutions that have a low technological readiness level (TRL; Lenderink *et al.* 2022). Here, first, clients should provide space in the procurement criteria for more radical innovations and, second, risk should be distributed more fairly between market parties and clients, especially since the benefits of the circular solutions often only become apparent over the long term. Hopefully this will lead to a situation in which market parties prioritize adopting circular solutions without specific calls from the client since only doing the bare minimum would lead them becoming side-lined in future projects.

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Appendix A. List of grey literature used

No.	Source document
Policy documents	
1	Transitieteam Bouw, 2018. Transitie-agenda circulaire bouweconomie. [Transition agenda circular construction economy.]
2	Provincie Overijssel, 2020. Samen krijgen we de Twentse cirkel rond! [Together we close the Twentse loop!]
3	Transitieteam Bouw, 2018. Naar een circulaire bouweconomie: Uitvoeringsprogramma 2019. [To a circular construction economy: implementation program 2019.]
4	Transitieteam Bouw, 2019. Naar een circulaire bouweconomie: Uitvoeringsprogramma 2020. [To a circular construction economy: implementation program 2020.]
5	Ministerie van IenW, 2020. Bijlagen I, II, II bij het Uitvoeringsprogramma Circulaire Economie 2020-2023. [Appendices I, II, III to the Implementation programme Circular Economy 2020-2023.]
6	Rijkswaterstaat, 2020. Jaarrapportage 2019: Impulsprogramma Circulaire Economie. [Annual report 2019: Impulsprogramma Circular Economy].
7	Ministerie van IenW, 2020. Strategie "Naar klimaatneutrale en circulaire rijksinfraprojecten". [Strategy "to climate-neutral and circular national infrastructure projects".]
8	Ministerie van IenW, 2015. Beleidsverkenning Circulaire economie in de Bouw. [Circular economy in the Dutch construction sector.]
Industry and sector documents	
9	CB'23, 2021. About platform CB'23. Retrieved from: http://www.platformcb23.nl/english (September 2021).
10	Cirkelstad, 2021. Green paper – nieuwe spelregels in de bouw: Circulair bouwen na Corona [Green paper – New construction rules: Circular construction after Corona].
Cross-sectoral publications	
11	Circle Economy, 2020. The circularity gap report: The Netherlands
12	Rijksoverheid, 2016. Nederland circulair in 2050. [The Netherlands circular in 2050.]
Agreements	
13	Grondstoffenakkoord, 2017. Intentieovereenkomst om te komen tot transitieagenda's voor de Circulaire Economie. [Letter of intent to develop transition agendas for the Circular Economy.]

Appendix B. List of interviewees

No.	Interviewee Type
Public client organizations (governmental organization)	
1	Programme manager infrastructure at Dutch province[b]
2	Programme manager infrastructure agency
3	Programme manager infrastructure agency[b]
4	Policy coordinator water board association[a]
Ministries (civil servants)	
5	Coordinator Ministry of Interior and Kingdom Relations[a,b]
6	Policy officer Ministry of Infrastructure and Water Management[a,b]
7	Coordinator Ministry of Infrastructure and Water Management[a]

(*continued*)

Continued.

No.	Interviewee Type
Industry (industry organization)	
8	Consultant sustainable and circular construction[b]
9	Consultant sustainable and circular construction[b]
10	Consultant sustainable and circular construction[b]
11	Sustainability coordinator contractor organization
12	Project coordinator contractor organization
13	Consultant sustainable and circular construction[a,b]
Knowledge institutions	
14	Asphalt expert independent research organization
15	Circular infrastructure scholar[b]
Network organizations, platforms, and associations (network organization)	
16	Director circularity network organization[a,b]
17	Sustainability manager industry association[a,b]
Financial, legal, and process experts (experts)	
18	Economic expert sustainable construction
19	Legal expert sustainable construction
20	Standardization expert[a]

[a]Is/was affiliated with the Transition Team mission arena. [b]Is/was affiliated with the CB'23 mission arena.