FROM CIRCULAR TO SUSTAINABLE

THE IMPLEMENTATION OF CIRCULAR ECONOMY IN TRANSPORT INFRASTRUCTURE PROJECTS IN CHINA AND THE NETHERLANDS

LIU Xinyu

FROM CIRCULAR TO SUSTAINABLE: THE IMPLEMENTATION OF CIRCULAR ECONOMY IN TRANSPORT INFRASTRUCTURE PROJECTS IN CHINA AND THE NETHERLANDS

DISSERTATION

for the purpose of obtaining

the degree of doctor at Delft University of Technology

by the authority of the Rector Magnificus,

prof.dr.ir. T.H.J.J. van der Hagen,

chair of the Board for Doctorates

to be publicly defended

on Wednesday October 15, 2025 at 12:30

by

Xinyu LIU

Born in Liaoning, China

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus	Chairperson
Prof. dr.ir. M.J.C.M. Hertogh	Delft University of Technology, promotor
Prof. dr. W.M. de Jong	Erasmus University Rotterdam, promotor
Dr. D.F.J. Schraven	Delft University of Technology, copromotor

Independent members:

Prof.dr. T. Hoppe	University of Twente
Prof.dr. P.W.C. Chan	Delft University of Technology
Dr. K. Qian	Delft University of Technology
Dr. M. Pang	Chongqing University, China

Reserve member:

Prof. dr. H.L.M. Bakker	Delft University of Technology

The author acknowledge funding offered by the China Scholarship Council (No. 201606040174).

Cover Photos: Canva.com

Cover design: WU, Jiarong (Maastricht University; Bielefeld University)

Bookmark Photos: the ("circular") transport infrastructures at Miniatur Wunderland Hamburg, Germany, taken during the *EurOMA*[1] *Sustainable Operations and Supply Chain Forum* (Hamburg, Germany, Mar. 2024)

Printed by ProefschriftMaken

ISBN 978-94-6384-844-2

[1] European Operations Management Association

Table of Contents

List of Tables

List of Figures

Summary

Implementing Circular Economy (CE) principles is often considered as a key contributor to greater sustainability in the construction sector. This idea presents a promising avenue for addressing the environmental crisis. However, there are several issues to be dealt with: 1) in addition to suffering from considerable wastes, progress towards sustainability is particularly slow in the sector; 2) the scalable implementation of CE is inherently difficult to achieve; 3) there is most attention about sustainability focuses on buildings, rather than on infrastructures. As a major kind of infrastructure, there is an urgent need for transport infrastructures to be circular and sustainable.

This dissertation addresses the abovementioned issues by answering the Central Research Question (CRQ) of this research:

"How to implement CE in transport infrastructure projects, with the aim to achieve sustainability?"

Since without circular and sustainable projects, the whole sector cannot be circular and sustainable. The thesis primarily focuses on China and the Netherlands, as they are leading CE countries but pursue CE in different ways, which makes a valuable comparison.

The circular transition in the construction sector involves a whole-systems perspective, from construction or building materials (material level) up to assets in their functional forms (asset level). Both groups receive increasing attention in pursuing CE and sustainability. However, little is known about the material-asset relationship connecting the ability of circular strategies to realize sustainability. Chapter 2 of this thesis addresses this gap through a bibliometric analysis and qualitative deliberation into this relationship. The bibliometric analysis is performed on a sizeable relevant body of literature (3974 articles from Scopus), thereby supporting a bigger picture of the academic landscape. In addition to the bibliometric analysis, a deeper review after scrutinizing the meanings of key terms is also done to zoom in. In so doing, insights are derived on the overall academic use of circular strategies (R strategies) to pursue sustainability in the context of construction materials and assets. The review results identified 33 construction materials and 12 specific assets as associated objects in the reviewed literature. On R strategies, Reduce, Reuse, and Recycle are the three most prominent; and high-order strategies like Rethink, Refuse, and Remanufacture tend to be overlooked. Regarding sustainability dimensions, the term Environmental is the most studied dimension, and Social the least. Chapter 2 fills the gap by taking the initiative to study the relationship between CE strategies and sustainability in the context of assets and construction materials. During the process, the asset and construction material lists proposed can be a reference for other scholars in the future. The results of Chapter 2 show that larger-scale bibliometric analysis and deeper literature review may need to be used collectively, as different patterns in literature can be seen with the two approaches.

After studying relevant literature with Chapter 2, in Chapter 3 we investigated the real case in a CE-representative city, Jingmen in China. It turned out that implementing CE in transport infrastructure projects was quite revolutionary for the practitioners there. Therefore, taking a step back, we studied how professionals involved in a real high-speed railway station project in Jingmen envision the use of sustainability and CE for the planning and construction of the railway station per se and its surrounding areas. We reviewed policy documents and

interviewed 20 local professionals using the Triple Bottom Line (TBL) framework. The analysis reveals opportunities for improvement towards sustainability and the interdependence between the dimensions in the TBL framework for the railway station and its surroundings. The case shows that local professionals identify ample opportunities for improvement (presented as "sustainability ideas"), but none appear truly sustainable (connected to environmental, economic and social sustainability simultaneously). These insights provide evidence that the hierarchical introduction of transition(s) creates a cognitive silo for local professionals when envisioning sustainability ideas. In the TBL framework, Chapter 3 finds a useful and novel approach to break down the silos, because the TBL stresses the interdependence between the various sustainability dimensions.

After exploring the problem, the solutions are approached. In Chapter 4, we used the Sectoral Innovation Systems (SIS) approach to assess CE in the infrastructure construction sector in both China and the Netherlands to discern how key functions of SIS are related to challenges to CE introduction on the one hand, and solution directions on the other. A survey was conducted among 50 different stakeholders in China and the Netherlands (23 and 27 respectively). In addition, relevant text documents (e.g., policy documents, industry reports, etc.) were analyzed. Observed problems pertain to underdeveloped technologies (i.e., bio-materials, biological processes, and digital technology), a lack of knowledge and interacting platforms, as well as a poor match with existing laws and regulations. Compared to the Netherlands, innovation at a lower level can be encouraged in China. For the Dutch case, the main problems observed were: underdeveloped technologies, a lack of knowledge, and the absence of a CE law. Chapter 4 ends with suggestions for CE introduction in both the Chinese and Dutch infrastructure construction sectors as well as corresponding directions for future research.

Finally, departing from the sector perspective, Chapter 5 drills down to the project perspective, aiming to guide the implementation of CE in transport infrastructure projects. To achieve this goal, literature review and case study were adopted as the research methods. After reviewing existing well-established CE frameworks, the iReSOLVE (implement, Regenerate, Share, Optimize, Loop, Virtualize, Exchange) framework is recognized as the most comprehensive one. Upon it, an analytical/implementation framework containing specific-related aspects of CE in urban transport infrastructure projects (which belong to meso-scale) is proposed (coined as the 4Wh-iReSOLVE framework). The 4Wh means Who, When, Where, and What. The proposed framework offers insight into potential CE activities for transport infrastructure projects and assists in assessing the performance as well as impacts of CE of these projects, to cover the gap of the neglected meso-scale[2]. Ten circular viaduct project initiatives in the Netherlands are used as cases for analysis with the 4Wh-iReSOLVE framework. The results present the highlights of the circular viaduct initiatives in the Netherlands, with CE activities categorized into five groups (Design-related strategies, General CE strategies, Implementation, management and related digital technologies, Materials, as well as Environmental sustainability). As verified by several experts of the projects studied, it can be concluded that the 4Wh-iReSOLVE framework is suitable for transport infrastructure project CE analyses and implementations. It can potentially be a suggested guideline in future policy

[2] According to the Cambridge dictionary, scale means the size or level of something (in this thesis).

documents.

The following figure presents the different scales and levels Chapters 2-5 cover and the relationship among them:

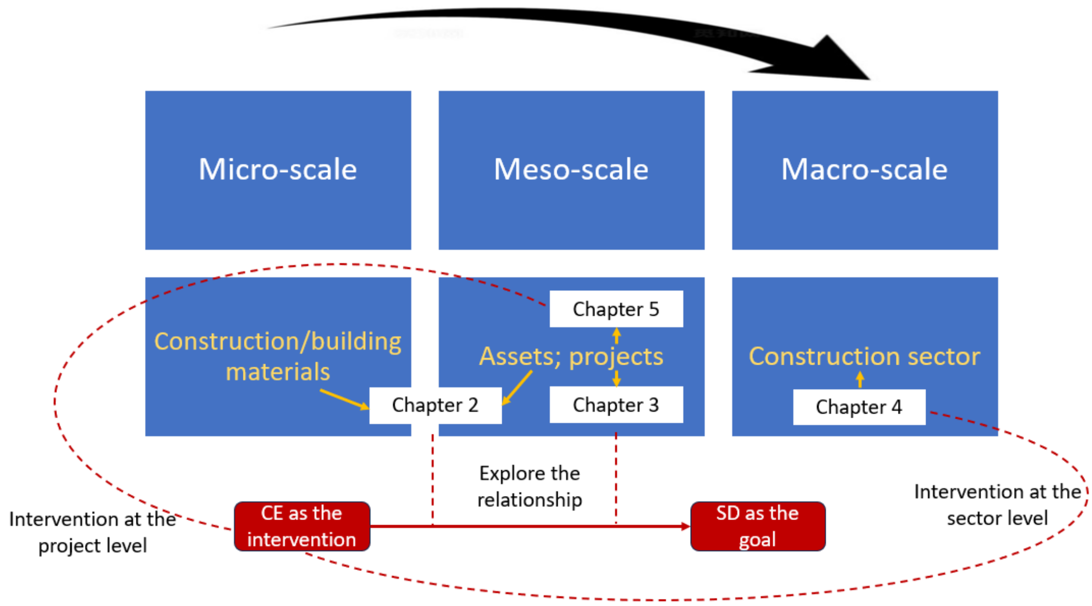


Figure (1.2) The different levels and scales covered in this research

In terms of scientific contribution, this research integrates micro-, meso-, and macro-scales with respect to CE for transport infrastructures, during which the ambiguity of the three scales brought by different articles (e.g., (Pomponi and Moncaster, 2017), (Kirchherr et al., 2017), (Heshmati, 2015), (Su et al., 2013)) has also been clarified. In addition, ways forward for better CE implementation have been proposed both at the sector level (macro-scale) and the project level (meso-scale).

As for practical relevance, this study provides knowledge for different stakeholders of the infrastructure construction sector to better implement CE by studying both the Netherlands and China. Different from earlier research (e.g., (Adriaanse et al., 2010)), a list of first and secondary stakeholder roles of the sector is also proposed for future use. In our case, with the stakeholder roles list, different sets of questions were assigned to the two general groups to help acquire data of good quality.

In Chapter 4, this dissertation presents further directions for both China and the Netherlands to implement CE in the infrastructure construction sector better, which can also be referred to by other countries. In Chapter 5, the CE application framework can be used by different stakeholders of transport infrastructure projects to analyze and implement CE.

As for future research, in Chapter 3, only one case in China was conducted due to the time limitation. Since Chapter 4 is about the comparison of China and the Netherlands, a counterpart case study in the Netherlands can be a better add-on. Besides, in Chapter 4, only Jiangsu Province was chosen as a representative area of China, partly because China is much larger than the Netherlands. In the future, a broader coverage of China is suggested to help have a better understanding of the CE situation in the infrastructure construction sector in

China. Besides, a larger coverage of different stakeholders in both countries with a large number of easier simple-click questions in the online survey would reflect China and the Netherlands better. In Chapter 5, the framework was only applied to existing project documents, and the project type is just viaduct. In the future, it can be applied to different types of projects during the planning phase, and the situation of such projects can be studied later to have better ideas about the application of the 4Wh-iRESOLVE framework.

1. Introduction

1.1 The Necessity to be Circular and Sustainable for Transport Infrastructure Projects

Academia and practice have recognized the Circular Economy (CE) as a key approach in sustainable urban development (Joensuu et al., 2020). The intensive construction of built environment and infrastructure projects has considerable environmental, economic, as well as social impacts and affects the achievement of Sustainable Development (SD) (Morrissey et al., 2012; Shen et al., 2011). Different regions therein grapple with challenges for effective deployment of material usage. For example, China is experiencing large-scale construction of buildings and infrastructures, resulting in a shortage of domestic supplies of resources and severe environmental impacts (Huang et al., 2013). In Europe, the construction and usage of buildings contributes to more than 40% of the total energy consumption and greenhouse gas (GHG) emissions (Lechtenböhmer & Schüring, 2011; Maduta et al., 2023). Globally, the construction sector accounts for more than 35% of global energy consumption, nearly 40% of all energy-related CO_2 emissions, and almost 45% of global resource consumption (Dahy, 2019). Therefore, it is no surprise that CE and sustainability in the built environment have received increased attention from scholars and practitioners.

As global urbanization is still pacing up, more and more urban construction works are needed. Increasing demand on infrastructures in terms of energy consumption, raw material demand, and GHG emissions poses a serious threat to sustainability (Molina-Moreno et al., 2017). Projections highlight that a growing population with rising average wealth could push global material extraction up to 183 billion tonnes per year by 2050[3] (in 2024, it is 106.6 billion metric tons (Schandl et al., 2024)). Europe sends over 50% of its waste straight to landfill and incinerators, which generate toxic and climate-damaging emissions, destroying valuable resources and resulting in an enormous missed opportunity for job creation[4]. This warrants a shift away from the traditional "linear" material-related practices, which are based on a "take-make-dispose" mode of dealing with materials. This shift has already been initiated in the European Commission (EC), by verdict of the "Roadmap to a Resource Efficient Europe" (2011) and the later commitment of "The Action Plan towards the Circular Economy" (2015) (Domenech and Bahn-Walkowiak, 2017), as well as the Europe 2020 initiative[5].

At the same time, besides suffering from low productivity and considerable waste, progress towards sustainability is particularly slow in the construction sector, not only as a

[3] https://www.adelphi.de/en/publication/moving-towards-circular-economy-emas (accessed on Sept 24th, 2022)

[4] http://www.seas-at-risk.org/images/pdf/High_res_NGOstatement.pdf (accessed on Sept 21st, 2018)

[5] https://ec.europa.eu/eu2020/pdf/COMPLET%20EN%20BARROSO%20%20%20007%20-%20Europe%202020%20-%20EN%20version.pdf (accessed on Feb 17th, 2025)

whole but also in project-level initiatives (Faber & Hoppe, 2013; Hubbard & Hubbard, 2019; Vermeulen & Hovens, 2006). One reason lies in the character of the sector: it is closed, fragmented, conservative, risk-averse, and has a large number of diverse stakeholders and the complex nature of the projects (Van Bueren, 2009; Chen et al., 2022). In general, fragmentation in the construction industry arises from two areas within the traditional construction process, i.e., the construction work process where the most significant division is in the separation of the design and construction phase, and the construction structure itself (Mohd Nawi et al., 2014). Being very conservative and risk-averse, traditionally the construction sector is reluctant to adopt new technologies and ideas (Craveiro et al., 2012). As for diverse stakeholders, there are, for example, clients, contractors, subcontractors, investors, suppliers, designers, users, to name a few. In addition, constructions are highly heterogeneous environments, with critical information and coordination needs (Adriaanse et al., 2010).

Besides, most attention about sustainability focuses on buildings rather than on infrastructures, with high-profile BREEAM (Building Research Establishment Environmental Assessment Method) and LEED (Leadership in Energy and Environmental Design) projects taking the center stage (Hubbard and Hubbard, 2019). This different extent of academic attention can be embodied by the number of academic articles acquired by search queries applied to Scopus[6].

Infrastructures cover a wide spectrum, including power supplies, water supply, sewers, telecommunications, to name a few. As a major kind of infrastructure, transport infrastructures need to be sustainable and circular as well. An example of a few is that O'Leary et al. (2024) investigated the importance of CE implementation strategies, barriers and enablers for UK rail infrastructure projects. Considering that more academic attention is needed, this thesis focuses on transport infrastructures.

1.2 The Closeness between Sustainability and Circular Economy (CE)

Compared with the long history of the Earth, the time span of human activities is much shorter. However, since the Industrial Revolution, in many areas of the world, environmental conditions are gradually out of control (e.g., biodiversity loss, climate change, etc.). Therefore, SD or sustainability has become a widely accepted policy aim for the global community in recent decades. The Brundtland report defined Sustainable Development as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Sauvé et al., 2016, p. 51).

Along with degrading environmental conditions is the linear way the current economic process is organized, in which a lot of materials are wasted after consumption, together with the depletion of resources. To combat such unsustainable practices, the global production and consumption pattern should be "circular", which aligns with one of the Sustainable Development Goals (SDGs), SDG 12 Sustainable Consumption and Production (SCP). The CE

[6] With TITLE-ABS-KEY ("sustainab*" AND "buildings"), 101732 results were obtained; while with TITLE-ABS-KEY ("sustainab*" AND "infrastructure*"), 58911 results were obtained , let alone when "buildings" rather than "building" is used in the search.

system diagram, known as the butterfly diagram, illustrates the continuous flow of materials in a CE (Fig. 1.1, drawn by Ellen Macarthur Foundation (EMF))[7]. From a human-centric viewpoint, the left part of the butterfly diagram illustrates that the biological world is circular and sustainable, i.e., in the biological cycle, the nutrients from biodegradable materials are returned to the Earth to regenerate nature. Following the same philosophy, the right side of the butterfly diagram depicts the technical cycle, which is a closed-loop system, run through sharing, maintenance, reuse, remanufacturing, and recycling (Skene and Oarga-Mulec, 2024).

There are many different definitions of CE. After the analysis of 114 CE definitions, Kirchherr et al. (2017) presented the definition of CE as "A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro-, meso- and macro-levels, with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations" (pp. 224-225). From this definition, it can be discerned that sustainability and CE are closely connected. CE is an increasingly attractive approach to tackling current sustainability challenges (Klein et al., 2020); additionally, SD is frequently considered the principal aim of CE (Kirchherr et al., 2023). For example, Geissdoerfer et al. (2018)'s research indicated that circular businesses and circular supply chains help in realizing sustainability ambitions. Being adopted as an SD strategy (for reducing waste and enhancing resource efficiency) and seen as an effective way towards SD, CE has been identified as a sustainable alternative to the current linear economic model and started to penetrate from both macro and micro scales to the intermediate meso-scale, such as eco-industrial parks (Belaud et al., 2019; Liu and Côté, 2017; Martín Gómez et al., 2018; Ogunmakinde, 2019; Ranta et al., 2018; Tumilar et al., 2021; Zeng et al., 2017; Zhao et al., 2018, 2017). In line with the CE definition adopted earlier, the meso-scale is the scale in which the urban infrastructure construction works fall.

[7] https://ellenmacarthurfoundation.org/circular-economy-diagram (accessed on Jan 16th, 2023)

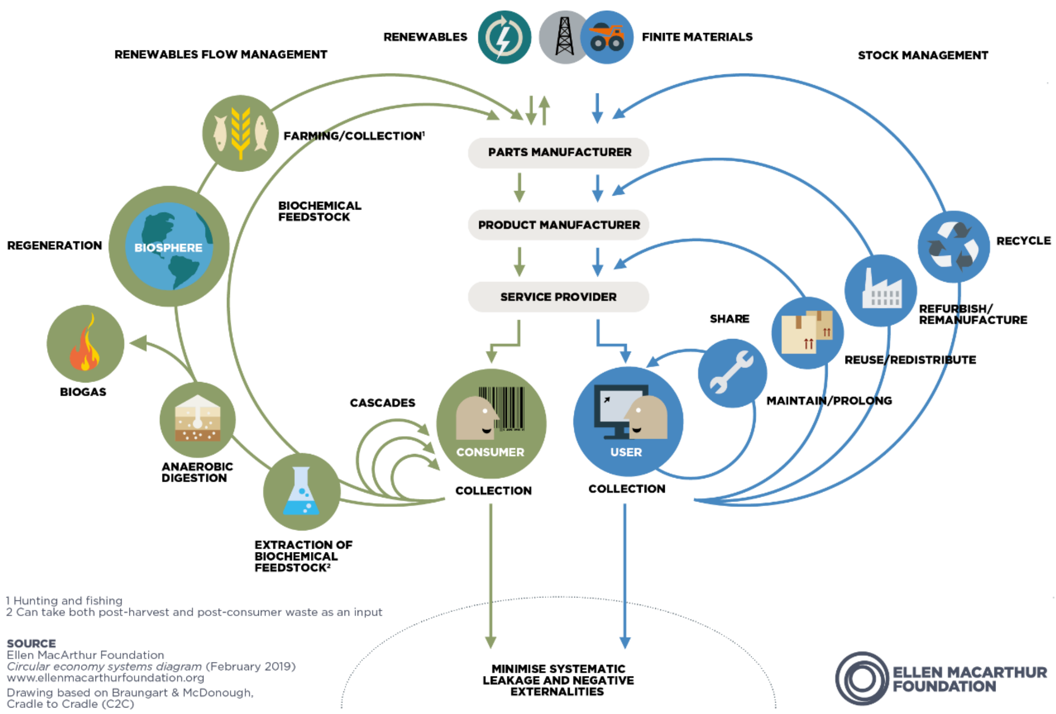


Figure 1.1 The butterfly diagram (Ellen Macarthur Foundation (EMF))

1.3 Problem Statement

The former section describes CE as an intervention to achieve sustainability (the ultimate goal). The CE has been employed in the manufacturing, agricultural, textile, and steel industries, but its implementation varies (Ogunmakinde, 2019). Furthermore, the scalable implementation (implementation in different scales, especially scale-up) of CE is inherently difficult to achieve, and it is well-recognized that CE transition is a multi-dimensional challenge involving environmental, economic, technological, societal, governmental, and behavioral factors (Pomponi and Moncaster, 2017; Yu et al., 2022). Kumar & Chopra (2022) also classified the implementation challenges under five barrier categories: Technological, Financial, Infrastructural, Institutional, and Societal. For the construction sector, the areas of major challenges are generally summarized as: design & construction strategies, supply chain management, policy strategies for CE adoption, End-of-Life (EoL) principles, Construction and Demolition Waste (CDW) management strategies, information exchanges & analytics for CE (Antwi-Afari et al., 2021). These challenges are closely related to the unique characteristics of the construction sector mentioned earlier. Yu et al. (2022) (p. 2) already explained clearly: first, the material consumption pattern in this industry provides neither convenience nor a fair starting point to tackle CE challenges; second, the fragmented structure of this industry has been blamed for its low efficiency for decades. As a sub-domain of the sector, the challenges are also the same for transport infrastructure projects, which create infrastructure assets as entities.

1.4 Research Questions

This dissertation addresses the abovementioned problem by answering the Central

Research Question (CRQ) of this research:

"How to implement CE in transport infrastructure projects, with the aim to achieve sustainability?"

Since without circular and sustainable projects implemented, the whole sector cannot be circular and sustainable. Thus this thesis focuses on the sector and projects. To answer this CRQ, four Sub Research Questions (SRQ) are presented:

SRQ1: What research studies contribute to achieving sustainability in the construction sector through circular activities at the interface between assets in the built environment and construction (building) materials?

SRQ2: How do local professionals envision sustainability ideas in pursuit of addressing multiple sustainability transitions in a (transport) infrastructure construction project?

SRQ3: Taking an SIS (Sectoral Innovation System(s)) perspective, what are the main barriers blocking the implementation of CE in the Chinese and Dutch infrastructure construction sector and the possible solutions to resolve these barriers?

SRQ4: What does a framework approach to learn and inspire CE for transport infrastructure projects look like?

SRQ1 is concerning the preliminary exploration of different scales between assets and materials through the literature study, aimed at problem finding; answering SRQ2 is about the exploration of the question further: how the implementation of CE and SD is addressed in a real-world case study, also aiming at problem finding; SRQ3 triggers the sector level exploration to find solutions; while answering SRQ 4 is the process of project level solution.

1.5 Research Design

This section describes the research design to help understand the reasoning behind the SRQs. Corresponding to the four SRQs, there are four steps covering micro-, meso- and-macro scales (Fig. 1.2 illustrates the different levels and scales covered in this research): the first two steps are explorative studies in the academic literature and an empirical case respectively, aimed at clarifying the implementation problem the construction sector is faced with; the following two steps deal with the implementation of CE principles at different levels of initiation (sector level and project level[8]), aiming to find solutions. With the scales and levels covered, this thesis offers a comprehensive lens to transport infrastructures.

[8] "scale" and "level" are synonyms, but the former is typically used with "micro", "meso" and "macro".

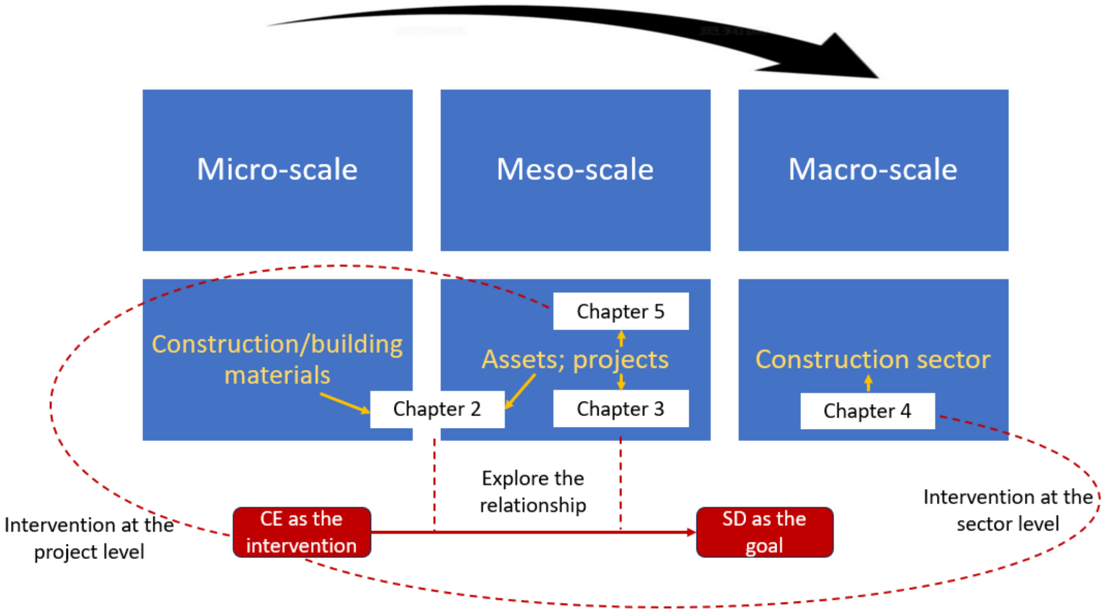


Figure 1.2 The different levels and scales covered in this research (own figure)

In more detail:

Step 1: Chapter 2 Tracing circular strategies in the construction literature: an analysis of their use for sustainability goals and on different materials/assets

Chapter 2 generates an understanding of relevant literature and focuses on two levels of assets (in terms of entities): the assets per se (i.e., infrastructures and buildings; meso-scale) and the construction/building materials (micro-scale) that form the assets. For the sector to be sustainable via CE, both levels are necessary. During this step, the asset list and construction/building material list were proposed for further bibliometric analysis and in-depth review. The two methods supplement each other, because the bibliometric analysis of a larger scale of literature can offer a bigger view of the general "climate" while the in-depth review zooms in on the most relevant literature to overcome the possible misleading "cloud" brought by the bibliometric analysis. With the two methods, the objective of Step 1 is to offer insights into the CE implementation problem of infrastructures from the literature.

Step 2: Chapter 3 Navigating Transitions for Sustainable Infrastructures—The Case of a New High-Speed Railway Station in Jingmen, China

After answering sub-question 1, the related literature is understood, then the next question is "What is happening in the practice of a real case?" Chapter 3 describes our explorative process about the CE situation in the real world, by a case study of a planned high-speed railway station (HSRS; meso-scale) in a CE demonstration city in China. In addition to being one of the CE demonstration cities in China, Jingmen was chosen as the case study area because it is a middle-sized city in China (in terms of population, economic status, and so on), and as such a representative of many other cities in China. Therefore, different from many other studies, the focus of Chapter 3 is not the famous cities of China (e.g., Beijing, Shanghai, Hong Kong, etc.). Initially, CE was the focus of the data acquisition of this step to understand the relationship between CE and sustainability, but after a few interviews with local HSRS stakeholders, it became clear that CE is still too revolutionary to be implemented, even in Jingmen. Nevertheless, this is understandable, considering the implementation problem about CE in transport infrastructure projects; therefore sustainability became a flexibly adjusted focus for this chapter to continue the research. It turned out that local practitioners had sustainability ideas in mind, so we wanted to check whether these were truly sustainable and whether some of them were actually reflection of CE. Semi-structured interviews were conducted with local HSRS stakeholders to see what they consider important for sustainability of the new station itself and the surrounding areas of the station respectively. Step 2 offers evidence of the problem by means of a real-world case study.

Step 3: Chapter 4 Introducing Circular Economy in the infrastructure construction sector: Comparing sectoral innovation systems in China and the Netherlands

Subsequently the question "Why is there such a problem and how to solve it?" appears on the table. Chapter 4 presents a study of the problem and potential ways to solve this problem from the sector perspective, with China and the Netherlands as the comparative focus areas. In addition to China, the Netherlands is a country in transition in terms of CE (in Europe). Because China and the Netherlands approach CE differently and there are also many differences in other aspects (e.g., political system, which may influence the implementation of CE), this combination offers a better understanding. As CE is a kind of innovation for the infrastructure construction sector (macro-scale), the Sector(al) Innovation Systems (SIS) approach was adopted for this step. Data were collected by online surveys from the infrastructure construction sector stakeholders in both countries. Since China is much larger in terms of area than its counterpart in this chapter, a representative province of China, Jiangsu was chosen to get data for the Chinese infrastructure construction sector. Step 3 provides potential directions for CE implementation at the sector level.

Step 4: Chapter 5 Towards an analytical framework of the CE in urban transport infrastructure projects: a meso-scale perspective

Chapter 5 deals with the question of how CE can be successfully implemented at the project level, with the help of a framework for inspiring CE activities. In this step, the analytical framework of CE (the 4Wh-iRESOLVE framework) in urban transport infrastructure projects was proposed based on a review of current well-developed CE frameworks (approaches, methods, etc.); subsequently the framework was applied to ten circular viaduct projects, to show the applicability of the framework. The results present the highlights of the circular viaduct initiatives in the Netherlands, with CE activities categorized into five groups (Design-related strategies, General CE strategies, implementation, management, and related digital technologies, Materials, as well as Environmental sustainability).

1.6 Research Outline

As shown above, Chapters 2-5 correspond with Steps 1-4, which are the main body of this thesis. Finally, the conclusion part is presented in Chapter 6. Fig. 1.3 shows the outline of this dissertation.

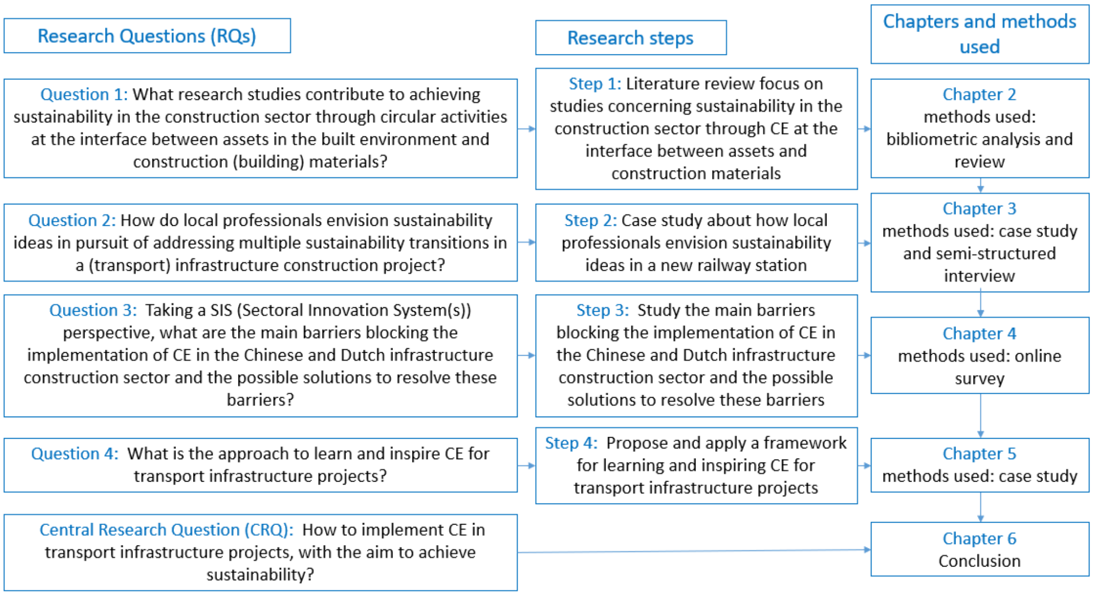


Figure 1.3 Research outline (own figure)

References for Chapter 1

Adriaanse, A., Voordijk, H., Dewulf, G., 2010. The use of interorganisational ICT in United States construction projects. Autom Constr 19, 73–83. https://doi.org/10.1016/j.autcon.2009.09.004

Antwi-Afari, P., Ng, S.T., Hossain, M.U., 2021. A review of the circularity gap in the construction industry through scientometric analysis. J Clean Prod 298, 126870. https://doi.org/10.1016/j.jclepro.2021.126870

Belaud, J.P., Adoue, C., Vialle, C., Chorro, A., Sablayrolles, C., 2019. A circular economy and industrial ecology toolbox for developing an eco-industrial park: perspectives from French policy. Clean Technol Environ Policy 21, 967–985. https://doi.org/10.1007/s10098-019-01677-1

Chen, Q., Feng, H., Garcia, B., Soto, D., 2022. Revamping construction supply chain processes with circular economy strategies: A systematic literature review. J Clean Prod 335, 130240. https://doi.org/10.1016/j.jclepro.2021.130240

Craveiro, F., Matos, J.M. de, Bártolo, H., Bártolo, P., 2012. An Innovation System for Building Manufacturing, in: ASME 2012 11th Biennial Conference on Engineering Systems Design and Analysis. Nantes, pp. 175–179. https://doi.org/https://doi.org/10.1115/ESDA2012-82772

Dahy, H., 2019. 'Materials as a Design Tool' Design Philosophy Applied in Three Innovative Research Pavilions Out of Sustainable Building Materials with Controlled End-Of-Life Scenarios. Buildings 9 (3), 1–13. https://doi.org/10.3390/buildings9030064

Domenech, T., Bahn-Walkowiak, B., 2017. Transition Towards a Resource Efficient Circular Economy in Europe: Policy Lessons From the EU and the Member States. Ecological Economics. https://doi.org/10.1016/j.ecolecon.2017.11.001

Faber, A., Hoppe, T., 2013. Co-constructing a sustainable built environment in the

Netherlands-Dynamics and opportunities in an environmental sectoral innovation system. Energy Policy 52, 628–638. https://doi.org/10.1016/j.enpol.2012.10.022

Geissdoerfer, M., Naomi, S., Monteiro, M., Carvalho, D., Evans, S., 2018. Business models and supply chains for the circular economy. J Clean Prod 190, 712–721. https://doi.org/10.1016/j.jclepro.2018.04.159

Huang, T., Shi, F., Tanikawa, H., Fei, J., Han, J., 2013. Materials demand and environmental impact of buildings construction and demolition in China based on dynamic material flow analysis. Resour Conserv Recycl 72, 91–101. https://doi.org/10.1016/j.resconrec.2012.12.013

Hubbard, S.M.L., Hubbard, B., 2019. A review of sustainability metrics for the construction and operation of airport and roadway infrastructure. Frontiers of Engineering Management 6, 433–452. https://doi.org/10.1007/s42524-019-0052-1

Joensuu, T., Edelman, H., Saari, A., 2020. Circular economy practices in the built environment. J Clean Prod 276, 124215. https://doi.org/10.1016/j.jclepro.2020.124215

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resour Conserv Recycl 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kirchherr, J., Yang, N.H.N., Schulze-Spüntrup, F., Heerink, M.J., Hartley, K., 2023. Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions. Resour Conserv Recycl. https://doi.org/10.1016/j.resconrec.2023.107001

Klein, N., Ramos, T.B., Deutz, P., 2020. Circular Economy Practices and Strategies in Public Sector Organizations: An Integrative Review. Sustainability (Switzerland) 12 (10), 4181.

Kumar, N.M., Chopra, S.S., 2022. Leveraging Blockchain and Smart Contract Technologies to Overcome Circular Economy Implementation Challenges. Sustainability (Switzerland) 14. https://doi.org/10.3390/su14159492

Lechtenböhmer, S., Schüring, A., 2011. The potential for large-scale savings from insulating residential buildings in the EU. Energy Effic 4, 257–270. https://doi.org/10.1007/s12053-010-9090-6

Liu, C., Côté, R., 2017. A framework for integrating ecosystem services into China's circular economy: The case of eco-industrial parks. Sustainability (Switzerland) 9. https://doi.org/10.3390/su9091510

Maduta, C., D'Agostino, D., Tsemekidi-Tzeiranaki, S., Castellazzi, L., Melica, G. Bertoldi, P., 2023. Towards climate neutrality within the European Union: Assessment of the Energy Performance of Buildings Directive implementation in Member States, ENERG BUILDINGS 301, 113716

Martín Gómez, A.M., Aguayo González, F., Marcos Bárcena, M., 2018. Smart eco-industrial parks: A circular economy implementation based on industrial metabolism. Resour Conserv Recycl 135, 58–69. https://doi.org/10.1016/j.resconrec.2017.08.007

Mohd Nawi, M.N., Baluch, N., Bahauddin, A.Y., 2014. Impact of fragmentation issue in construction industry: An overview. MATEC Web of Conferences 15, 1–8. https://doi.org/10.1051/matecconf/20141501009

Molina-moreno, V., Carlos, J., Jorge, S., 2017. Proposal to Foster Sustainability through Circular Economy-Based Engineering: A Profitable Chain from Waste Management to Tunnel Lighting. Sustainability 9, 1–9. https://doi.org/10.3390/su9122229

Morrissey, J., Iyer-raniga, U., Mclaughlin, P., Mills, A., 2012. A Strategic Project Appraisal framework for ecologically sustainable urban infrastructure. Environ Impact Assess Rev 33, 55–65. https://doi.org/10.1016/j.eiar.2011.10.005

Ogunmakinde, O.E., 2019. A review of circular economy development models in China, Germany and Japan. Recycling 4. https://doi.org/10.3390/recycling4030027

O'Leary, M.J., Osmani, M., Goodier, C., 2024. Circular economy implementation strategies, barriers and enablers for UK rail infrastructure projects. Resources, Conservation and Recycling Advances 21. https://doi.org/10.1016/j.rcradv.2023.200195

Pomponi, F., Moncaster, A., 2017. Circular economy for the built environment: A research framework. J Clean Prod 143, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Ranta, V., Aarikka-Stenroos, L., Ritala, P., Mäkinen, S.J., 2018. Exploring institutional drivers and barriers of the circular economy: A cross-regional comparison of China, the US, and Europe. Resour Conserv Recycl 135, 70–82. https://doi.org/10.1016/j.resconrec.2017.08.017

Sauvé, S., Bernard, S., Sloan, P., 2016. Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. Environ Dev 17, 48–56. https://doi.org/10.1016/j.envdev.2015.09.002

Schandl, H., Marcos-Martinez, R., West, J., Miatto, A., Lutter, S., Lieber, M., Giljum, S., Lenzen, M., Li, M., Wang, H., Tanikawa, H., Krausmann, F., Eisenmenger, N., & Fischer-Kowalski, M., 2024. Global material flows and resource productivity: The 2024 update. J. Ind. Ecol. 28, 2012–2031. https://doi.org/10.1111/jiec.13593

Shen, L., Asce, M., Wu, Y., Zhang, X., Ph, D., 2011. Key Assessment Indicators for the Sustainability of Infrastructure Projects. J Constr Eng Manag 137, 441–451. https://doi.org/10.1061/(ASCE)CO.1943-7862

Skene, K.R., Oarga-Mulec, A., 2024. The Circular Economy: The Butterfly Diagram, Systems Theory and the Economic Pluriverse. Journal of Circular Economy 2 (3). https://doi.org/10.55845/LIXE9236

Tumilar, A.S., Milani, D., Cohn, Z., Florin, N., Abbas, A., 2021. A modelling framework for the conceptual design of low-emission eco-industrial parks in the circular economy: A case for algae-centered business consortia. Water (Switzerland) 13. https://doi.org/10.3390/w13010069

Van Bueren, E., 2009. Greening Governance. An Evolutionary Approach to Policy Making for a Sustainable Built Environment. PhD Dissertation, TU Delft.

Vermeulen, W.J.V., Hovens, J., 2006. Competing explanations for adopting energy innovations for new office buildings. Energy Policy 34, 2719–2735. https://doi.org/10.1016/j.enpol.2005.04.009

Yu, Y., Yazan, D.M., Junjan, V., Iacob, M.E., 2022. Circular economy in the construction industry: A review of decision support tools based on Information & Communication Technologies. J Clean Prod 349, 131335. https://doi.org/10.1016/j.jclepro.2022.131335

Zeng, H., Chen, X., Xiao, X., Zhou, Z., 2017. Institutional pressures, sustainable supply chain management, and circular economy capability: Empirical evidence from Chinese eco-industrial park firms. J Clean Prod 155, 54–65. https://doi.org/10.1016/j.jclepro.2016.10.093

Zhao, Haoran, Guo, S., Zhao, Huiru, 2018. Comprehensive benefit evaluation of eco-industrial parks by employing the best-worst method based on circular economy and sustainability. Environ Dev Sustain 20, 1229–1253. https://doi.org/10.1007/s10668-017-9936-6

Zhao, H., Zhao, H., Guo, S., 2017. Evaluating the comprehensive benefit of eco-industrial parks by employing multi-criteria decision making approach for circular economy. J Clean Prod 142, 2262–2276. https://doi.org/10.1016/j.jclepro.2016.11.041

2. Tracing Circular Strategies in the Construction Literature: an Analysis of Their Use for Sustainability Goals and on Different Materials and Assets[9]

2.1 Introduction

The intensive construction of built environment and infrastructure projects has considerable environmental, economic, and social impacts and affects the achievement of SD (Morrissey et al., 2012; Shen et al., 2011). CE represents a recent attempt to conceptualize the integration of economic activity and environmental well-being sustainably (Su et al., 2013; Merli et al., 2018; Murray et al., 2017). As CE is contrary to the traditional "take—make—use—dispose" pattern, it is paramount that assets in the built environment tangibly transition to CE.

CE makes a difference by focusing on resources like materials, products, and components from which assets (i.e., buildings and infrastructures) are composed. CE targets the reduction of construction wastes, as well as the massive lowering of primary construction and building materials consumption, thereby substantially minimizing the associated environmental burdens in the construction sector (Hossain and Ng, 2018; Chen et al., 2022). This has high potential because, traditionally, the production and consumption of materials are known to pollute the air, water, and land (Madurwar et al., 2013a). Therefore, it is also crucial for the material level to develop circular and sustainable strategies regarding production and consumption.

For these circular and sustainable ideas to be effective, it can be expected that the assets of the built environment and the associated materials are interdependent when it comes to implementation. For example, research studies could develop circular solutions for assets in the built environment by replacing traditional materials with sustainable ones. Other studies could develop the reuse of secondary building materials intended to replace primary materials into a new infrastructure asset like a bridge. In fact, the proposed interdependence between materials and assets can be recognized as the connection point. It is meaningful to better understand the scientific advances for the construction sector (delivering infrastructures and buildings) in this interdependence (Huang et al., 2018). However, to the best of our knowledge, no such study has been conducted on this interface yet.

This chapter aims to address this gap by answering the question: "What do research studies contribute to furthering sustainability in the construction sector through circular activities at the interface between assets in the built environment and construction (building) materials?" To answer this question, this study adopted two approaches: literature review and bibliometric analysis. Regarding the review, the authors first collected and identified research articles contributing to the interface of assets and materials in pursuance of sustainability via CE. Secondly, the abstracts of these articles were reviewed and used to generate insight about the circular strategies (or circular activities, which will be explained later in Section 2.3) that are applied to achieve sustainability from the perspective of specific assets and materials.

---

[9] This chapter is based on: **Liu, X.Y.,** Schraven, D., Ma, W.T., de Jong, M. and Hertogh, M. (2025) "Tracing circular strategies in the construction literature: an analysis of their use for sustainability goals and on different materials and assets" ***Cleaner Environmental Systems*** (under the 2nd round review)

Besides the review, a broader bibliometric analysis of author keywords in articles covering assets and construction (building) materials was conducted to provide a more general view of the literature.

2.2 Background

The Brundtland Commission introduced sustainability in 1987. Before this, SD had already emerged in the early to mid-1980s. Later, an action plan (called Agenda 21) for the transition to sustainability was introduced in 1992 at the Earth Summit of the United Nations in Rio de Janeiro (Liu et al., 2016).

In the same year, the Framework for Strategic Sustainable Development was conceived, which is also known as The Natural Step Framework (Missimer et al., 2010; Missimer and Rob, 2017). Looking forward, the United Nations agenda for 2030 depicts 17 SDGs (Allen et al., 2018). To help achieve the goal of SD, the TBL was first introduced by John Elkington in 1994, and it is often used in sustainability-related research (Goh et al., 2020).

For the construction sector, Ortiz et al. (2009) reviewed sustainability in the construction industry using Life Cycle Assessment (LCA) studies. Also, sustainability policy practices in the construction sector were investigated by Zuo et al. (2012). On the relationship between infrastructure and sustainability, there is also a large body of research: dealing with topics such as sustainable infrastructure development (Yuan and Yang, 2008), sustainability indicators in the context of infrastructure (e.g., (Alsulami and Mohamed, 2010)), infrastructure sustainability objectives (e.g., (Elbarkouky, 2012)), sustainability appraisal in infrastructure projects (Ugwu et al., 2006), sustainable urban infrastructure (Luiza et al., 2018), etc. There is also research focusing on sustainable construction materials (Raut et al., 2011; Madurwar et al., 2013; Kissi et al., 2018; Hossain et al., 2019), and sustainable building materials (Dahy, 2019b).

CE, as the other ambition, aims to regenerate products and materials at their end of life and keep products, components, and materials at their highest value as long as possible. CE has gained increasing attention in Europe and worldwide as a viable way for our society to increase prosperity while reducing dependence on primary materials and energy. With its system-wide perspective, CE has the potential to help make better decisions about resource use, design out waste, provide added value for businesses, and secure these for future generations (Ellen MacArthur Foundation, 2018a).

The notion of CE has deep historical and philosophical origins. The idea of feedback and cycles in real-world systems is ancient. The CE concept cannot be traced back to a single date or author. However, its practical applications to modern economic systems and industrial processes have gained momentum since the late 1970s, led by a small number of academics and thought leaders (e.g., David Pearce and Walter Stahel (Ellen MacArthur Foundation, 2018b; Andersen, 2007)).

Various R frameworks (3R, 4R, 6R, 9R) for CE have been used in academia since the early 2000s (King et al., 2006; Kirchherr et al., 2017). For some other more specific applications, frameworks for CE have been proposed, like the Complex Value Optimisation for Resource Recovery framework (Iacovidou et al., 2017), the ProbBiz4CE framework (Witjes and Lozano, 2016), as well as the backcasting and eco-design for CE framework (Mendoza et al., 2017).

In the construction sector, CE applications have focused primarily on closing the loops of construction and demolition waste (C&DW) (Pomponi and Moncaster, 2017), while more recently on other directions such as digital technologies (Illankoon and Vithanage, 2023). Closing loops are achieved, for example, by studying the possibilities of new material sources like sewage sludge ash (Smol et al., 2015). Esa et al. (2017)'s research dealt with C&DW; similarly, Ghisellini et al. (2018) reviewed and organized the recent literature within the framework of CE to explore how its fundamental principles (Reduce, Reuse, and Recycle) were applied to the management of C&DW. As one of a few, Leising et al. (2018) addressed the interdependence between assets and materials by focusing on the collaboration to develop and operate circular buildings and their material supply chains. An interesting study by Roberto et al. (2018) shows how CE can lead to environmental advantages (through reduction, reusability, adaptability, and recyclability of building components) in the prefabricated building sector. Ossio et al. (2023) proposed a definition for Circular Construction (CC) in the built environment.

The key observation in the literature is that there is a strong interdependence between assets and materials when achieving sustainability or CE. At the same time, it underscores the lack of more detailed insights regarding specific assets and materials. In this research, we theoretically frame that the interdependence between assets and materials derives from the construction and deconstruction of assets with materials. Through this interdependence, we conceptualize that circular strategies intervene in this relationship through choices and the use of technologies that change the material input for assets. For example, by reusing secondary materials or adopting more efficient technologies, we can reduce the construction sector's negative consequences (environmental, economic, and social) and make it more sustainable. This idea is reflected in Fig. 2.1 below.

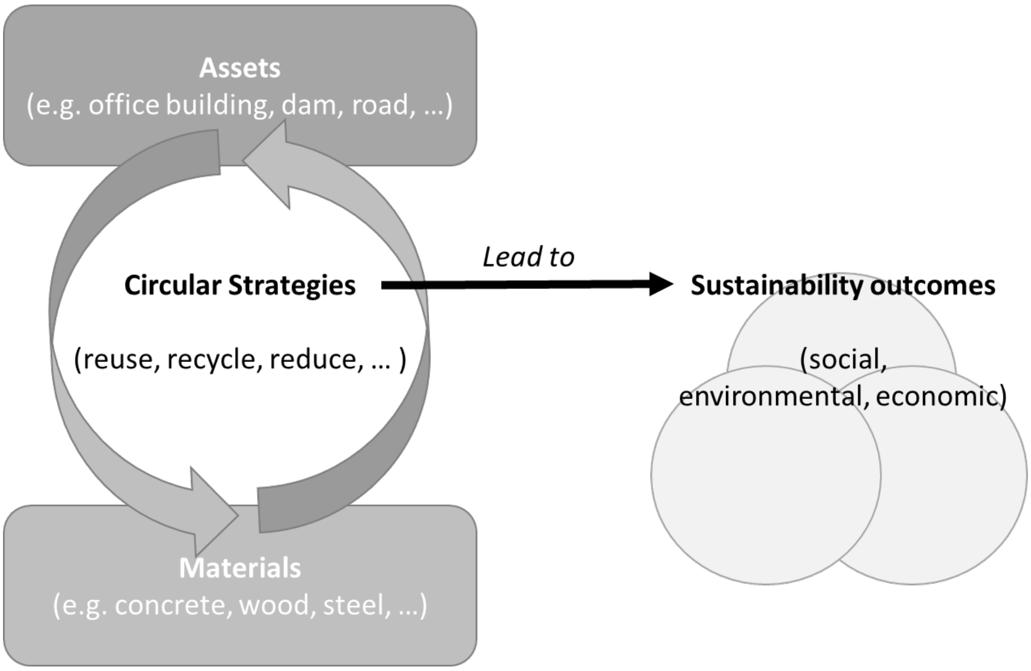


Figure 2.1 Conceptual framework for circular strategies and their influence on sustainability outcomes

Fig. 2.1 represents the relationship between CE strategies in the built environment and the impact the strategies have on sustainability. On the left side, the flow of CE strategies is represented and starts with assets and materials. One route begins with the curved arrow from the asset at the top left corner. It could, for example, represent the demolition of an office building or a dam. At the end of this asset's life, a circular strategy, like "Recycle" requires decomposing the asset into various streams of materials, for example, concrete and/or steel. Another route starts with the curved arrow from the material at the bottom left corner. Here, a certain kind of secondary construction material will be redistributed by a CE strategy to new destinations to serve a specific function into a new asset. For example, wood could be reused for a new office building. Both routes correspond to a closing of the material loop. The effect that a CE strategy has on the outcome of sustainability is represented by the straight arrow in the middle pointing to the TBL framework on the right-hand side. A CE strategy can, for example, lead to lower CO_2 emissions in the long run.

For this figure to be used to examine the literature, a few critical notes should be mentioned. First, this figure contains the core concepts of this study (i.e., CE strategies and Sustainability) that are referred to at a high level or low level of abstraction. Authors more often use a high level of abstraction to refer to the concept as a container term, like the notion that sustainability can be about both social welfare and environmental footprint. In contrast, a low level of abstraction is used by articles to refer to more operational terms that bring a more precise usage of the concept in action, like a recycling strategy. Following this, we denote that there are different levels of *concept clarity* in how articles refer to and use these concepts in their studies.

Even though the term "Recycling" can be self-explanatory and operational, its effect on different materials may still be different. For example, recycling wood or concrete might have different sustainability outcomes because of different material characteristics. For these different contexts to be noticeable, we also denote that the relationship between CE and sustainability outcomes depends on *context clarity*, which is defined as the specificity of which material and asset are involved.

These notions of concept and context clarity form a cornerstone in disentangling the literary contributions on the relationship between CE strategies and sustainability outcomes. In the next section, we develop a line of argument and methodology to study this in more detail.

2.3 Methodology

In this section, we describe the methodology (depicted in Fig. 2.2). A systematic and reproducible approach is needed to capture the relevant articles for this study. In doing so, Scopus is used as the database to search and extract the articles to be analyzed and reviewed. Scopus is suitable for this purpose because it is a well-established repository for searching academic publications and one of the most comprehensive and standardized literature databases for exporting data (Falagas et al., 2008; de Jong et al., 2015). The search period was confined to the period between 1988 and 2024. The year 1987 marks the publication of the Brundtland Report, which is the first work to raise concerns about SD and sustainability. The year 2024 is the most recent completed publication year at the time of revising this study. Our review focuses on academic journal articles and reviews as these represent the steadier product of the knowledge output behind studies.

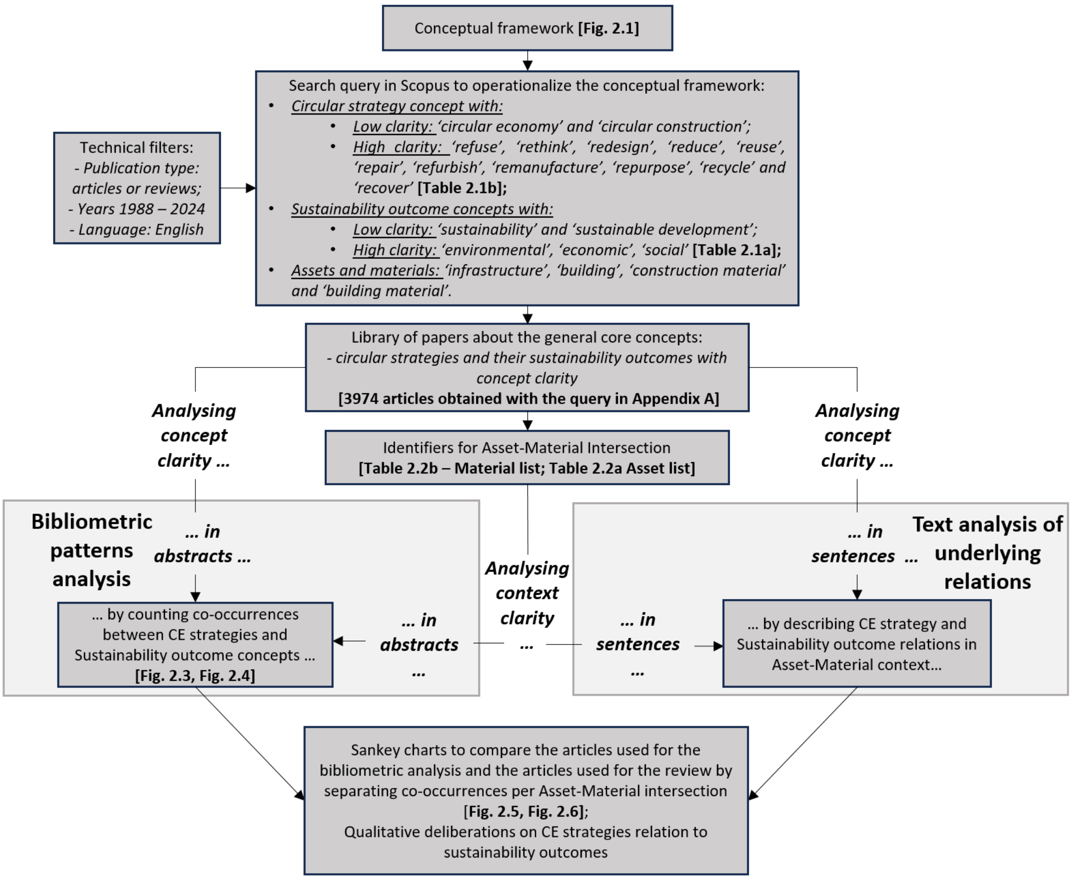


Figure 2.2 Research design (own figure; CE: Circular Economy)

The first step in setting up a search query for Scopus is to operationalize the relevant scope. For this, we searched journal articles combining reference to the asset and material levels as scope referrals. As Fig. 2.1 indicates, many variant types and names exist for assets and materials, which could easily make a query unnecessarily complicated and vulnerable to criticism. Additionally, many of these terms may represent different meanings (e.g., "road" or "concrete"), which may distract from the subject. Therefore, a transparent search strategy was chosen using overarching terms that could reasonably validate the correct meaning of the terms for this study. In essence, overarching words are used for the asset level (i.e., "infrastructure" and "building" in single and plural forms) and material level (i.e., "construction material" and "building material", also in single and plural forms) in the Scopus database.

In addition, the study's focus still needs to be featured: how circular strategies lead to sustainability outcomes. The literature uses these concepts, sometimes specific and sometimes abstract. Therefore, we had to apply additional filtering terms with low or high levels of concept clarity. In essence, circular strategies and sustainability outcomes were defined at respectively high and low levels of clarity. The terms "Circular Economy" and "Circular Construction" were used as terms of circular strategies at a low level of clarity. The specific words from the 9R framework (from R0 to R9), as defined by Potting et al. (2017), were used as circular strategies of a high level of clarity. We completed the list of 11R strategies by also adding "Redesign" as a typical strategy in the construction sector (Chan et al., 1999). See Table 2.1b for the 11R strategies. Similarly, for sustainability, the literal terms

"Sustainability" and "Sustainable Development" were used as the low level of clarity; and we adopted the TBL dimensions (environmental, economic, and social) as the high level of concept clarity as these are more detailed dimensions (Wilson, 1997) with distinctive definitions (see Table 2.1a). This distinction at two levels of concept clarity for CE and sustainability was included in the search query in Appendix A, generating 3974 hits.

Table 2.1a List of the definitions of TBL terms used to select articles (TBL: Triple Bottom Line)

No.	TBL outcome	Definitions of the TBL terms
1.	Environmental	Referring to environmental services, including spatial functions, waste disposal, natural resource supply, and life support*
2.	Economic	Referring to the ability to produce goods and services on a continuing basis**
3.	Social	Referring to having either positive or negative impact on systems, processes, organizations, and activities on people and social life ***

*Provided by OECD[10] ; **Provided by Harris (2003)[11], ***Provided by Balaman (2019)

[10] https://stats.oecd.org/glossary/detail.asp?ID=6424 (assessed on Sept 14, 2022)

[11] https://isecoeco.org/pdf/susdev.pdf (assessed on Sept 14, 2022)

Table 2.2b List of the definitions of the "11Rs" used to select articles (CE: Circular Economy)

No.	R strategies	Definitions of the terms starting with "R" in terms of CE
1.	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product*
2.	Rethink	Make product use more intensive (e.g. by sharing a product)*
3.	Redesign	Redesign activity involves the act of redesigning next generation products **
4.	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials*
5.	Reuse	Reuse by another consumer of a discarded product that is still in good condition and fulfills its original function*
6.	Repair	Repair and maintenance of defective products so it can be used with their original function*
7.	Refurbish	Restore an old product and bring it up to date*
8.	Remanufacture	Use parts of a discarded product in a new product with the same function*
9.	Repurpose	Use discarded product or its parts in a new product with a different function*
10.	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality*
11.	Recover	Incineration of material with energy recovery*

*Provided by Potting et al. (2017); **Provided by Jawahir and Bradley (2016)

As a second step, the scope had to be further contextualized for studying the relations, which was about more specific terms for assets and materials. Therefore, we counted and ranked the author keywords of the 3974 articles to shortlist the selected terms related to assets and materials. Relevant author keywords that appeared more than once were included in an asset and material lists. These lists were then crosschecked with document analysis from (Hammond and Jones, 2008) and professional sources[12] as well as with a construction materials expert for completeness and comprehensiveness. These two lists (in Table 2.2a and 2.2b) are used to identify the clarity of the context in which the CE and sustainability terms are studied, which we call the asset-material intersections. The above-mentioned 3974 hits, the two lists, and sustainability/CE terms were used for the bibliometric analysis.

[12] https://simplicable.com/new/building-materials;
http://www.fao.org/fishery/static/FAO_Training/FAO_Training/General/x6708e/x6708e03.htm;
https://theconstructor.org/building/types-of-building-materials-construction/699/;
https://www.designingbuildings.co.uk/wiki/Construction_materials (all assessed on Sept 24, 2019)

Table 2.2a The construction and building material list

No.	Material	No.	Material	No.	Material
1	aggregate	16	glass	31	polystyrene
2	aluminium	17	graphene	32	polyurethane
3	asphalt	18	graphite	33	polyvinyl chloride
4	bamboo	19	granite	34	rock
5	basalt	20	gravel	35	rubber
6	bitumen	21	gypsum	36	sand
7	cardboard	22	lumber	37	sludge
8	carpet	23	metal	38	soil
9	cement	24	mortar	39	steel
10	ceramic	25	mud	40	stone
11	clay	26	papercrete	41	timber
12	coal	27	plaster	42	wood
13	concrete	28	plastic	43	wool
14	copper	29	plywood	44	zinc
15	flax	30	polyethylene		

Table 2.2b The asset list

No.	Asset	No.	Asset
1	asset	11	infrastructure
2	aqueduct	12	motorway
3	bridge	13	pavement
4	building	14	port
5	dam	15	rail
6	embankment	16	railway
7	harbor/harbour	17	reservoir
8	highway	18	road
9	hospital	19	tunnel
10	house		

For the deeper review, the articles were further categorized into four groups using the four search queries in Appendix B. Additionally, validation steps are followed to remove invalid articles to represent the subjects under study (i.e., CE and Sustainability) and the scope of the study (i.e., construction materials and assets). This first means all four elements (CE, sustainability, asset and material) need to be present in the article title, abstract, or keywords and relevant in terms of the CE context. At the same time, on the subjects, both the low and high-level abstraction words of CE and Sustainability should represent the concepts under study. For CE specifically, precise definitions are used (see Table 2.2) to obtain articles with the relevant meanings to 9R strategies (by Potting et al., 2017) and to "Redesign" (by Jawahir and Bradley, 2016).

Table 2.3 Number of articles filtered and identified (including duplication among groups)

	Group 1	Group 2	Group 3	Group 4
Number of articles after searching with the query	131	1948	1087	2373
Number of articles left for review	6	20	43	104

The articles[13] were further reviewed to understand how the circular strategies and sustainability outcomes relate to different contexts, which was done by analyzing the titles and abstracts of the studies more carefully at the sentence level.

2.4 Results

This section reports the results of the literature analysis. It is divided into three sections. First, Section 2.4.1 discusses the bibliometric analysis of the 3974 articles. Next, Section 2.4.2 presents a review of the titles and abstracts of the 125 articles finally filtered. Finally, Section 2.4.3 compares the Sankey charts covering the articles used in Sections 2.4.1 and 2.4.2.

2.4.1 Descriptive Statistics of the Bibliometric Analysis (The Relations of Circular Economy (CE) to Sustainability Outcomes)

Author keywords can reveal insights into how active certain concepts are used by the academic community to share the central concepts related to their studies. For this reason, the relations of these concepts of the literature can shed light on the level of both circular strategy adoptions and sustainability outcomes.

The CE terms and their relations to sustainability outcomes are shown in Fig. 2.3.

[13] 125 in total, excluding duplications

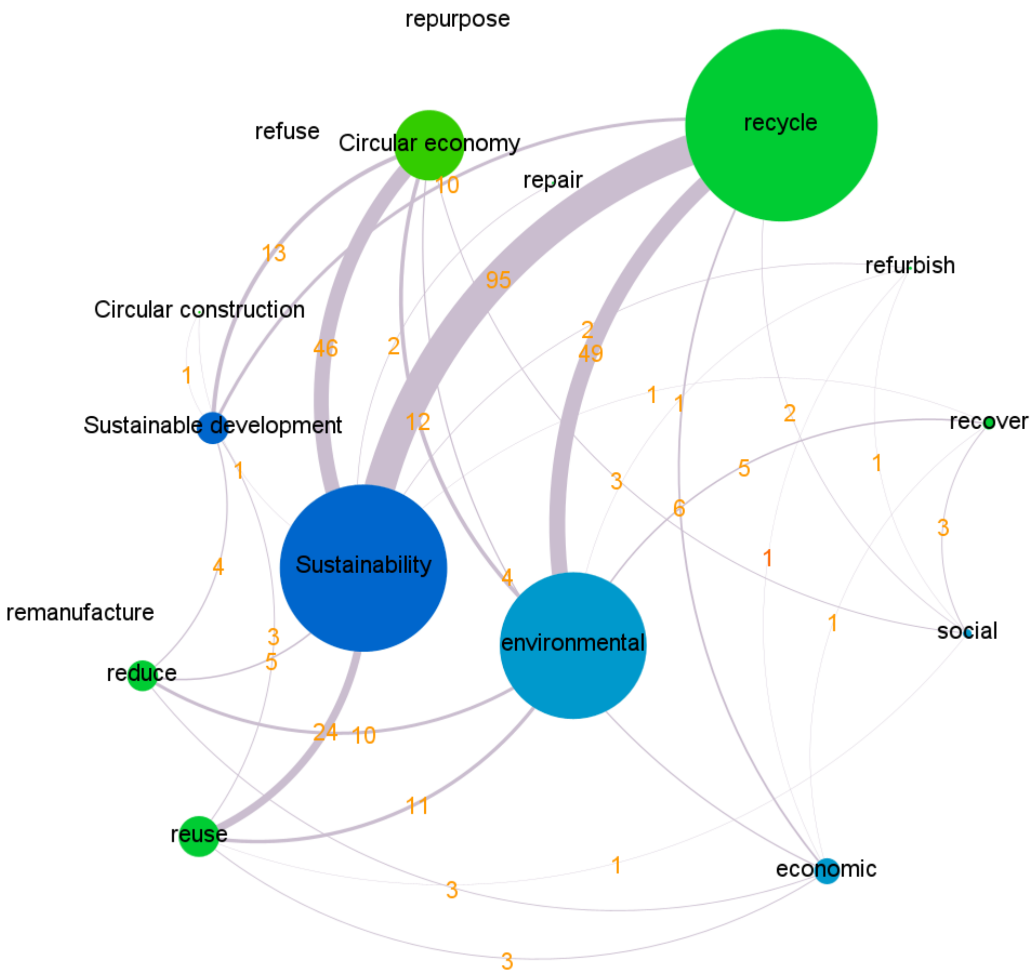


Figure 2.3 The relations of Circular Economy (CE) to sustainability outcomes[14]

A few points are clear from this figure: relations are not very strong, and for the most part, the relations are incidental (with relatively low frequencies shown with the numbers). Out of all the relationships, "'Recycle' and 'Sustainability'" is the most notable one, followed by "'Recycle' and 'Environmental'" with 49 associations, which shows that recycling is the most dominant strategy in the construction field that is investigated for its contribution to sustainability outcomes.

Out of all the TBL dimensions, it is remarkable to note that "Social" occurs the fewest times of all three; "Environmental" is by far the most frequent one, signalling a more significant emphasis on environmental considerations than overarching higher abstract ones.

Overall, the other R strategies almost all have incidental linkages with sustainability outcomes. "Reuse", as the second "largest" R strategy, links 24 times to "Sustainability".

[14] Different forms of the terms were considered, for example "reduce", "reduction" and "reducing". The same applies to Fig. 2.4, Fig. 2.5 and Fig. 2.6.

“Reduce” links incidentally to Sustainability terms except “Social”. The strategy “Refuse”, “Repurpose” and “Remanufacture” are not yet brought in association with sustainability outcomes.

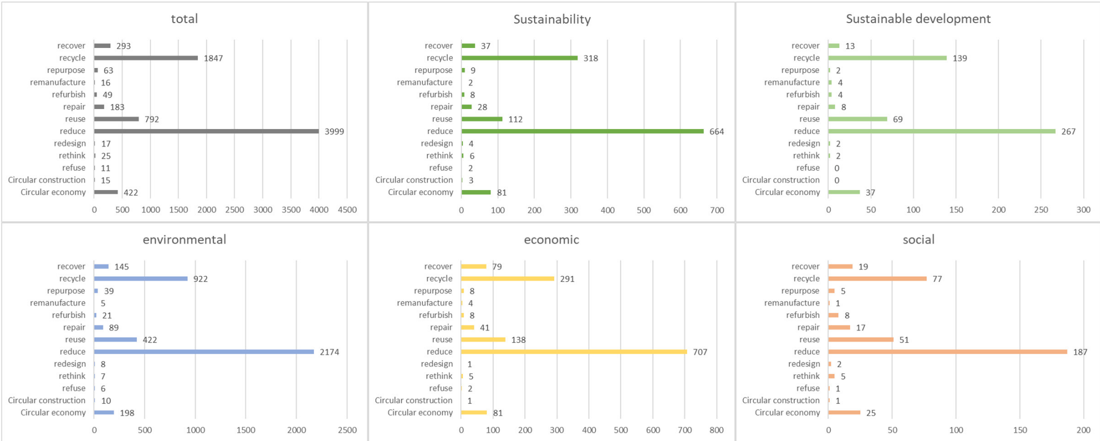


Figure 2.4 The co-occurrence of the combinations of Circular Economy (CE) terms and Sustainability terms from the article titles and abstracts

Fig. 2.4 displays the co-occurrence of the combinations of CE terms and Sustainability terms from the title and abstract parts.

Regarding CE container terms, “Circular Economy” was mentioned many times more than “Circular Construction”. This suggests that CE has received attention, but the academic community has not yet reasonably specified “Circular Construction” as a proper way to engage in construction for the sector. At the operational term level of CE, we glean that out of the “11Rs”, all were covered in the top-left corner (the “Total” part). It is interesting to note that “Refuse”, “Rethink”, “Remanufacture”, “Repurpose” and “Redesign” were not found as often as the other R strategies in the set. This shows that these strategies are not yet actively absorbed in the minds of academics in construction-related literature.

An additional observation is that “Reduce” and “Recycle” are mentioned most of the time in the literature. “Reduce” is a common word being used with different kinds of objects. “Recycle” is clearly a strategy that draws quite some academic relevance for the construction sector, as it typically concerns the changing of forms, structure, composition, and properties of varied materials, and numerous tests, as well as experiments, have been done with recycled materials.

A few middle-range strategies have received attention in the literature, including “Reuse” and “Repair”. These strategies mark the middle order of circular strategies engaged by authors to date, leaving a gap in the highest circular strategies: “Refuse”, “Rethink”, and “Redesign”.

Finally, “Recover”, as the lowest level strategy, received the fourth largest amount of attention. This may suggest that the academic literature has not yet abandoned the usefulness of this strategy. A much more important reason is that “Recover” was used by some academics with a different meaning than that in Table 2.1. For example, “recovery of construction and demolition waste” (Puskás et al., 2014) does not refer to energy production by incineration but generally as a way for another use of the waste.

2.4.2 In-depth Review

By reading the titles and abstracts of the extracted articles, CE/the 11R terms and Sustainability/TBL terms (environmental, economic, social) are summarized, together with any assets and construction (building) materials that appear in the corresponding titles or abstracts.

2.4.2.1 Overview of the Reviewed Literature

"Reduce", "Reuse", and "Recycle" are the three R strategies that appear most often. Of the three sustainability aspects, "Environmental(ly)" is the one studied most, and "Social" the least. There are 12 different assets (the majority are buildings) and 33 different construction materials. Those materials and assets are presented in more detailed forms in the following sections, which are structured by the angle of CE.

2.4.2.2 "Circular Economy"

A few notable observations can be made for the papers that mentioned CE the most explicitly in the corpus. First, we discussed a typical interpretation of CE from more generic sources with no particular emphasis on any type of asset and materials (e.g., (Wiedenhofer et al., 2024)). Second, we found some notable orientations about studies connecting CE more closely to a material-specific item (e.g., (Bakar et al., 2024; Caponetto et al., 2023; Przybek and Łach, 2024; Sheshadri et al., 2024)).

CE, as a new paradigm of technological and economic development, is a restorative and regenerative industrial economic approach that promotes resource efficiency to reduce waste and environmental burdens (Eberhardt et al., 2019; Maury-Ramírez et al., 2022; Zandonella Callegher et al., 2023), thus the interest in CE within the construction sector is constantly increasing (Maria et al., 2021). Both at the EU and Member State level, CE and resource efficiency policies are promoting the production of **lower-impact building materials with secondary material input** (Nußholz et al., 2019) (e.g., e-waste (Kumar and Verma, 2024), agricultural and plastic waste (Messahel et al., 2023)). There is also a need to move towards a more CE by widely using a combination of **alternative low-carbon construction materials**, alternative technologies and practices (Morel et al., 2021).

For example, Briones-Llorente et al. (2020) contributed to both CE and SD by designing an ecological mortar with environmental benefits, because it is manufactured with critical recycled industrial waste such as Electric Arc Furnace (EAF) slag and Polyurethane Foam (PF); the authors designed an energy-efficient prefabricated block with the mortar, and assessed its energy performance in a (hospital) building.

For moving toward CE, reducing natural resource consumption, and environmental protection, the complete utilization of waste concrete offers unique opportunities (Villagrán-Zaccardi et al., 2022), and cement reduction as well as cement substitutes have become popular research topics (Lung et al., 2018), as cement is used globally in construction materials for nearly all civil infrastructure systems, and the magnitude of cement production leads to more than 7% of annual anthropogenic GHG emissions (Miller et al., 2021; Yousaf et al., 2024). An instance is waste-based pervious concrete for climate-resilient pavements (Lung et al., 2018). In line with this, Shah et al. (2021)'s research focused on the application of Alum Sludge (AS) and Brick Dust (BD) in Self-Compacting Concrete (SCC) for sustainable infrastructure development.

Taking these all in, we can say that research that connects to CE more literally is mainly about cement or concrete, the two common and closely-related construction materials.

2.4.2.3 "Reduce"

In addition to technologies, the articles here tend to connect "Reduce" to "Environmental" (except (Bai et al., 2024)). In more detail:

The use of wood and wood-based products has a positive effect on the environment, e.g. the reduction of waste and other emissions or climate change mitigation, and these products can be used in both residential and non-residential buildings (Jochem et al., 2016). Apart from reducing the amount of virgin asphalt cement and fine aggregate required in hot mix asphaltic concrete (HMAC), the reuse of roofing shingle waste also minimizes the environmental problems related to the disposal of waste in landfills (Watson et al., 1998). The Sandbar Breakwater (an innovative nature-based port solution) is advantageous as the required rock volumes are reduced significantly, and large sediment drift naturally supplements the sand filling works during construction, saving construction time and minimizing the environmental impact (van der Spek et al., 2020). Heeren and Hellweg (2019) presented a bottom-up building stock model that uses three-dimensional and geo-referenced building data to determine volumetric information of material stocks in Swiss residential buildings; they found that the new modeling approach supports the development of tailored strategies to reduce the material footprint and environmental impacts of buildings as well as settlements, and the cumulated environmental impact is slightly reduced for the wood-based scenario. Cechin et al. (2022) demonstrated that besides contributing to the reduction of natural resource extraction, the waste materials (Dam's Iron Ore Tailings (IOT), Blast Furnace Slag (BFS) from charcoal, and Foundry Sand (FS)) jointly used in construction materials, also enable their correct disposal, minimize environmental impacts. The use of recycled mortar is a good strategy to reduce wastes from construction activities, saving the cost of construction materials and enhancing environmental conservation (Musyoki et al., 2022). Paikara and Gyawali (2023) developed the aerated lightweight mortar, which not only enhances seismic resilience by reducing building weight but also serves as an eco-friendly alternative to traditional burnt clay bricks, mitigating environmental impact. The development of prefabricated concrete (PC) buildings can potentially reduce the consumption of resources and energy, also meet the requirements of low carbon and environmental protection in the construction industry (Li et al., 2021).

In terms of technologies, coreless filament winding is an emerging fabrication technology in building construction with the potential to decrease construction material consumption significantly (Mindermann et al., 2022); Abdellatief et al. (2023) reviewed the sustainability of geopolymer foam concrete (GFC), which is a material developed by combing of foam concrete (or foamed concrete (Mydin et al., 2023; Rudziewicz et al., 2023)) with geopolymer technologies; microalloying is known to allow for reduced steel consumption (Pradeep Kumar et al., 2021), the authors performed a sustainability analysis of it in terms of embodied energy and CO_2. Microalloyed steels, often referred to as high strength low alloy (HSLA) steels, are low-carbon steels with the strength increased by small amounts of alloying elements such as niobium, vanadium, titanium, molybdenum or boron, singly or in combinations (Lenard, 2014); Yaseen et al. (2024) advanced broader sustainability objectives by advocating for the use of nanotechnology in construction materials, underscoring the significance of nanostructured materials in the future of architecture.

In most cases, **reducing materials will reduce environmental impacts (or bring environmental benefits)** (Guan et al., 2023).

2.4.2.4 "Reuse"

This section shows that "Reuse" can be used as a lifecycle phase and a strategy strongly connected with different materials.

It has been demonstrated that the reuse of elements and materials is an environmentally responsible option that turns the current linear model of building materials and elements into a cyclical one, which pushes toward reconsidering the construction design of concrete buildings to support future disassembly, facilitating reuse and adaptation (Salama, 2017). Following such thought, Eberhardt et al. (2019) conducted a case study in a Danish office building where the concrete structure is designed for disassembly (DfD) for subsequent reuse; according to the authors, the substitution of other material choices (e.g., glass and wood) for the concrete structure exhibited a potential increase in impact savings. According to Hawkins et al. (2021), concrete is found to have a higher environmental impact than steel, with the climate response of both dominated by the large initial emissions of material production and construction, out of all life cycle stages, including reuse.

There is a strong demand for environmentally safe reuse and effective disposal methods for municipal solid waste (MSW) due to the increasing amount of waste generated by the various residential buildings and commercial establishments, so Srinivas and Kumar (2009) demonstrated a feasible way of using incinerated MSW ash as a cement replacement material to produce quality bricks. Similarly, an optimum concrete mixture using Municipal Solid Waste Incineration (MSWI) residues as aggregates was formulated (del Valle-Zermeño et al., 2013); the authors considered and assessed the environmental behavior whilst maximizing the reuse of air pollution control (APC) fly ash and found that the material studied might be mainly used in embankments, where high mechanical properties are not needed and environmental safety is assured. Concerning ashes, the Bagasse ash (BA, as industrial waste) can be reused as a cost-effective and green construction material for the SD of civil infrastructure (Dang et al., 2021); as for ashes from natural origins, Rocha et al. (2022) evaluated the use of Açaí seed ash (ASA) from the Brazilian Amazon as partial Portland cement replacement in self-leveling mortars (SLM) for social-interest buildings, proposing the reuse of waste. As for sediments, reusing calcined dredged sediments as a sustainable building material can reduce GHG emissions, and save significant energy consumption and costs (Hadj Sadok et al., 2022).

"Reuse" is also found to be used with "Recycle" together. Kumanayake and Luo (2018) concluded that in order to achieve low-energy and low-carbon buildings in Sri Lanka, several strategies were identified, including material recycling and reuse. While in the UK, the main environmental benefit of houses is from reusing the bricks and recycling the aggregates (Cuéllar-Franca and Azapagic, 2012). Abouhamad and Abu-Hamd (2021) developed a life cycle assessment framework for embodied environmental impacts of building construction systems, from cradle-to-grave plus recycling and reuse possibilities. Dorsey (2022) underscored the importance of reusing, salvaging, and recycling building materials as a pragmatic way to reduce both CO_2 emissions and building costs. Besides, the recyclability of plastic formworks enables the reuse of material and environmental sustainability, such formworks can be used for example in bridges (Lo, 2017). According to Bajno et al. (2021), demolition wood can be reused in construction, can be safely recycled as it quickly decomposes, or can be used as a source of renewable energy. At the city scale, the material flows (sand and gravel, cement, asphalt, and construction waste) during the past decade for constructing major urban engineering projects such as roads, bridges, flood prevention projects, storm drainage and sewerage pipes, and buildings are analyzed for the metropolis of Taipei (Huang and Hsu, 2003); the authors found that the recycling and reuse of construction waste can not only create a circular pattern of urban metabolism but is also vital to the SD of Taipei.

Except for the cases in the last paragraph when used simultaneously with "Recycle" and when used as a descriptor of lifecycle phase, "Reuse" is often linked to various waste materials (Bulatbekova et al., 2024; Kucukdogan et al., 2024; Czarnecki and Rudner, 2023; Suarez-riera et al., 2024).

2.4.2.5 "Repair"

Only six papers concern "Repair", which can be associated with asset management or maintenance. The first instance is Pineda et al. (2017) focused on the environmental and structural implications of grouting using mortar, one of the most commonly used techniques in repairing, strengthening, and retrofitting damaged masonry buildings. This is a typical example showing that "Repair" is currently related to retrofitting (old) buildings.

The second is the use of cast asphalt concrete in the upper layers of road surfaces as a replacement for layers made of traditional fine-grained asphalt concrete, which will not only increase the pace of construction and repair but also the durability and quality of the road pavement (Bieliatynskyi et al., 2022).

As for self-healing concrete, it can be characterized by the capability of concrete to repair its cracks autogenously or autonomously (Kaushal, 2024). Similarly, Nur and Dewi (2024) highlighted the potency of microalgae in biocement production and their pivotal role in facilitating self-healing properties in concrete structures. Microbially induced calcite precipitation (MICP) is a promising technique for the maintenance of concrete structures due to its novel approach in concrete technology for healing (Gebremedhin and Eryürük, 2024). Wong et al., (2024) highlighted how environmental parameters, such as pH, temperature, oxygen, and moisture critically affect the repair efficacy.

2.4.2.6 "Recycle"

Construction industries worldwide have understood that recycling of road construction materials is vital for the SD of infrastructure (Pradhan and Sahoo, 2022). Recycled materials have been shown to lower the environmental risk associated with some raw material production processes (Gallo et al., 2022). As mentioned before, "Recycle" usually concerns tests and experiments in terms of aspects such as recyclability, processing costs and profitability, recovery and grade of specific components, environmentally friendly features, toxicity, biodegradability, mechanical performance and so on (Vantadori et al., 2019; e.g., (Tijani et al., 2022)). The sustainable usage of recycled plastic and demolition wastes as alternative construction materials has numerous environmental and economic advantages, for instance, polyethylene plastic granules with up to 5% content were found to be suitable as a road construction material, when blended in supplementary amounts with demolition wastes (Arulrajah et al., 2017a; Reddy et al., 2022). Tang et al. (2021a) studied the fracture behaviors of rubber-modified recycled aggregate concrete (RRAC). del Río-Merino et al.

(2022) also presented previous experimental studies on the mechanical characterization of recycled gypsum composites. As post-consumer waste recycling, Edun & Hachem-Vermette (2021, 2022) examined selected post-consumer waste materials for use in the building envelope, including end-of-life tyres, polyethene terephthalate (PET) bottles, and paper/cardboard fibers. Alqahtani et al. (2021) quantitatively validated the use of green recycled plastic aggregates as a substitute to conventional aggregates to save limited natural resources. For building insulation, Majumder et al. (2021) provided a detailed analysis of the thermal characterization of recycled materials; while Fedorik et al. (2021) assessed the hygrothermal properties of eight new peat-, recycled paper-, wood shaving-, and feather-based insulation materials. Arulrajah et al. (2017b) did an engineering and environmental evaluation of recycled waste foundry sand as a sustainable subgrade fill and pipe-bedding construction material, which can satisfactorily be used as fill material in embankments and pipe-bedding applications; similarly, biomass bottom ashes could be used as filler in road embankments, cement-treated materials or non-structural concrete, depending on the replacement percentage (Hinojosa et al., 2014).

Concerning transport infrastructures, according to Zhao and Liu (2018), recycled asphalt pavement (RAP) has been widely used in the construction of transportation infrastructure. It was also presented that using recyclable materials in asphalt pavement is a fundamental design approach for limiting the construction industry's environmental impact and reducing the overall costs of road infrastructure (Moon and Falchetto, 2020; Hoy and Horpibulsuk, 2024).

Some articles also mentioned “Environmental”. Voit et al. (2020) concluded that by replacing energy- and CO_2-intensive cement types with slag-pozzolanic cement (CEM V) and using recycled aggregate, a significant contribution to environmental sustainability can be provided while still meeting the material requirements to achieve a service lifetime for the tunnel structure of up to 200 years. Some or all of the cement can be replaced using recycled materials or industrial by-products (Lăzărescu et al., 2022). Biswas et al. (2017) showed that using recycled steel and electricity generated from solar radiation for concrete materials and concrete production could further reduce the environmental impacts of the Qatari products. The use of recycled aggregate is essential for the environmental sustainability of the construction industry because it can not only reduce the need for waste landfills but can also reduce the depletion of natural aggregates (Shin and Kim, 2022; Wattanapanich et al., 2024). It can be used in road engineering, geotechnical engineering, and structural engineering (Sun et al., 2021). The production of lightweight aggregates from waste is regarded as an environmentally benign means of recycling waste into materials for green building construction (Chien et al., 2020). The lightweight properties of the foamed recycled glass coupled with its satisfactory engineering and environmental results, particularly its high friction angle, indicate that the material is ideal for usage as a lightweight construction material in engineering applications such as non-structural fills in embankments, retaining wall backfill and pipe bedding (Arulrajah et al., 2015).

In terms of material categories, 1) wood is recyclable and renewable, and using it in multistory apartment construction (WMC) has a climate-positive advantage with buildings acting as long-term carbon storage (Toppinen et al., 2022); replacing concrete and steel with wood is one potential strategy to decrease emissions (Myllyviita et al., 2022); 2) in addition to the mentioned literature about glass, recycled glass waste (or recycled waste glass, RWG) is one of the most attractive waste materials that can be used to create sustainable concrete compounds (Qaidi et al., 2022; Ahmed and Rana, 2023); waste glass powder (WGP) and recycled concrete powder (RCP) can replace Portland cement partially (Herki, 2024); recycled expanded glass aggregate (EGA) was innovatively used as a phase change materials (PCM) carrier to fabricate form-stable PCM composite (Yousefi et al., 2021); 3) as for the recycling of plastic waste (Ponomarev et al., 2022), it is considered one of the viable approaches to overcome the existing problems of solid waste and the requirement of raw materials for building constructions (Soni et al., 2022); Ki et al. (2021) presented the applications of waste plastic films (WPFs) in urban infrastructure and construction materials, especially bearing loads; in terms of processing and recycling, thermoplastics have advantages (Serra-Parareda et al., 2021); 4) concerning earthen materials, rammed earth (RE) is a low-tech recyclable building material with good heat storage and moisture absorption performance that can better maintain the stability of the indoor thermal environment and improve indoor comfort (Yu et al., 2022); formulated from various soil types and recycled mineral waste, Compacted Mineral Mixtures (CMMs) have the potential of being sustainable, resilient, and low-carbon (Bühler et al., 2023). In addition to the categories above, recycled waste carton pulp has the potential as a suitable reinforcement for the promotion of lightweight earthen wall block materials (Stanislas et al., 2021); Waste Facial Masks can also be recycled as a construction material (Idrees et al., 2022).

Other than materials, an MP (Material Passport) acts as a design optimization tool, as well as an inventory of all materials embedded in a building and displays the recycling potential and environmental impact of buildings; it is demonstrated in a residential building, whereby a variant in timber and a variant in concrete construction are evaluated (Honic et al., 2019a). In addition, Kuittinen (2016) calculated the carbon footprint using LCA for five different concrete structure alternatives and five different cement mixes for the same school buildings design. They conducted an LCA and optimization-based decision analysis of construction waste recycling for a LEED-certified university building. At the policy level, Tang et al. (2021b) illustrated the significant resource and environmental saving potential of prolonging the building lifetime and strengthening recycling practices, and highlighted the great need for effective policy intervention for waste management infrastructure planning in advance.

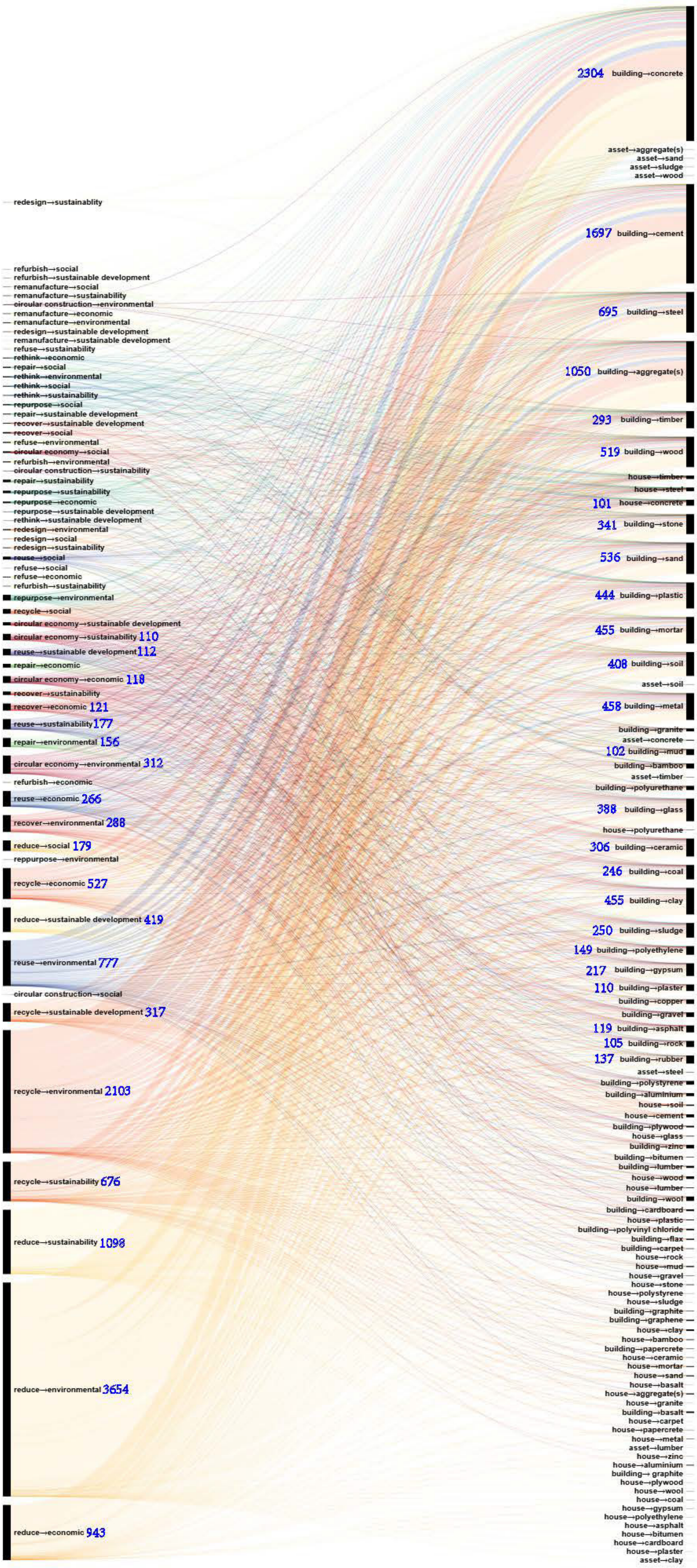
The main observation is “Recycle” can be related to diverse kinds of materials (e.g., (Wang et al., 2023)), often concerning experiments or tests. Recycled materials or materials containing recycled content tend to be applied in non-structural parts of assets or non-structurally. “Recycle” is inclined to contribute to the “Environmental” dimension of sustainability.

2.4.2.7 Other R Strategies

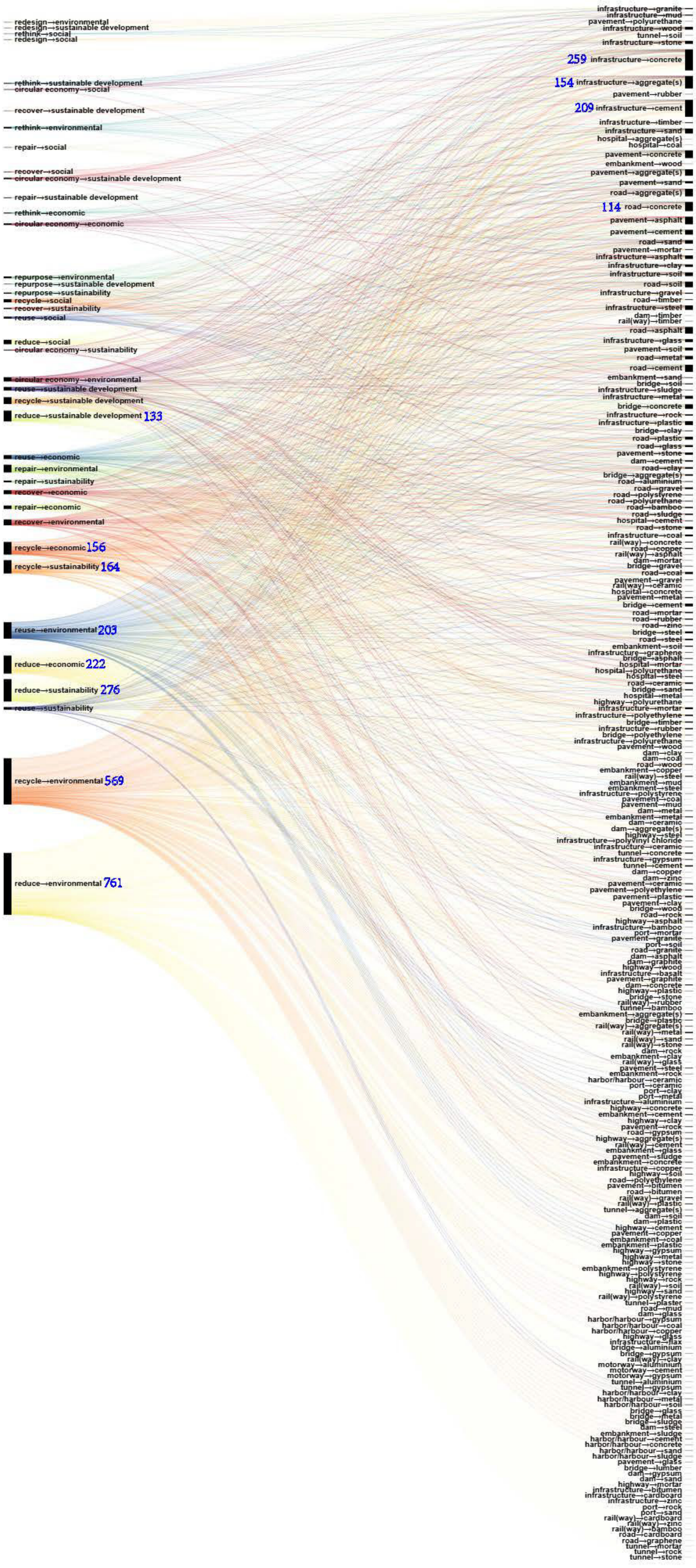
Although in the methodology section the situations of excluding certain articles are already described, the reasons for the absence of the other R strategies are elaborated. For “Recover”, as mentioned, the major reason is that most articles used it as a general CE strategy descriptor, which is different from the definition in Table 2.1b. The number of articles containing “Refuse”, “Rethink”, “Refurbish”, “Remanufacture”, “Repurpose”, and “Redesign” is not high. For “Refuse”, it was used as a noun (e.g. “the valorisation of refuse derived fuel” and "cement refuse"), or it is not relevantly used (i.e., "refusal of the local bamboo building tradition"); for "Rethink", the reason is not itself, but due to other elements of analysis (i.e., the "asset" element, which is "building" was used as a verb); for "Refurbish", the reason is the construction material term was not used as construction material (e.g. "electricity generated from coal"), or again "building" was used as a verb (e.g. "current building standards"); for "Remanufacture" and "Repurpose" (aside from (Aziz et al., 2024; Siciliano et al., 2023)), it is still because "building" was used as a verb (e.g., "the building and civil construction industries" and "building materials"); for "Redesign", the reason is also the material element is not relevant (e.g., "coal burning to provide heat").

2.4.3 Circular Economy (CE) strategies and Sustainability outcomes with relation to Material and Asset Contexts

This section comprehensively contains CE strategies, sustainability outcomes together with material and assets contexts. It presented Sankey charts of the article corpus used for the bibliometric analysis, with the building group (Fig. 2.5 (a)) and the infrastructure group (Fig. 2.5 (b)) separately. Similarly, Sankey charts of the article corpus of the in-depth review are shown in Fig. 2.6. Therefore, Fig. 2.5 and Fig. 2.6 can be compared easily.



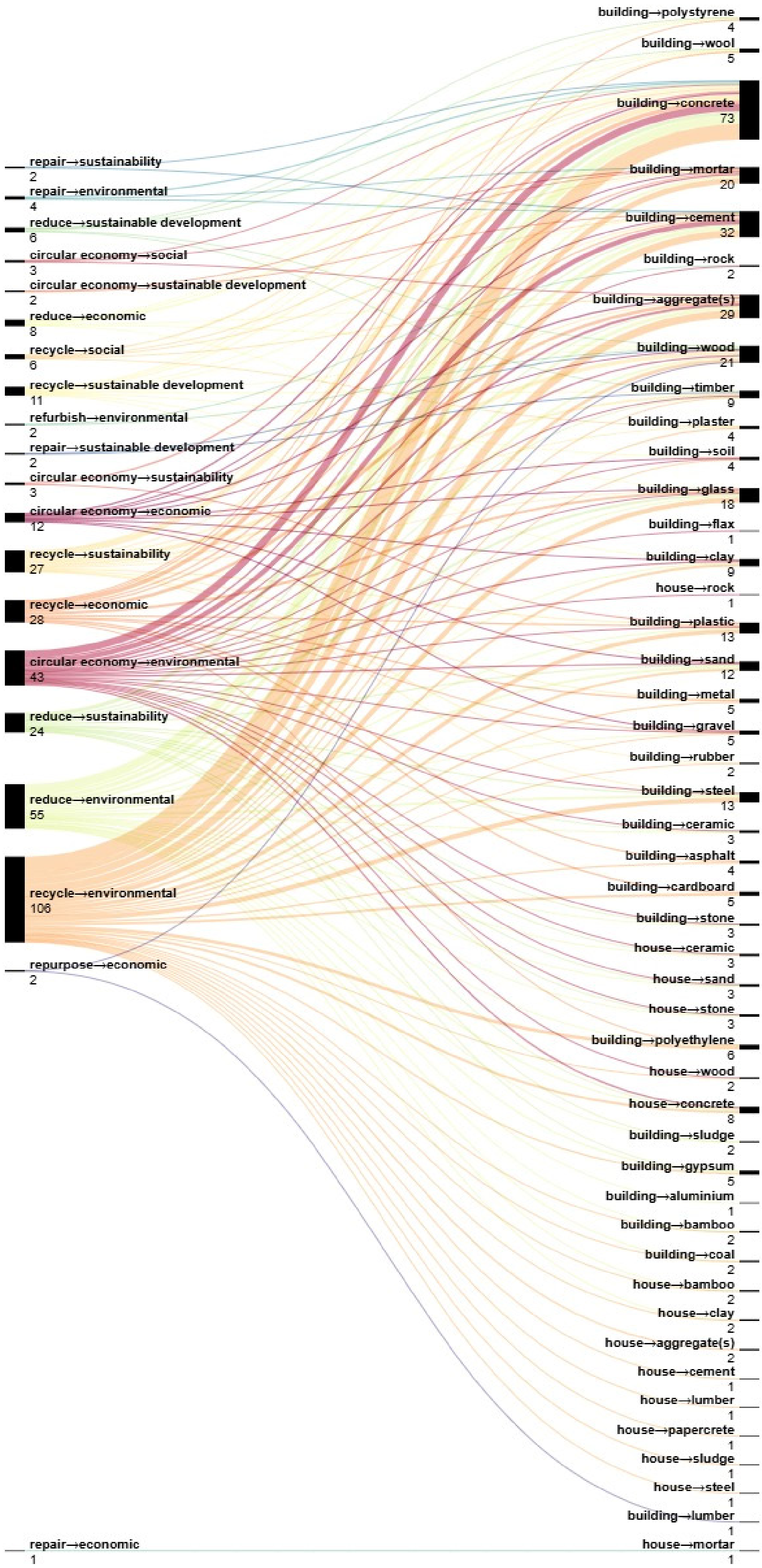
(a) the building group



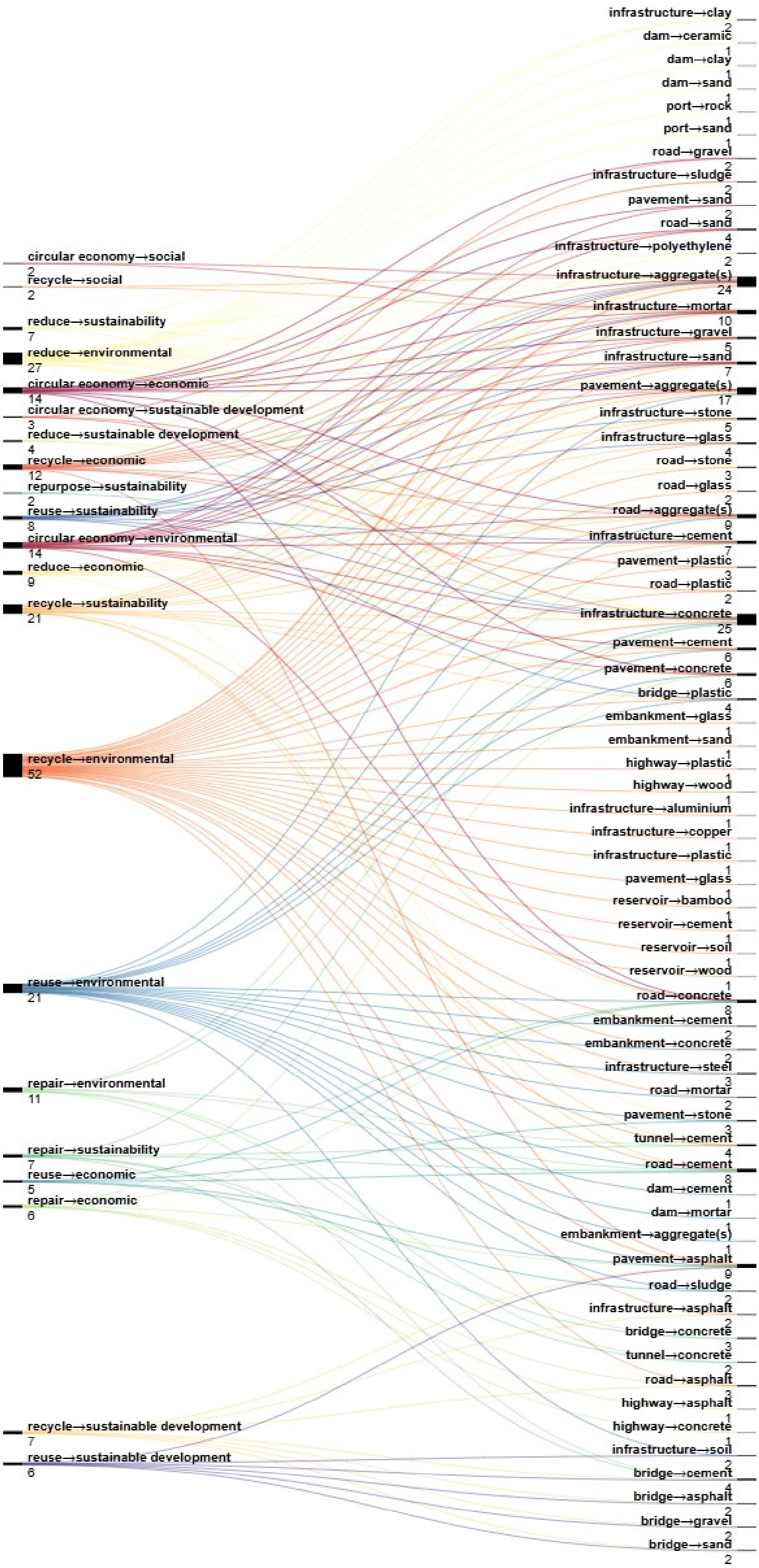
(b) the infrastructure group

Figure 2.5 The Sankey figure of Circular Economy (CE) strategies and sustainability outcomes with relations to material and asset contexts based on the literature used for the bibliometric analysis “reduc→environmental” is the most obvious for both Fig. 2.5 (a) and Fig. 2.5 (b). For the building group of Fig. 2.5, it can be noted that “Concrete” and “Cement” are strongly connected to “Building”, as they are the most dominantly used construction materials internationally. Unlike infrastructure, “Building” is a more homogeneous asset type, albeit for different functions, like offices, residential buildings, and so on. As for the infrastructure group, “Concrete” is dominantly linked to “Infrastructure”. In terms of assets, there is far less variety in the building group than in the infrastructure group, which may be explained by the heterogeneity of the latter group; as for example, bridges have a very different composition than railways.

Another observation worth noting about Fig. 2.5 is that, in terms of materials, the situation is the opposite, which shows that more kinds of materials are used for different buildings than for infrastructures. The materials in Fig. 2.5 (b) all appear in Fig. 2.5 (a).



(a) the building group



(b) the infrastructure group

Figure 2.6 The Sankey figure of Circular Economy (CE) strategies and sustainability outcomes with relations to material and asset contexts based on the reviewed literature (own figure)

For the building group of Fig. 2.6, it can be noted that "Concrete" and "Cement" are strongly connected to "Building", followed by "Aggregate(s)", "Wood", and "Mortar". Besides "Building", "House" is the other asset type. Different from Fig. 2.5 (a), "Recycle and Environmental" is the most mentioned in the left part of Fig. 2.6 (a). As for the infrastructure group, "Mortar" is a relatively obvious material after "Concrete" and "Aggregate", which is also different from Fig. 2.5 (b) (i.e., "Cement" is one of the dominant materials). In terms of assets, there is far more variety in the infrastructure group than the building group, which is the same with Fig. 2.5. "Recycle and Environmental" occupies the most significant part of Fig. 2.6 (b) as well. Still, for Fig. 2.5 (b), the biggest pair on the left side is "Reduce and Environmental".

2.5 Discussion

"CE", "Reduce", "Reuse", "Repair" and "Recycle" are used to structure the results of Section 2.4, as they are the most dominant CE terms in Fig. 2.6. Besides the results shown in Section 2.4, we also observed some other studies about experimental tests of newly developed materials. Since the definitions of the 11R strategies (Table 2.1) were adopted for the review process, many articles were excluded. One significant case is for "Reduce". There are articles about reducing carbon emissions (Buchanan and Levine, 1999), CO_2 emissions (Deventer et al., 2012; Woon et al., 2016), carbon footprint (Kinuthia and Oti, 2012), GHGs (Kidalova et al., 2012), environmental footprint (Zhang et al., 2014), global warming potential (Kua and Kamath, 2014), negative environmental impact (Pruteanu et al., 2016), environmental pollution (Jiao and Li, 2018), pollution (Zhang et al., 2018) and so on. Although the "Reduce" here does not have the same meaning as the "Reduce" given in Table 2.1, such articles also contribute to environmental sustainability. Energy reduction also draws attention. Considering the global environmental problems and SD, there is an urgent need to reduce energy consumption and GHG emissions in the construction sector (Baglivo and Congedo, 2015; Wu et al., 2012). One of the main strategies to minimize environmental impacts and energy consumption is maximizing recycling rates (Honic et al., 2019b). Much research has been devoted over the past 30 years to the development of construction materials that can lower the environmental and economic costs of buildings over their entire life by reducing embodied energy, minimizing air conditioning needs, and cutting down demolition waste (Gallipoli et al., 2017).

However, "Reduce" does not appear as frequently as "Recycle" and "Reuse" in the keywords analyzed by the author, probably because "Reduce" is a quite commonly used word, which cannot represent the main content of articles quite well. With the examples of "Reduce" and "Recover" as well as the comparison between Fig. 2.5 and Fig. 2.6, it is argued that although the bibliometric analysis serves a supportive role to the review (since the former covers a much bigger spectrum), the bigger coverage can also have some pieces of "cloud" above the deeper review part. Such "cloud" may mislead our understanding of literature. Besides "Recycle", "Reuse", and "Reduce" (as the most commonly used "3R"), "Repair", "Repurpose", and "Refurbish" can also be found in Fig. 2.6; while "Recover", "Remanufacture", "Redesign", "Rethink", and "Refuse" are missing, most of which are at the higher level of CE strategies (Morseletto, 2020). Compared to 3R, "Remanufacture", "Redesign", "Rethink", and "Refuse" are more about thinking change rather than technologies. It is suggested that higher-level strategies with huge CE potential should be given more attention in the future.

The building sector is strategically important for achieving sustainability (Traverso et al., 2010). From the front end, the appropriate selection of construction materials plays a major role in a building's sustainable profile (Ros-Dosdá et al., 2019). Sustainable design introduces nonpolluting materials and assemblies with lower energy requirements as well as higher durability and recyclability (Loftness et al., 2007). At the end of a building's life cycle, a major fraction of building materials is transformed into waste (Honic et al., 2019a). These are compatible with Fig. 2.1. Among many other adopted techniques, using recycled materials is one of the recommended methods to lower the environmental effects of construction materials (Gardezi et al., 2015; Itoh et al., 2000). One material often related to "Recycle" is concrete.

Concrete is the premier construction material used widely across the world in all types of engineering works, including infrastructures, low and high-rise buildings, and defence installations, while it has a long service life for buildings and transportation infrastructures (Desai and Limbachiya, 2006; Ashley and Lemay, 2008; Rahardjo, 2024; Wang et al., 2024; Soultanidis and Voudrias, 2023; Soonsawad et al., 2024). It plays a very important role as it gives strength to the structure of buildings (Yadav and Singh, 2018). However, as environmental awareness grows, societal demand for more environmentally friendly products increases (Cobut et al., 2016). Wood (including timber), being a natural, renewable material that sequesters carbon, is a natural fit for newer construction with enhanced sustainability goals (Milaj et al., 2017; Ren et al., 2024; Ottenhaus et al., 2023). It is the only renewable construction material and the only building material that has positive effects on the CO_2 balance (Licciardello et al., 2017). However, one of the weaknesses of timber systems is their limited sound insulation capacity, which may explain the reuse of wood materials is marginal at this point (Balmori et al., 2024; Størdal et al., 2024). Unlike most materials in Fig. 2.5, wood is not mineral-based and is therefore easier to obtain and process, which makes it fundamentally unique.

Besides "Recycle", the most efficient way for the construction industry to approach sustainability is to reuse waste materials and by-products from other industrial activities (Nidzam et al., 2016). Such waste materials and by-products include water treatment plant sludge and processed tea waste (Sahu et al., 2019). These are examples showing that implementing CE is not only just inside the construction sector but is interlinked with other sectors. "Reuse" is considered to be a material- and carbon-saving practice highly recommended in the construction sector as it can address both carbon emission and waste regulatory targets (Iacovidou and Purnell, 2016). Compared to "Recycle", generally, "Reuse" should be preferred if possible (which is consonant with the hierarchy in Table 2.1) because it keeps the value (such as the energy input for production) of certain components. Similarly, the R strategies at higher levels in Table 2.1 should be paid more attention to; as proposed, some may not need technological change, but a simple thought transition.

As for assets, the green building (Chatterjee, 2009; Jayasinghe et al., 2016; Luna-Cañas et al., 2014) affords a high level of environmental, economic, and engineering performance (Samer, 2013). Green buildings would respect nature and endeavor to mitigate harmful effects on the environment and occupants. This is often interpreted as creating sustainable sites, consuming less energy and water, reusing materials, and providing excellent indoor environmental quality (Kensek et al., 2016). Considering occupants actually embody social sustainability. Besides being a type of asset, "green building" can also be a construction strategy.

2.6 Conclusion

According to the review, there is an obvious imbalance for both the 11R strategies and TBL terms, i.e., "Reduce", "Reuse" and "Recycle" are studied more than the other R strategies; "Environmental" and "Economic" are studied more than "Social". "Reduce", "Reuse" and "Recycle" stand out because the 3R framework is the most prominent R framework; it is also at the core of the 2008 Circular Economy Promotion Law of the People's Republic of China (Kirchherr et al., 2017), although the latter is not the reason in our case. "Social" is not studied that much, probably because compared with "Environmental" and "Economic", the impacts related to it are more difficult to quantify.

In terms of building materials, the wood group (including wood, timber, lumber, plywood) in this paper is proposed to be valued. Additionally, from the asset perspective, buildings have a more significant proportion than infrastructures in Fig. 2.6. The other parts of the review also support such an observation. Essentially, the differences of buildings mainly lie in different functions (i.e., xxx building), while infrastructures have more diverse sub-categories. According to Gijzel et al. (2020), for a long time, the focus on sustainable construction has been on buildings and there was far less attention to infrastructures. At the container term level, sustainability attracts more academic attention than CE in the relevant literature. There is already much literature about sustainability, CE, and construction (building) materials or assets, which is still booming.

Although the analyses were conducted based on the titles, abstracts, and author keywords of the literature, this article offers a way to extract relevant literature by linking CE and sustainability with construction materials and assets, contributing to the academic debate concerning the relationship between CE and sustainability in asset and material contexts. The threads based on the reviewed studies in the Results section can be referred to by both scholars and practitioners.

Since the screening criteria for the review are quite strict, a larger-scale bibliometric analysis is also conducted to offer more information. The bibliometric analysis can support part of the observation from the review. However, we also propose that the bigger scale landscape brought by bibliometrics can sometimes be misleading if the results are not scrutinized carefully. Examples are "Recover", "Reduce" and "Building" in this study. Both the bibliometric analysis and small-scale review have their constraints, but combining them can offer a better understanding of the current literature. Finally, further research is suggested to focus more on the social aspect of sustainability in the construction sector and CE in infrastructures.

References for Chapter 2

Abdellatief, M., Abd, M., Hani, E., Aref, A., Ahmed, A.A., 2023. A state-of-the-art review on geopolymer foam concrete with solid waste materials: components, characteristics, and microstructure. Innov. Infrastruct. Solut. 8, 1–26. https://doi.org/10.1007/s41062-023-01202-w

Abouhamad, M., Abu-Hamd, M., 2021. Life cycle assessment framework for embodied environmental impacts of building construction systems. Sustainability (Switzerland) 13, 1–21. https://doi.org/10.3390/su13020461

Ahmed, K.S., Rana, L.R., 2023. Fresh and hardened properties of concrete containing recycled waste glass: A review. J. Build. Eng. 70, 106327. https://doi.org/10.1016/j.jobe.2023.106327

Alqahtani, F.K., Abotaleb, I.S., ElMenshawy, M., 2021. Life cycle cost analysis of lightweight green concrete utilizing recycled plastic aggregates. Journal of Building Engineering 40. https://doi.org/10.1016/j.jobe.2021.102670

Arulrajah, A., Disfani, M.M., Maghoolpilehrood, F., 2015. Engineering and environmental properties of foamed recycled glass as a lightweight engineering material. J Clean Prod 94, 369–375. https://doi.org/10.1016/j.jclepro.2015.01.080

Arulrajah, A., Yaghoubi, E., Choy, Y., Horpibulsuk, S., 2017a. Recycled plastic granules and demolition wastes as construction materials: Resilient moduli and strength characteristics. Constr Build Mater 147, 639–647. https://doi.org/10.1016/j.conbuildmat.2017.04.178

Arulrajah, A., Yaghoubi, E., Imteaz, M., Horpibulsuk, S., 2017b. Recycled waste foundry sand as a sustainable subgrade fill and pipe-bedding construction material: Engineering and environmental evaluation. Sustain Cities Soc 28, 343–349. https://doi.org/10.1016/j.scs.2016.10.009

Aziz, T., Aziz, H., Mahapakulchai, S., Charoenlarpnopparut, C., 2024. Optimizing compressive strength prediction using adversarial learning and hybrid regularization. Sci. Rep. 14, 1–14. https://doi.org/10.1038/s41598-024-69434-z

Bai, Y., Arulrajah, A., Horpibulsuk, S., Zhou, A., 2024. Geopolymer stabilization of carbon-negative gasified olive stone biochar as a subgrade construction material. Constr. Build. Mater. 442, 137617. https://doi.org/10.1016/j.conbuildmat.2024.137617

Bajno, D., Grzybowska, A., Bednarz, Ł., 2021. Old and modern wooden buildings in the context of sustainable development. Energies (Basel) 14. https://doi.org/10.3390/en14185975

Bakar, M.S.A., Gunasilan Manar, A.S., Rahman, M.R.A., Saad, M.R., Najeeb, M.I., Alhayek, A., Asyraf, M.R.M., 2024. An Overview of Fly-ash Geopolymer Composites in Sustainable Advance Construction Materials. Pertanika J. Sci. Technol. 32, 75–102.

Balaman, Sebnem Yilmaz, 2019. Sustainability Issues in Biomass-Based Production Chains, in: Balaman, S.Y. (Ed.), Decision-Making for Biomass-Based Production Chains. Academic Press, Cambridge, MA, p. 86.

Balmori, J., Casado-sanz, M., Quir, S., 2024. The Use of Waste Tyre Rubber Recycled Products in Lightweight Timber Frame Systems as Acoustic Insulation: A Comparative. Buildings 14, 35.

Bieliatynskyi, A., Yang, S., Pershakov, V., Shao, M., Ta, M., 2022. Investigation of the properties of cast asphalt concrete mixture with the addition of fiber from the fly ash of thermal

power plants. Materials Science-Poland 40, 125–146. https://doi.org/10.2478/msp-2022-0042
Biswas, W.K., Alhorr, Y., Lawania, K.K., Sarker, P.K., Elsarrag, E., 2017. Life cycle assessment for environmental product declaration of concrete in the Gulf States. Sustain Cities Soc 35, 36–46. https://doi.org/10.1016/j.scs.2017.07.011
Briones-Llorente, R., Barbosa, R., Almeida, M., García, E.A.M., Saiz, Á.R., 2020. Ecological design of new efficient energy-performance construction materials with rigid polyurethane foam waste. Polymers (Basel) 12, 1–25. https://doi.org/10.3390/POLYM12051048
Bulatbekova, D., Vashistha, P., Kim, H., Pyo, S., 2024. Effects of basic-oxygen furnace, electric-arc furnace, and ladle furnace slags on the hydration and durability properties of construction materials: A review. J. Build. Eng. 92, 109670. https://doi.org/10.1016/j.jobe.2024.109670
Bühler, M.M., Hollenbach, P., Michalski, A., Meyer, S., Birle, E., Off, R., Lang, C., Schmidt, W., Cudmani, R., Fritz, O., Baltes, G., Kortmann, G., 2023. The Industrialisation of Sustainable Construction: A Transdisciplinary Approach to the Large-Scale Introduction of Compacted Mineral Mixtures (CMMs) into Building Construction. Sustainability 15, 10677.
Caponetto, R., Cuomo, M., Detommaso, M., Giuffrida, G., Presti, A. Lo, Nocera, F., 2023. Performance Assessment of Giant Reed-Based Building Components. Sustain. 15, 2114. https://doi.org/10.3390/su15032114
Cechin, L., Mymrine, V., Avanci, M.A., Povaluk, A.E., 2022. Ceramics composites from iron ore tailings and blast furnace slag. Ceram Int 48, 10506–10515. https://doi.org/10.1016/j.ceramint.2021.12.260
Chan, A.P.C., Fan, L.C.N., Yu, A.T.W., 1999. Construction process reengineering: a case study. Logistics Information Management 12, 467–476. https://doi.org/10.1108/09576059910299045
Chen, Q., Feng, H., Garcia, B., Soto, D., 2022. Revamping construction supply chain processes with circular economy strategies: A systematic literature review. J. Clean. Prod. 335, 130240. https://doi.org/10.1016/j.jclepro.2021.130240
Chien, C.Y., Show, K.Y., Huang, C., Chang, Y.J., Lee, D.J., 2020. Effects of sodium salt additive to produce ultra lightweight aggregates from industrial sludge-marine clay mix: Laboratory trials. J Taiwan Inst Chem Eng 111, 105–109. https://doi.org/10.1016/j.jtice.2020.04.018
Cuéllar-Franca, R.M., Azapagic, A., 2012. Environmental impacts of the UK residential sector: Life cycle assessment of houses. Build Environ 54, 86–99. https://doi.org/10.1016/j.buildenv.2012.02.005
Czarnecki, S., Rudner, M., 2023. Recycling of Materials from Renovation and Demolition of Building Structures in the Spirit of Sustainable Material Engineering. Buildings 13, 1842.
Dang, L.C., Khabbaz, H., Ni, B.J., 2021. Improving engineering characteristics of expansive soils using industry waste as a sustainable application for reuse of bagasse ash. Transportation Geotechnics 31. https://doi.org/10.1016/j.trgeo.2021.100637
del Río-Merino, M., Vidales-Barriguete, A., Piña-Ramírez, C., Vitiello, V., Santa Cruz-Astorqui, J., Castelluccio, R., 2022. A review of the research about gypsum mortars with waste aggregates. Journal of Building Engineering. https://doi.org/10.1016/j.jobe.2021.103338

del Valle-Zermeño, R., Formosa, J., Chimenos, J.M., Martínez, M., Fernández, A.I., 2013. Aggregate material formulated with MSWI bottom ash and APC fly ash for use as secondary building material. Waste Management 33, 621–627. https://doi.org/10.1016/j.wasman.2012.09.015

Dorsey, B., 2022. Building a Foundation of Pragmatic Architectural Theory to Support More Sustainable or Regenerative Straw Bale Building and Code Adoption. Journal of Sustainability Research 4. https://doi.org/10.20900/jsr20220003

Eberhardt, L.C.M., Birgisdóttir, H., Birkved, M., 2019. Life cycle assessment of a Danish office building designed for disassembly. Building Research and Information 47, 666–680. https://doi.org/10.1080/09613218.2018.1517458

Edun, A., Hachem-Vermette, C., 2022. Post-consumer waste recycling for high performance building envelopes in cold climates: Assessing energy and environmental impacts. J Clean Prod 372. https://doi.org/10.1016/j.jclepro.2022.133686

Edun, A., Hachem-Vermette, C., 2021. Energy and environmental impact of recycled end of life tires applied in building envelopes. Journal of Building Engineering 39. https://doi.org/10.1016/j.jobe.2021.102242

Fedorik, F., Zach, J., Lehto, M., Kymäläinen, H.R., Kuisma, R., Jallinoja, M., Illikainen, K., Alitalo, S., 2021. Hygrothermal properties of advanced bio-based insulation materials. Energy Build 253. https://doi.org/10.1016/j.enbuild.2021.111528

Gallo, M., Moreschi, L., Del Borghi, A., 2022. A CRITICAL ENVIRONMENTAL ANALYSIS OF STRATEGIC MATERIALS TOWARDS ENERGY TRANSITION. Detritus 20, 3–12. https://doi.org/10.31025/2611-4135/2022.15223

Gebremedhin, M.D., Eryürük, K., 2024. Novel Strategies for Concrete Restoration: a Deep Dive into Microbially Induced Calcite Precipitation Technology. Iran. J. Sci. Technol. Trans. Civ. Eng. 49, 2123–2138. https://doi.org/10.1007/s40996-024-01587-3

Gijzel, D., Bosch-Rekveldt, M., Schraven, D., Hertogh, M., 2020. Integrating sustainability into major infrastructure projects: Four perspectives on sustainable tunnel development. Sustainability (Switzerland) 12, 1–18. https://doi.org/10.3390/SU12010006

Guan, X., Wang, L., Mo, L., 2023. Effects of ground coal bottom ash on the properties of cement- based materials under various curing temperatures. J. Build. Eng. 69, 106196. https://doi.org/10.1016/j.jobe.2023.106196

Hadj Sadok, R., Belas Belaribi, N., Mazouzi, R., Hadj Sadok, F., 2022. Life cycle assessment of cementitious materials based on calcined sediments from Chorfa II dam for low carbon binders as sustainable building materials. Science of the Total Environment 826. https://doi.org/10.1016/j.scitotenv.2022.154077

Hammond, G.P., Jones, C.I., 2008. Embodied energy and carbon in construction materials. Proc. Inst. Civ. Eng. - Energy 161, 87–98. https://doi.org/10.1680/ener.2008.161.2.87

Hawkins, W., Cooper, S., Allen, S., Roynon, J., Ibell, T., 2021. Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure. Structures 33, 90–98. https://doi.org/10.1016/j.istruc.2020.12.013

Heeren, N., Hellweg, S., 2019. Tracking Construction Material over Space and Time: Prospective and Geo-referenced Modeling of Building Stocks and Construction Material Flows. J Ind Ecol 23, 253–267. https://doi.org/10.1111/jiec.12739

Herki, B.M.A., 2024. Strength and Absorption Study on Eco-Efficient Concrete Using Recycled

Powders as Mineral Admixtures under Various. Recycling 9, 99.

Hinojosa, M.J.R., Galvín, A.P., Agrela, F., Perianes, M., Barbudo, A., 2014. Potential use of biomass bottom ash as alternative construction material: Conflictive chemical parameters according to technical regulations. Fuel 128, 248–259. https://doi.org/10.1016/j.fuel.2014.03.017

Honic, M., Kovacic, I., Rechberger, H., 2019. Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study. J Clean Prod 217, 787–797. https://doi.org/10.1016/j.jclepro.2019.01.212

Hoy, M., Horpibulsuk, S., 2024. Innovations in recycled construction materials: paving the way towards sustainable road infrastructure. Front. Built Environ. 1–10. https://doi.org/10.3389/fbuil.2024.1449970

Huang, S.L., Hsu, W.L., 2003. Materials flow analysis and emergy evaluation of Taipei's urban construction. Landsc Urban Plan 63, 61–74. https://doi.org/10.1016/S0169-2046(02)00152-4

Idrees, M., Akbar, A., Mohamed, A.M., Fathi, D., Saeed, F., 2022. Recycling of Waste Facial Masks as a Construction Material, a Step towards Sustainability. Materials 15. https://doi.org/10.3390/ma15051810

Illankoon, C., Vithanage, S.C., 2023. Closing the loop in the construction industry: A systematic literature review on the development of circular economy. J. Build. Eng. 76, 107362. https://doi.org/10.1016/j.jobe.2023.107362

Jawahir, I.S., Bradley, R., 2016. Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing. Procedia CIRP 40, 103–108. https://doi.org/10.1016/j.procir.2016.01.067

Jochem, D., Janzen, N., Weimar, H., 2016. Estimation of own and cross price elasticities of demand for wood-based products and associated substitutes in the German construction sector. J Clean Prod 137, 1216–1227. https://doi.org/10.1016/j.jclepro.2016.07.165

Kaushal, V., 2024. Sustainable and Innovative Self-Healing Concrete Technologies to Mitigate Environmental Impacts in Construction. CivilEng 5, 549–558.

Ki, D., Kang, S.Y., Ma, G., Oh, H.J., 2021. Application of Waste Plastic Films in Road Infrastructure and Construction. Frontiers in Sustainability 2. https://doi.org/10.3389/frsus.2021.756723

Kucukdogan, N., Sutcu, M., Ozturk, S., Yaprak, H., Memis, S., 2024. Energy & Buildings Phase change material incorporated paper pulp sludge/gypsum composite reinforced by slag and fly ash for energy efficient buildings: Solar thermal regulation, embody energy, sustainability index and cost analysis. Energy Build. 325, 114969. https://doi.org/10.1016/j.enbuild.2024.114969

Kuittinen, M., 2016. Does the use of recycled concrete lower the carbon footprint in humanitarian construction? Int J Disaster Resil Built Environ 7, 472–488.

Kumanayake, R.P., Luo, H., 2018. Cradle-to-gate life cycle assessment of energy and carbon of a residential building in Sri Lanka. J Natl Sci Found 46, 355–367. https://doi.org/10.4038/jnsfsr.v46i3.8487

Kumar, V., Verma, D.K., 2024. e-Waste in construction: a comprehensive bibliometric analysis and review of the literature. World J. Eng. https://doi.org/https://doi.org/10.1108/WJE-

12-2023-0504
Lăzărescu, A.-V., Ionescu, B.A., Hegyi, A., Florean, C., 2022. ALKALI-ACTIVATED FLY ASH BASED GEOPOLYMER PAVING BLOCKS: GREEN MATERIALS FOR FUTURE CONSERVATION OF RESOURCES.
Lenard, J.G., 2014. Material Attributes, in: Primer on Flat Rolling. Elsevier, pp. 163–191. https://doi.org/10.1016/B978-0-08-099418-5.00008-1
Li, X.J., Lai, J. yu, Ma, C. yun, Wang, C., 2021. Using BIM to research carbon footprint during the materialization phase of prefabricated concrete buildings: A China study. J Clean Prod 279. https://doi.org/10.1016/j.jclepro.2020.123454
Lo, C., 2017. Environmental benefits of renewable building materials: A case study in Taiwan. Energy Build 140, 236–244. https://doi.org/10.1016/j.enbuild.2017.02.010
Lung, H.H., Ran, H., Chuan, H.L., Ting, L.W., Mi, H.H., 2018. Waste-based pervious concrete for climate-resilient pavements. Materials 11, 1–17. https://doi.org/10.3390/ma11060900
Majumder, A., Canale, L., Mastino, C.C., Pacitto, A., Frattolillo, A., Dell'isola, M., 2021. Thermal characterization of recycled materials for building insulation. Energies (Basel) 14. https://doi.org/10.3390/en14123564
Maria, A. Di, Levasseur, A., Van Acker, K., 2021. Assessing the long term effects on climate change of metallurgical slags valorization as construction material: a comparison between static and dynamic global warming impacts. Mathematical Biosciences and Engineering 1, 88–111. https://doi.org/10.3934/ctr.2021005
Maury-Ramírez, A., Illera-Perozo, D., Mesa, J.A., 2022. Circular Economy in the Construction Sector: A Case Study of Santiago de Cali (Colombia). Sustainability (Switzerland) 14. https://doi.org/10.3390/su14031923
Messahel, B., Onyenokporo, N., Takyie, E., Beizaee, A., Oyinlola, M., 2023. Upcycling agricultural and plastic waste for sustainable construction: a review. Environ. Technol. Rev. 12, 37–59. https://doi.org/10.1080/21622515.2023.2169642
Miller, S.A., Habert, G., Myers, R.J., Harvey, J.T., 2021. Achieving net zero greenhouse gas emissions in the cement industry via value chain mitigation strategies. One Earth. https://doi.org/10.1016/j.oneear.2021.09.011
Mindermann, P., Pérez, M.G., Knippers, J., Gresser, G.T., 2022. Investigation of the Fabrication Suitability, Structural Performance, and Sustainability of Natural Fibers in Coreless Filament Winding. Materials 15. https://doi.org/10.3390/ma15093260
Moon, K.H., Falchetto, A.C., 2020. Double-recycled reclaimed asphalt pavement: A laboratory investigation at low temperatures based on different mathematical approaches. Materials 13. https://doi.org/10.3390/ma13133032
Morel, J.C., Charef, R., Hamard, E., Fabbri, A., Beckett, C., Bui, Q.B., 2021. Earth as construction material in the circular economy context: Practitioner perspectives on barriers to overcome. Philosophical Transactions of the Royal Society B: Biological Sciences. https://doi.org/10.1098/rstb.2020.0182
Musyoki, D.M., Muthengia, J.W., Ogunah, J., Mutitu, D.K., Kinuthia, J., Mwirichia, R., Thiong'o, J.K., Mulwa, M.O., Genson, M., 2022. Effect of Immobilizing Bacillus megaterium on the Compressive Strength and Water Absorption of Mortar. J Chem 2022. https://doi.org/10.1155/2022/7752812

Mydin, A.O., Khalid, M.S., Omar, R., Mohammed, H., Mahmood, S., Qaidi, A., Awoyera, P.O., 2023. Durability Properties of Lightweight Foamed Concrete Reinforced With'Musa Acuminate'Fibre. J. Adv. Res. Appl. Sci. Eng. Technol. 29, 145–158.

Myllyviita, T., Hurmekoski, E., Kunttu, J., 2022. Substitution impacts of Nordic wood-based multi-story building types: influence of the decarbonization of the energy sector and increased recycling of construction materials. Carbon Balance Manag 17. https://doi.org/10.1186/s13021-022-00205-x

Nußholz, J.L.K., Nygaard Rasmussen, F., Milios, L., 2019. Circular building materials: Carbon saving potential and the role of business model innovation and public policy. Resour Conserv Recycl 141, 308–316. https://doi.org/10.1016/j.resconrec.2018.10.036

Nur, M.M.A., Dewi, R.N., 2024. Biocatalysis and Agricultural Biotechnology Opportunities and challenges of microalgae in biocement production and self-repair mechanisms. Biocatal. Agric. Biotechnol. 56, 103048. https://doi.org/10.1016/j.bcab.2024.103048

Ossio, F., Salinas, C., Hernández, H., 2023. Circular economy in the built environment: A systematic literature review and definition of the circular construction concept. J. Clean. Prod. 414. https://doi.org/10.1016/j.jclepro.2023.137738

Ottenhaus, L.M., Yan, Z., Brandner, R., Leardini, P., Fink, G., Jockwer, R., 2023. Design for adaptability, disassembly and reuse – A review of reversible timber connection systems. Constr. Build. Mater. 400, 132823. https://doi.org/10.1016/j.conbuildmat.2023.132823

Paikara, R.K., Gyawali, T.R., 2023. Influence of aluminum powder content and powder-to-sand ratio on the physical and mechanical properties of aerated lightweight mortar. Clean. Mater. 10, 100213. https://doi.org/10.1016/j.clema.2023.100213

Pineda, P., García-Martínez, A., Castizo-Morales, D., 2017. Environmental and structural analysis of cement-based vs. natural material-based grouting mortars. Results from the assessment of strengthening works. Constr Build Mater 138, 528–547. https://doi.org/10.1016/j.conbuildmat.2017.02.013

Ponomarev, A. V., Gohs, U., T Ratnam, C., Horak, C., 2022. Keystone and stumbling blocks in the use of ionizing radiation for recycling plastics. Radiation Physics and Chemistry 201. https://doi.org/10.1016/j.radphyschem.2022.110397

Pomponi, F., Moncaster, A., 2017. Circular economy for the built environment: A research framework. J Clean Prod 143, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Pradeep Kumar, P., Santos, D.A., Braham, E.J., Sellers, D.G., Banerjee, S., Dixit, M.K., 2021. Punching above its weight: Life cycle energy accounting and environmental assessment of vanadium microalloying in reinforcement bar steel. Environ Sci Process Impacts 23, 275–290. https://doi.org/10.1039/d0em00424c

Pradhan, S.K., Sahoo, U.C., 2022. Use of Mahua oil for rejuvenation of the aged binder through laboratory investigations. International Journal of Transportation Science and Technology 11, 32–45. https://doi.org/10.1016/j.ijtst.2020.11.002

Przybek, A., Łach, M., 2024. Research on the Physical Properties of an Eco-Friendly Layered Geopolymer Composite. Materials (Basel). 17, 4937. https://doi.org/10.3390/ma17194937

Puskás, A., Corbu, O., Szilágyi, H., Moga, L.M., 2014. Construction waste disposal practices: The recycling and recovery of waste. WIT Transactions on Ecology and the Environment 191, 1313–1321. https://doi.org/10.2495/SC141102

Qaidi, S., Najm, H.M., Abed, S.M., Özkılıç, Y.O., Al Dughaishi, H., Alosta, M., Sabri, M.M.S., Alkhatib, F., Milad, A., 2022. Concrete Containing Waste Glass as an Environmentally Friendly Aggregate: A Review on Fresh and Mechanical Characteristics. Materials. https://doi.org/10.3390/ma15186222

Rahardjo, A., 2024. Suitability of Foamed Concrete for the Composite Floor System in Mid-to-High-Rise Modular Buildings: Design, Structural, and Sustainability Perspectives. Sustainability 16, 1624.

Reddy, N.G., Vidya, A., Sri Mullapudi, R., 2022. Review of the Utilization of Plastic Wastes as a Resource Material in Civil Engineering Infrastructure Applications. J Hazard Toxic Radioact Waste 26. https://doi.org/10.1061/(asce)hz.2153-5515.0000717

Ren, H., Bahrami, A., Cehlin, M., Wallhagen, M., 2024. Flexural Behavior of Cross-Laminated Timber Panels with Environmentally Friendly Timber Edge Connections. Buildings 14, 1455.

Rocha, J.H.A., de Siqueira, A.A., de Oliveira, M.A.B., Castro, L. da S., Caldas, L.R., Monteiro, N.B.R., Toledo Filho, R.D., 2022. Circular Bioeconomy in the Amazon Rainforest: Evaluation of Açaí Seed Ash as a Regional Solution for Partial Cement Replacement. Sustainability (Switzerland) 14. https://doi.org/10.3390/su142114436

Rudziewicz, M., Maroszek, M., Góra, M., Dziura, P., Mróz, K., Hager, I., Hebda, M., 2023. Feasibility Review of Aerated Materials Application in 3D Concrete Printing. Materials (Basel). 16, 6032.

Salama, W., 2017. Design of concrete buildings for disassembly: An explorative review. International Journal of Sustainable Built Environment 6, 617–635. https://doi.org/10.1016/j.ijsbe.2017.03.005

Serra-Parareda, F., Alba, J., Tarrés, Q., Espinach, F.X., Mutjé, P., Delgado-Aguilar, M., 2021. Characterization of $CaCO_3$ filled poly(Lactic) acid and bio polyethylene materials for building applications. Polymers (Basel) 13. https://doi.org/10.3390/polym13193323

Shah, S.A.R., Ahmad, H., Alhazmi, H., Anwar, M.K., Iqbal, F., 2021. Utilization of self-consolidated green material for sustainable development: An environment friendly waste materials application for circular economy. Polymers (Basel) 13. https://doi.org/10.3390/polym13172985

Sheshadri, A., Marathe, S., Bettadapura Manjunath, M., Jayasimhan, A., Sadowski, Ł., 2024. Effective Utilization of Foundry Waste as Aggregates in Developing Eco-Friendly Alkali-Activated and Conventional Concretes for Sustainable Pavement Infrastructure. Pract. Period. Struct. Des. Constr. 29. https://doi.org/10.1061/ppscfx.sceng-1501

Shin, B., Kim, S., 2022. CO_2 emission and construction cost reduction effect in cases of recycled aggregate utilized for nonstructural building materials in South Korea. J Clean Prod 360. https://doi.org/10.1016/j.jclepro.2022.131962

Siciliano, A.P., Zhao, X., Fedderwitz, R., Ramakrishnan, K., Dai, J., Gong, A., Zhu, J.Y., Ko, J., Hu, L., 2023. Sustainable Wood-Waste-Based Thermal Insulation Foam for Building Energy Efficiency. Buildings 13, 840.

Soni, A., Das, P.K., Sarma, M.J., 2022. Application of MOORA Method for Parametric Optimization of Manufacturing Process of Floor Tiles Using Waste Plastics. Process Integration and Optimization for Sustainability 6, 113–123. https://doi.org/10.1007/s41660-021-00205-3

Soonsawad, N., Marcos-Martinez, R., Schandl, H., 2024. City-scale assessment of the material and environmental footprint of buildings using an advanced building information model: A case study from Canberra, Australia. J. Ind. Ecol. 28, 247–261. https://doi.org/10.1111/jiec.13456

Soultanidis, V., Voudrias, E.A., 2023. Modelling of demolition waste generation: Application to Greek residential buildings. Waste Manag. Res. 41, 1469–1479. https://doi.org/10.1177/0734242X231155818

Srinivas, P., Kumar, K.S., 2009. Utilization of incinerated municipal solid waste ash in the manufacture of cement hollow bricks. Nature Environment and Pollution Technology 8, 329–334.

Stanislas, T.T., Tendo, J.F., Teixeira, R.S., Ojo, E.B., Komadja, G.C., Kadivar, M., Junior, H.S., 2021. Effect of cellulose pulp fibres on the physical, mechanical, and thermal performance of extruded earth-based materials. Journal of Building Engineering 39. https://doi.org/10.1016/j.jobe.2021.102259

Størdal, S., Gangsø, M.R., Lien, G., Sjølie, H.K., 2024. Drivers of housing developers' perception on future construction reuse material premium for wood. J. Clean. Prod. 476, 143642. https://doi.org/10.1016/j.jclepro.2024.143642

Suarez-riera, D., Restuccia, L., Falliano, D., Ferro, G.A., Tuliani, J., Pavese, M., Lavagna, L., 2024. An Overview of Methods to Enhance the Environmental Performance of Cement-Based Materials. Infrastructures 9, 94.

Sun, J., Chen, J., Liao, X., Tian, A., Hao, J., Wang, Y., Tang, Q., 2021. The workability and crack resistance of natural and recycled aggregate mortar based on expansion agent through an environmental study. Sustainability (Switzerland) 13, 1–12. https://doi.org/10.3390/su13020491

Tang, S., Zhang, L., Hao, Y., Chang, Y., Liu, G., Liu, Q., Li, X., 2021. System dynamics modeling for construction material flows of urban residential building: A case study of Beijing, China. Resour Conserv Recycl 168. https://doi.org/10.1016/j.resconrec.2020.105298

Tang, Y., Feng, W., Chen, Z., Nong, Y., Guan, S., Sun, J., 2021. Fracture behavior of a sustainable material: Recycled concrete with waste crumb rubber subjected to elevated temperatures. J Clean Prod 318. https://doi.org/10.1016/j.jclepro.2021.128553

Tijani, M.A., Ajagbe, W.O., Agbede, O.A., 2022. Recycling sorghum husk and palm kernel shell wastes for pervious concrete production. J Clean Prod 380. https://doi.org/10.1016/j.jclepro.2022.134976

Toppinen, A., Aaltio, A., Lähtinen, K., Jussila, J., Toivonen, R., 2022. "It all depends on the project"—A business ecosystem in residential wooden multistory construction in Finland. Front Built Environ 8. https://doi.org/10.3389/fbuil.2022.1046954

van der Spek, B.J., Bijl, E., van de Sande, B., Poortman, S., Heijboer, D., Bliek, B., 2020. Sandbar breakwater: An innovative nature-based port solution. Water (Switzerland) 12. https://doi.org/10.3390/w12051446

Villagrán-Zaccardi, Y.A., Marsh, A.T.M., Sosa, M.E., Zega, C.J., De Belie, N., Bernal, S.A., 2022. Complete re-utilization of waste concretes–Valorisation pathways and research needs. Resour Conserv Recycl. https://doi.org/10.1016/j.resconrec.2021.105955

Voit, K., Zeman, O., Janotka, I., Adamcova, R., Bergmeister, K., 2020. High-durability concrete using eco-friendly slag-pozzolanic cements and recycled aggregate. Applied Sciences

(Switzerland) 10, 1–21. https://doi.org/10.3390/app10228307
Wang, L., Zhang, R., Liu, Z., Shirakawa, H., Tanikawa, H., 2024. From expansion to efficiency: Machine learning-based forecasting of Japan's building material stocks under demographic declines. Sci. Total Environ. 951, 175634. https://doi.org/10.1016/j.scitotenv.2024.175634
Wang, X.Q., Chen, P., Chow, C.L., Lau, D., 2023. Review Artificial-intelligence-led revolution of construction materials: From molecules to Industry 4.0. Matter 6, 1831–1859. https://doi.org/10.1016/j.matt.2023.04.016
Watson, D.E., Johnson, A., Sharma, H.R., 1998. Georgia's experience with recycled roofing shingles in asphaltic concrete. Transportation Research Record: Journal of the Transportation Research Board 1638, 129–133.
Wattanapanich, C., Imjai, T., Sridhar, R., Garcia, R., Thomas, B.S., 2024. Optimizing Recycled Aggregate Concrete for Severe Conditions Through Machine Learning Techniques: A Review. Eng. Sci. 31, 1191.
Wiedenhofer, D., Streeck, J., Wieland, H., Grammer, B., Baumgart, A., Plank, B., Helbig, C., Pauliuk, S., Haberl, H., Krausmann, F., 2024. From extraction to end-uses and waste management: Modeling economy-wide material cycles and stock dynamics around the world. J. Ind. Ecol. 28, 1464–1480. https://doi.org/10.1111/jiec.13575
Wilson, J., 1997. Cannibals with forks: The triple bottom line of 21st-century business. Capstone, Oxford.
Wong, P.Y., Mal, J., Sandak, A., Luo, L., Jian, J., Pradhan, N., 2024. Advances in microbial self-healing concrete: A critical review of mechanisms, developments, and future directions. Sci. Total Environ. 947, 174553. https://doi.org/10.1016/j.scitotenv.2024.174553
Yaseen, A.H., Ghazi, A., Al-Hatem, A.I., Rajab, A.B., Bodnar, N., Jasim, W.A., Ahmed, O.S., Salman, A.S., 2024. Nanostructured Materials in Sustainable Construction: A Comprehensive Review of Durability, Thermal Efficiency, and Environmental Impact. J. Nanostructures 14, 1082–1096. https://doi.org/10.22052/JNS.2024.04.010
Yousaf, A., Khan, S.A., Koç, M., 2024. 3DP for sustainable built environment – Synthesis and thermomechanical characterization of composite materials based on local soil and date palm fiber waste. J. Clean. Prod. 481. https://doi.org/10.1016/j.jclepro.2024.144050
Yousefi, A., Tang, W., Khavarian, M., Fang, C., 2021. Development of novel form-stable phase change material (PCM) composite using recycled expanded glass for thermal energy storage in cementitious composite. Renew Energy 175, 14–28. https://doi.org/10.1016/j.renene.2021.04.123
Yu, S., Hao, S., Mu, J., Tian, D., Zhao, M., 2022. Research on Optimization of the Thermal Performance of Composite Rammed Earth Construction. Energies (Basel) 15. https://doi.org/10.3390/en15041519
Zandonella Callegher, C., Grazieschi, G., Wilczynski, E., Oberegger, U.F., Pezzutto, S., 2023. Assessment of Building Materials in the European Residential Building Stock: An Analysis at EU27 Level. Sustain. 15, 8840. https://doi.org/10.3390/su15118840
Zhao, S., Liu, J., 2018. Using recycled asphalt pavement in construction of transportation infrastructure: Alaska experience. J Clean Prod 177, 155–168. https://doi.org/10.1016/j.jclepro.2017.12.104

3. Navigating Transitions for Sustainable Infrastructures—The Case of a New High-Speed Railway Station in Jingmen, China[15]

3.1 Introduction

Increasing demand on infrastructures in terms of energy consumption, raw material demand, and GHGs pose a serious threat to sustainability (Molina-moreno et al., 2017). This demand in itself has spurred infrastructure construction. In China alone, the construction works contribute to one-third of pollution such as construction waste ("The 12th Five Year Special Planning for the Development of Green Construction Technology.", n.d.). With respect to material use, on the one hand, construction works are known to require large amounts of new materials, whereas, on the other hand, they generate large amounts of waste, resulting in such a negative environmental impact (Nuñez-cacho and Jaroslaw, 2018; Wu et al., 2019). In China, construction waste totals well over 100 million tons per year, roughly 45% of overall societal waste ("The 12th Five Year Special Planning for the Development of Green Construction Technology.", n.d.). Furthermore, nearly half of the national CO_2 emissions can be attributed to infrastructures (Yang and Qi, 2016).

To address these challenges, new sustainability solutions for infrastructure construction need to recognize the interdependence of the benefits gained and the impact of new solutions across multiple dimensions of sustainability. For example, the re-use of second-hand construction materials for new construction actually provides economic benefits, because it typically requires less monetary input compared with new construction materials. From the environmental side, re-use means, for example, less need for the production of new materials or saving CO_2 emissions. These benefits show that ideas to increase sustainability can have interdependent effects across multiple dimensions. Recent reports on sustainability transitions are becoming increasingly aware of the importance of these interdependencies in global developments ("Standards Setters and Framework Providers to Support Better Reporting on the Sustainable Development Goals.", n.d.) like CE (Witjes and Lozano, 2016), which adheres to both economic and environmental aspects of sustainability (Pla-julián, 2019). The multidimensional character of the concept of sustainability in a multitude of transitions can create barriers to sustainability, and how to deal with them currently remains unresolved in literature on implementing sustainability (Turnheim and Nykvist, 2019; Webb et al., 2018).

To gain more insight into the issues surrounding the multidimensional character of sustainability in a multitude of transitions, this article focuses on an infrastructure project at the local level of a city in China, more specifically on a transport infrastructure project. On the one hand, the local public professionals need to address a multitude of transition requirements in infrastructure design. Specifically, they are simultaneously exposed to multiple programs and laws when planning and constructing new infrastructures. However, to what extent these are aligned remains unclear. For example, Chinese cities are faced with

[15] This chapter has been published as: **Liu, X.Y.,** Schraven, D., de Bruijne, M., de Jong, M. and Hertogh, M. (2019) "Navigating Transitions for Sustainable Infrastructures – The Case of a New High-Speed Railway Station in Jingmen, China" ***Sustainability*** 11 (15), 4197. https://doi.org/10.3390/su11154197

different national programs and laws, like the National CE Promotion Law (2008, 2018), the 13th Five-Year Eco-Environment Protection Planning (2016) and the Mid- and Long-Term Railway Network Planning (2016). As a consequence, resources could be lacking, or dilemmas can arise during these projects as a result of different or even conflicting requirements. On the other hand, planning officials are also offered the opportunity to incorporate multiple sustainability ideas in these infrastructure designs potentially upping the impact. In essence, this leaves the question, "How do local professionals envision sustainability ideas in pursuit of addressing multiple sustainability transitions in a (transport) infrastructure construction project?"

This paper aims to answer this question by investigating a case about the planning and construction of a railway station which is intended to connect a Chinese city, Jingmen, to two new national high-speed railway lines running across China. This case was chosen because of three unique characteristics. First, the research team had in-depth access to local public professionals who faced multiple sustainability transition policies between late 2018 and early 2019. Second, the timing of this study allowed for actual relevant input from the professionals, as they were in the midst of conceptualizing an integrated design of the railway station before finalizing the project construction plans. This particular timing allowed for the case study to identify issues and difficulties during the actual planning process. Third, the city of Jingmen offers a unique insight into the dealings of local professionals, because the city is not internationally known for any iconic or front-running projects. This makes this case stand out as an "average case". Previous studies focused on special and iconic cases of urban sustainability, ranging from mega infrastructure projects, like the bridge connecting Hong Kong, Zhuhai and Macau (Marsden, 2011), and "front-running" cities, such as Dalian (Geng et al., 2009), Taipei (Lee and Huang, 2007), Shenzhen, Beijing and Shanghai (Guo et al., 2017). The iconic state of these projects provides them financial resources to undertake these transitions, which cities like Jingmen lack.

This study adopts a TBL approach in Section 3.2 and Section 3.3 to explore the multidimensional character of the transitions more in depth. Following this approach, Section 3.4 unveils that, in the Jingmen case, sustainability was not fully envisioned by local professionals. Section 3.5 debates that although multiple policy documents outlined how to implement sustainability or CE, these actually seem to act as "precooked" silo type initiatives and only specific sectors are expected to pitch in for the specific transition. This creates a cognitive silo for local professionals when approaching them head-on. However, when abstracting the transition focus, the integral nature of ideas makes breaking out of the silos possible. This study found the TBL principle a useful and novel approach to break from the silos, because it stresses the interdependence between the various sustainability dimensions and, thereby, offers a useful analytical approach.

3.2 Literature Review

3.2.1 Sustainability

The concept of sustainability evolved throughout the 1970s and 1980s (Cowan et al., 2010). At a generic level, SD is oftentimes understood as a practical process in which economy, environment and society are brought together in a balanced way, particularly by reconciling conflicts among these three elements (Giddings et al., 2002). Sustainability relies on the successful maintenance and enhancement of the three dimensions of sustainability, i.e., environmental, social, and economic resources (Kazamia and Smith, 2014).

Out of these three dimensions, environmental sustainability is perhaps the first one which comes to mind as sustainability. It can be defined as "the maintenance of important environmental functions, and hence the maintenance of the capacity of the capital stock to provide those functions" (Ekins, 2011) (p. 637). Environmental functions refer to environmental services, including spatial functions, waste disposal, natural resource supply and life support ("Environmental Functions.", n.d.). Second, with economic sustainability, it represents that "an economically sustainable system is able to produce goods and services on a continuing basis" (Assefa and Frostell, 2007) (p. 64). It means the use of various strategies for employing existing resources optimally so that a responsible and beneficial balance can be achieved over the longer term ("Economic Sustainability.", n.d.). Lastly, social sustainability can be defined by "identifying and managing business impacts on people" ("Social Sustainability.", n.d.). Relevant values stemming from social sustainability include "equality, diversity, democracy, and interconnectedness" (Borgonovi and Compagni, 2013).

The interdependence among these separate dimensions has been coined as TBL by John Elkington in the late 90s in his book *Cannibals with Forks: The Triple Bottom Line of 21st Century Business* (1997). Figure 3.1 depicts this interdependence of the three sustainability dimensions, as three encircled areas which partially overlap like a Venn diagram. The overlaps represent the interdependence among the dimensions to reach sustainability. If a measure is plotted in the area with an overlap between two dimensions, then benefits are sought for both dimensions. For example, if a measure seeks improvement for both social and environmental sustainability, then it could be environmentally friendly and socially responsible but perhaps very expensive economically. The three dimensions have been used as separate and overlapping foci to improve sustainability in various studies (Ahi and Searcy, 2015; Dubey et al., 2017; Glaser and Diele, 2004; Kazamia and Smith, 2014; Zhong and Wu, 2015), as performance indicators (Ugwu and Haupt, 2007) or a set of desired outcomes (Bradley and Frank, 2009; Lindner et al., 2012).

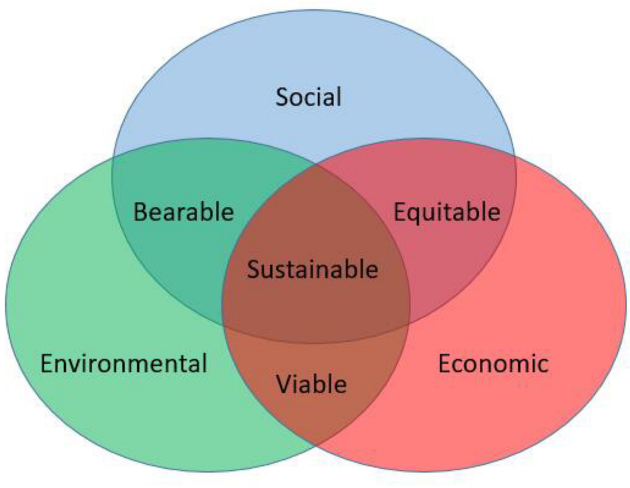


Figure 3.1 The Three Dimensions of Sustainability. Based on ("File: Sustainable development. svg.", n.d.)

Ultimately, the TBL reasons that half-hearted improvement suggestions are in fact not fully sustainable. In fact, Figure 3.1 illustrates that an idea or a measure is only truly sustainable if it aims to benefit all the three dimensions in the center. Following this line of reasoning, Ahi and Searcy (Ahi and Searcy, 2015) (p. 2882) claimed that "implementing sustainability requires a TBL approach" and, thereby, we suggest that true sustainability is interdependent on each of these dimensions simultaneously.

Thus, according to the TBL perspective, the ultimate sustainability goal can be considered to lie at the intersection of the three dimensions (see Figure 3.1). Both in practice and in research, work has focused on the development of methods to assess the desirable outcome of sustainability. In practice, standards are actually conceived and shared on the overlap of the three dimensions by the Global Reporting Initiative (GRI) reports, for infrastructure among other sectors ("Standards Setters and Framework Providers to Support Better Reporting on the Sustainable Development Goals.", n.d.). In science, assessment models are known as Sustainability Impact Assessments (or SIAs) (Bradley and Frank, 2009; Lindner et al., 2012), like for underground infrastructure construction projects (Basiago, 1999). In essence, the dimensions enable users to assess in what way changes contribute to and/or affect sustainability.

3.2.2 Sustainability Transitions

Various sustainability transition movements can be identified worldwide. Some are clearly driven by global agreements and agendas, like the SDGs of the United Nations (UN) and the Paris Accord (Jackson et al., 2018). For example, the SDGs form a global agenda for international cooperation on SD since 2015 until 2030 ("The Sustainable Development Goals.," n.d.). Apart from these international agreements, national laws and programs also mobilize a multitude of sustainability transition movements for public professionals. Sometimes these transition movements are aligned as part of "national" strategies, but sometimes they also "behave" independently from each other.

In China, governments at the national, regional and local levels establish more specific agreements, agendas or even more concrete programs, policies or enact specific laws. *The National Sustainable Development Report of P. R. China* introduces the general thoughts of the Chinese central government for moving towards SD ("The National Sustainable Development Report of P. R. China.", n.d.). Likewise, in Europe, there is *A Sustainable Europe 2030 Strategy*, an overarching strategy—the successor of the EU2020 strategy. This strategy defines both interim and long-term targets as well as timelines over and above short political cycles, laying out Europe's vision of a sustainable future until and beyond Agenda 2030 ("Europe moving towards a sustainable future.", n.d.).

There are various ways in which policies and programs can contribute to the pursuit of sustainability transitions, for example, the energy transition (Kern and Smith, 2008; Alessandro et al., 2010; Child et al., 2018) and digital transition (Lock et al., 2017). Perhaps one of the most notable paths is the movement toward CE (Sauvé et al., 2016). In scientific debates, CE has been conceptually compared to sustainability and recognized as pursuing the same goals (Zhu, 2018), although not entirely the same (Geissdoerfer et al., 2017). Research has recognized that CE practices overlap with multiple SDGs (Schroeder, 2018). With regard to the TBL, it is regarded that CE adheres to both economic and environmental dimensions of sustainability (Witjes and Lozano, 2016).

In sum, there are various sustainability transition agendas. Each of these stimulates and pushes professionals into various directions, oftentimes contributing to different transition movements. This creates a massive challenge for public professionals who have to abide to local and national government regulations when working on projects, in particular the multitude of sustainability transitions which remains unresolved in the academic debate on implementing sustainability (Turnheim and Nykvist, 2019; Webb et al., 2018). The next section reviews the more delicate challenges and state-of-the-art knowledge about the integration of these agendas into infrastructure planning and construction.

3.2.3 Sustainability in Infrastructure Planning and Construction

Infrastructure projects represent major investment and construction initiatives with attendant environmental, economic and societal impacts across multiple scales (Morrissey et al., 2012). It is considered important that these projects adhere to the principles of SD (Shen et al., 2011).

A lot of research that focuses on sustainability and infrastructures deals with sustainability appraisal, assessment/evaluation (Koo et al., 2009; Ugwu et al., 2006a, 2006b; Ugwu and Haupt, 2007; Zavrl and Zeren, 2010), indicators (Fernández-sánchez and Rodríguez-lópez, 2010; Shen et al., 2011), and frameworks (Elbarkouky and Cairo, 2012; Karaca et al., 2015; Morrissey et al., 2012). Amasuomo et al. (2015) reviewed SD and sustainability approaches for infrastructure projects in the UK. In essence, it appears important that sustainability gains a foothold in infrastructure projects.

More specific literature on incorporating sustainability inside transport infrastructure experiences similar developments, like the creation of sustainability assessment/evaluation (Bueno et al., 2017; Reza et al., 2014) and frameworks/approaches (Tsai and Chang, 2012). Incorporating sustainability inside transport infrastructures can be quite challenging. On this point, Goh and Yang (2014) provided insights into the major challenges of implementing sustainability in highway project development in terms of financial concerns and obligations from a stakeholder perspective.

An interesting perspective with regard to understanding sustainability inside infrastructure projects has been proposed and investigated by Mostafa et al. (2014). They conceived, from a stakeholder-centric perspective, how each of the sustainability dimensions can be properly captured. In their stakeholder-sensitive, social welfare–oriented sustainability benefit analysis (S3) model, they developed a method that shows how stakeholder input affects the planning and design of infrastructure systems and what collective benefits result from tension across the social, environmental, and economic sustainability dimensions. In essence, it suggests that the TBL framework forms a plausible approach to study idea generation and the potential of infrastructure interdependencies. In the next section, we construct an analytical approach based on the TBL to empirically investigate how professionals envision "sustainability ideas" in pursuit of addressing multiple sustainability ambitions in infrastructure development.

3.3 Case Materials and Methods

This section introduces the case material and the methods used. First, the background to the project case of a high-speed railway station in Jingmen, called Jingmen West Railway Station (JWRS), is briefly described. Thereafter, it is elaborated how this case is addressed with regard to data collection and analysis. Some key methodological choices and details are provided.

3.3.1 Background to the City of Jingmen and the Jinmen West Railway Station (JWRS)

Jingmen is a city like hundreds of others in mainland China. It is a “Fifth-tier” city (According to one Chinese media (*Yicai*), of the 338 listed cities in 2017, Jingmen is one of the 129 “Fifth-tier” cities, ranking after four “First-tier” cities, 15 “New First-tier” cities, 30 “Second-tier” cities, 70 “Third-tier” cities and 90 “Fourth-tier” cities. The list is based on the “concentration of commercial resources”, “the extent of transport hub”, “the vitality of citizens”, “the diversity of lifestyles” and “the flexibility of the future” of the cities (“Yicai.”, n.d.)). Figure 3.2 shows that Jingmen is located in the central province of Hubei. From a socio-economic perspective, Hubei Province mirrors China on average. Hubei’s Gross Domestic Product (GDP) per capita (52,458 RMB in 2016) closely resembles the national average level (53,935 RMB in 2016). Jingmen is located in central Hubei and has 1,625,000 residents in the city, and 2,901,300 in the wider metropolitan administrative region (2016). Jingmen’s GDP per capita is 52,470 RMB (2016).

A key characteristic of Chinese cities including Jingmen is the central authority of the Municipal Party Secretary and the Mayor. These powerful local actors play an important role in the local governance context. Local government departments and agencies are hierarchically placed under these authorities.

As part of a larger sustainability transition, the city of Jingmen faces various infrastructural planning, design and construction issues in relation to sustainability. For example, it pursues sustainable transport solutions inside the city and simultaneously aims to redevelop its industrial parks in light of the city’s circular economic agenda. Amidst these challenges, the city is also faced with the design and construction of the JWRS.

Jingmen plans to build the JWRS with five railway platforms and eleven railroad tracks. Such a station is typical in China. The local officials regard JWRS as an important transport infrastructure project for the city. The JWRS will form a crucial hub in the national high-speed rail network. Two crucial Chinese high-speed railway lines (the Hohhot-Nanning High-Speed Railway and the Shanghai-Chongqing High-Speed Railway) will connect in the prospective location.

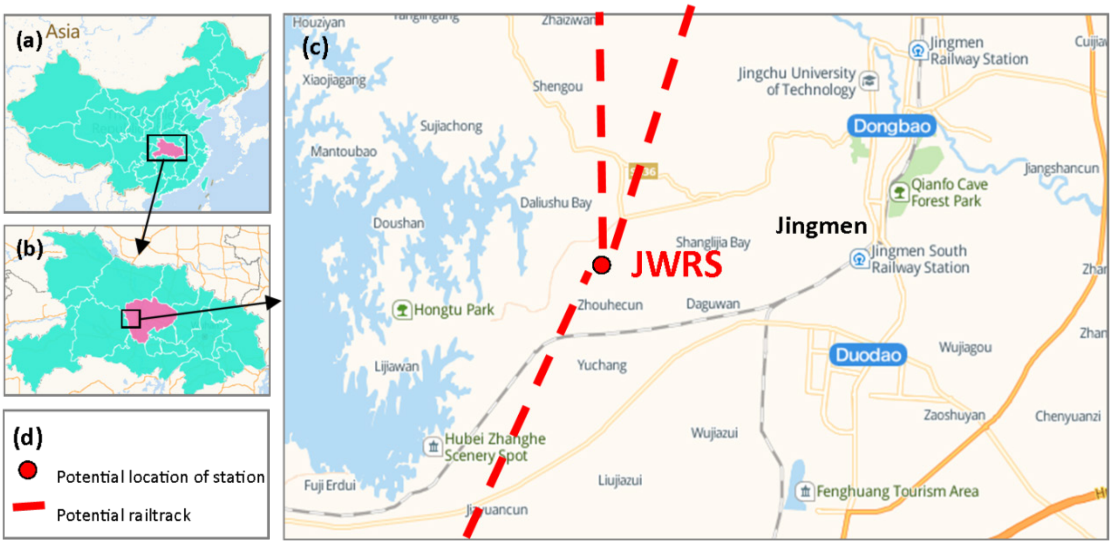


Figure 3.2 The Location of Jingmen within Hubei Province and China (The red circle stands for the general location of the Jingmen West Railway Station (JWRS)). (a): China; (b): Hubei; (c): Potential location of JWRS and its surrounding areas; (d): Legend for (c)

When the case study period commenced, the JWRS was in its planning stage. The project posed a unique first-hand challenge for city professionals in dealing with multiple sustainability goals and sustainability transitions. The planning, design and construction of the railway station and its surrounding areas are influenced by the necessity of the city of Jingmen to reduce its CO_2 emissions. Furthermore, the city is designated as one of the CE Demonstration cities in China ("Development and Reform Commission of Jingmen.", n.d.), which brings additional sustainability goals. The authors were aware of this before going to Jingmen. These various sustainability transitions provide an excellent opportunity to observe and understand how urban infrastructure projects are typically realized in the Chinese governance context and to what extent these play a role in searching for measures and ideas that can achieve sustainability.

In first contacts with the city of Jingmen, in preparation of the case study, a few initial interviews were held with three public professionals (from the Jingmen Urban and Rural Planning Bureau and the Reform and Development Commission of Jingmen). The interviews proved indispensable in determining the right focus for the study. It became clear that although Jingmen is a CE Demonstration city, implementing CE in the planning, design or construction of new infrastructures appeared to be too revolutionary. This provided the preliminary indication that local professionals are not always aware of the potential value of CE or ready to adopt CE ideas into transport infrastructure planning, design and construction. Hence, it confirmed the suitability of a more generic enquiry on sustainability to disclose ideas toward sustainability from local professionals.

In short, the research focuses on, for a new transport infrastructure project, what potential opportunities to improve sustainability local public professionals envision. A few methodological choices must be addressed in order to clarify the scope, focus and outcome of the case study.

3.3.2 Methodology to the Jinmen West Railway Station (JWRS) Case Study

The planning and design of the JWRS is approached as a case study. This means that the information obtained pertains to the study object itself and its context. The research was conducted on site in the city of Jingmen, so that the research could be conducted in close collaboration with representatives from the local government. As a result of this, the research could benefit from relative direct access to sources of information from local government organizations involved in the project. Via this way secondary literature and supportive documents could be obtained and interviews could be organized.

The object of study was separated in content-based and context-based data collection practices. First, it appeared that the development and planning process were different for the railway station and its nearby surrounding areas. This created an opportunity where "sustainability ideas" could affect either the station, the surrounding area or both. The focus of the research project was thus deliberately scoped to encompass both JWRS and the surrounding areas of the station.

First, this study involved a review of policy documents to understand which programs, laws and policies were directly or indirectly involved in the JWRS development and the sustainability transitions. The data were obtained from Chinese National Government, Hubei Government and Jingmen Government via their government websites. These provided information regarding the transport sector, planning of the station and sustainability transitions.

The search for policy documents resulted in a total of 11 documents, from the local, regional and national governments in China. These documents were searched (in Chinese) and reviewed for implications of sustainability transitions, CE, general planning and transport/railway sector that could affect the planning, design and construction of the JWRS and its surrounding areas. The overview of the policy documents is shown in the Results Section of this chapter.

Next, interviews were conducted with representative public professionals, whose work is related to the JWRS and its surrounding areas. The "sustainability ideas" that these actors envisioned for the whole JWRS project were obtained. To collect and analyze the data from these interviews, we used the TBL as an analytical framework to assess the focus of suggested improvements. In the analysis stage, we plotted the responses of the professionals. The three TBL dimensions enable us to analyze how public professionals view sustainability and what opportunities for improvement they identify.

The interviews were conducted by means of a TBL-oriented line of enquiry, splitting specific questions up into environmental, economic and social sustainability. Since it was reckoned that the development and planning of the railway station and its surrounding areas were separate, both these objects were objects of enquiry. The questions in the interview were prepared with a focus on obtaining ideas for improving the sustainability for the JWRS and its surrounding areas. The interviews were semi-structured to allow for multiple ideas to surface per question.

The interview protocol consisted of the following open-ended questions:

Q1: What do you think is important for the environmental sustainability of Jingmen West Railway Station?

Q2: What do you think is important for the environmental sustainability of the development of surrounding areas of Jingmen West Railway Station?

Q3: What do you think is important for the economic sustainability of Jingmen West Railway Station?

Q4: What do you think is important for the economic sustainability of the development of surrounding areas of Jingmen West Railway Station?

Q5: What do you think is important for the social sustainability of Jingmen West Railway Station?

Q6: What do you think is important for the social sustainability of the development of surrounding areas of Jingmen West Railway Station?

The interviews were conducted mainly with public professionals from the city of Jingmen. A few choices with regard to the selection of interviewees warrant justification. For the case, it was important to enquire professionals from the departments and agencies which have a role in the development of the railway station and the surrounding areas. Therefore, local government agencies with this focus were identified and selected. Second, since the JWRS was in its planning stage, external companies or organizations were not yet involved in the design and planning of the project. Therefore, the selected respondents were predominantly from various government departments and branches within the city. In addition, an interviewee from a local university, Jingchu University of Technology, was added to the set of respondents to obtain a more comprehensive view of the JWRS and its surrounding area. This resulted in a mixed background of interviewees, from engineers to policy makers. Figure 3.3 shows the various departments/branches/agencies of public professionals who were selected for the interviews.

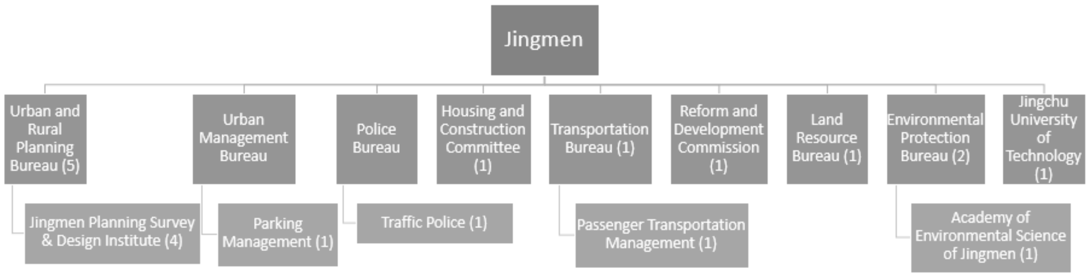


Figure 3.3 The Working Places of the Interviewees in Jingmen. The numbers in the parentheses represent the number of interviewees in certain department/branch/agency (own figure)

A total number of twenty semi-structured interviews were held in Jingmen with representatives from local governmental bodies and public research institutes. The interviews lasted from half an hour to one hour and were conducted in Chinese. The interview period was concentrated within two weeks so that the information obtained from the interviewees were referring to roughly the same timeframe. Nineteen interviews were recorded and transcribed with the explicit agreement of the interviewees. One interview was summarized with written notes only. Core information was extracted from the transcripts as well as notes and then was translated into English.

Since the line of enquiry was prepared along the TBL-based structure, the TBL was also used as the actual data structure for the analysis. Content analysis is commonly used for analyzing qualitative data (Elo et al., 2014; Hospital et al., 2002), and therefore it was used to analyze the information from the interviews. Thus, the analytical focus of these interviews was novel. Ideas were extracted from transcripts pertaining to the relevant dimension of sustainability and objects of study. In this way, a list of 263 "sustainability ideas" was obtained. This list was then reviewed to eliminate any reoccurrences. These were earmarked as reoccurring ideas. For example, one interviewee said "pay attention to the protection of water quality", while another expressed "pay attention to the protection of local water resources nearby"; these ideas were classified as similar ideas and subsequently merged together. The resulting associative structure contained ideas of the environmental, economic and social dimensions of sustainability for both the station and the surrounding areas.

To provide more insight into the associative structures of the ideas with the TBL framework, the ideas were mapped in social network graphs. The mapping was provided by the software Pajek, a social network graph analysis package ("Exploratory Social Network Analysis with Pajek.", 2007). The analysis itself is a 2-mode social graph, which provides an overview of the relations between "sustainability ideas" and the dimensions of sustainability. The overview of the "sustainability ideas" was mapped in the TBL structure for the railway station in Figure 3.5 and for the surrounding area of the JWRS in Figure 3.6 in the Results Section of this chapter.

3.4 Results

The results are shown in two phases. First, we reviewed the most essential elements of the policy documents with regard to the sustainability requirements, CE and transport infrastructures. This part contains the review and analysis of government transport, planning, sustainability and CE policies (Section 3.4.1). Section 3.4.2 discusses the interview results with regard to the relation between the "sustainability ideas" and the dimensions each idea is associated with.

3.4.1 Policy Regarding Sustainability Transitions, CE, Transport, Planning and the Jinmen West Railway Station (JWRS)

Since 1992, China has set down SD as a basic national strategy (Zhang and Wen, 2008), while CE, as an official national development goal and China's basic national policy, was put in law ("The Promotion Law of People's Republic of China (full).", n.d.; Zeng et al., 2017) and China issued more than 200 CE-related national standards after 2008. Following a top-down way, governments of different levels all over China promulgate their policies gradually.

Jingmen was designated as the National CE Demonstration Pilot City in 2007 (the only one in Hubei Province); in 2014, Jingmen qualified to become one from the list of National CE Demonstration Cities.

Figure 3.4 maps the various policy documents relevant to this study. They were produced by the three levels of government, i.e., the national level (China), the regional level (Hubei Province) and the local level (city of Jingmen). The figure plots the various documents and the level of government that issued the document and the corresponding releasing year.

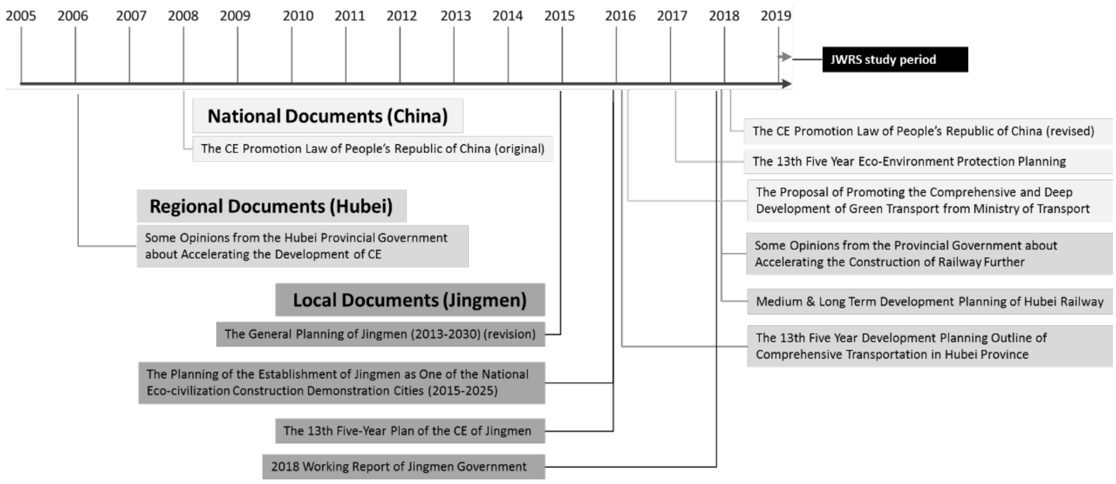


Figure 3.4 Documents Relevant for Sustainability Transition, Circular Economy (CE), Planning and Transport Infrastructure

3.4.1.1 National Policy Documents from the Chinese Government

At the national level, several key documents which contain requirements and policies for CE can be identified. They are the *"CE Promotion Law of People's Republic of China"* in 2008, which was revised in 2018, the *Eco-Environment Protection Planning*, approved by the State Council in 2017, and the *Proposal of Promoting the Comprehensive and Deep Development of Green Transport* from the Ministry of Transport.

The CE Promotion Law is an important piece of national legislation which connects SD and CE transition throughout the country. The law claims the development of CE facilitates resource efficiency and environmental protection ("The Promotion Law of People's Republic of China (full).", n.d.), and provides guidelines to develop CE as a strategy to facilitate policies of lower level governments. The law states that CE is promoted when regional governments make annual plans about civil economic and social development or when departments make plans for environmental protection or science and technology. An example of an environmental protection measure could be the organization of the resource use among companies in industrial parks. The law supports and encourages local governments to engage in these projects and enables finance, investments and governmental procurement of these initiatives, like science and technology development and educational activities.

The *13th Five-Year Eco-Environment Protection Planning* was issued in 2016 by the State Council. It outlined various requirements in light of sustainability. For instance, the intention of the Chinese government to execute the UN's SDG agenda for 2030 is one of them. It specifically elaborated on the development of agricultural technologies (e.g., water-saving, circular and organic processes) ("Notice from the State Council about the release of *the 13th Five Year Eco-Environment Protection Planning*.", n.d.).

In 2017, the Chinese Ministry of Transport proposed to promote the development of new green transport solutions. It proposed to change the transportation services and develop a green, circular and low-carbon transportation system ("The Proposal of Promoting the Comprehensive and Deep Development of Green Transport from Ministry of Transport.", n.d.).

The documents illustrate that the focus on sustainability and CE is embedded strongly in diverse high-level Chinese policies and is considered of national interest. Plans and proposals typically zoom in on developments in the agricultural and industrial sectors. In the documents, an explicit linkage is made between sustainability and CE.

3.4.1.2 Regional Policy Documents from Hubei Province

At the regional level, several policy documents were found to be of considerable interest. The *Opinions from the Hubei Provincial Government about the Acceleration of CE* from 2006 preceded the national CE promotion law and provided a detailed analysis of CE transition that was needed. For example, it discussed the setup of a scientific CE assessment indicator system and accounting institutions. Also, it already iterated the need for making and realizing CE development promotion plans, by means of technological support systems, advisory service systems and provincial financing schemes into science and education *("Opinions from the Hubei Provincial Government about the Acceleration of CE.*", n.d.).

In relation to the planned railway station, Hubei Province issued three important policy documents. One is *Hubei's 13th Five-Year plan towards a Comprehensive Transportation System* (2016). This document established a priority on ecological and green development of the whole process of transport planning, design, construction and management. The aim was to accelerate the construction of a green, circular and low-carbon transportation system ("Notice from Hubei Provincial Government about the Releasing of the 13th Five Year plan in 2016 for Hubei on a Comprehensive Transportation System.", n.d.).

In 2018, two further documents directly influenced the construction of a provincial railway system. First, there were some opinions iterated by the Hubei Government to accelerate the construction of a railway network with a focus on the SD of the railways. Second, a medium- and long-term development plan from the Hubei Provincial Development and Reform Commission confirmed this goal for the railway sector.

Interestingly, Hubei Province, via its policy documents, shows a strong connection to CE transition, albeit at a very generic level. For specific infrastructure plans on railways, the reviewed documents suggest a broadening of the efforts to implement sustainability.

3.4.1.3 Local Policy Documents from Jingmen

At the local level, a handful of documents which were related to the JWRS case were reviewed. In 2015, a general planning document for Jingmen was issued for the active period until 2030. In this plan, Jingmen called for SD plans and referred to the protection and rational use of natural resources (water, land, energy, etc.). It also stressed on the need to realize a sustainable transport system, which means an efficient and complete set of transportation connections and facilities. CE was mentioned to a far lesser extent, only as a means of facilitating energy savings and emission reduction.

In 2016, two developmental plans were issued specifically to introduce and implement the national programs to enhance the sustainable character of Jingmen. First, a plan was issued which made Jingmen to become a "National Eco-civilization Construction Demonstration City" for the period 2015 until 2025. This indicated that the city had decided to focus on environmental protection and the construction of an eco-city with the urban-rural SD. Additionally, the plan for this label called for Jingmen to task itself with the ambition to reduce the environmental pollution via sustainable consumption, i.e., more green products and less waste disposal.

The “Eco-civilization Construction Demonstration City” program also carried CE ambitions. This policy document focused particularly on the construction of a CE platform for Jingmen’s various industrial parks (e.g., Chemical Circular Industrial Park and the Electric Waste Circular Industrial Park in Jingshan (a subordinate county of Jingmen)). Furthermore, the program also mentioned initiatives such as enterprise loans for green technology development and the development of rural regions like the “China Agricultural Valley”.

The second plan was Jingmen’s Five-Year plan, in which it stated its ambitions for CE and its desire to become a “CE Demonstration City” in 2016. The plan noted that new projects needed to apply principles of CE. However, the plan did not specify the types of projects. It appeared to refer mostly to enterprises and demonstration parks and to focus on resource efficiency as well as financial and fiscal possibilities to support CE developments in these areas.

In 2018, Jingmen issued a working report in which it positioned itself as a CE Demonstration City. The report again focused on recycling and reuse initiatives in the chemical and agricultural sectors.

It is remarkable to note that with regard to sustainability, the local government recognized the task in hand to be related to transport and railway system. However, with regard to CE, the local documents do not recognize the value in construction works of transport infrastructures such as railway stations, even though Jingmen is actually considered to hold two positions as a demonstration area, i.e., a CE Demonstration City and the Eco-Civilization Construction Demonstration City/County (the Jingshan County in Jingmen).

In summary, *The CE Promotion Law of People’s Republic of China* notes that developing CE is necessary to realize SD. Generally, national policies identify main directions, while local policies specify measures in more detail. However, in general planning or CE-related policy documents, transport infrastructure was not specifically mentioned. While in the transportation related policy documents, SD or CE are only briefly mentioned. This policy analysis explains why CE is not embedded into Jingmen’s transport infrastructure projects as was expressed by the three officials from the Reform and Development Commission of Jingmen and Jingmen Urban and Rural Bureau. Although Jingmen is one of the CE Demonstration Cities in China, CE implementations are mainly focused on chemical, agricultural and service industries, the so-called “traditional” CE practice areas.

3.4.2 “Sustainability Ideas” Envisioned for the Jinmen West Railway Station (JWRS) and Its Surrounding Areas

For the JWRS case specifically, the “sustainability ideas” are portrayed in two social network graphs, one for ideas pertaining to the railway station itself in Figure 3.5 and the other for the surrounding areas of the JWRS in Figure 3.6. The size of the nodes and the width of the lines are proportional to the number of times the respective ideas were proposed by the interviewees.

3.4.2.1 Top “Sustainability Ideas” Mentioned according to Jingmen Professionals for the Jinmen West Railway Station (JWRS) and Its Surrounding Areas

Judging from the size of the nodes, the railway station and its surrounding areas both generate a number of ideas that were mentioned at least six times by interviewees (see Table 3.1). With regard to the JWRS itself the idea that was mentioned most often was “pay attention to water quality/wastewater” (10 times out of 20 interviewees). This is, in itself, not surprising since the JWRS is planned quite close to the local Cheqiao Reservoir. However, the ideas were “only” associated with environmental sustainability and not very interdependent in terms of sustainability. Professionals seemingly provide priority to develop measures that help reduce as well as treat wastewater and avoid a negative environmental impact on the reservoir.

The second top idea is “pay attention to the compensation of land acquisition”, which considers the impact of the JWRS plans on residents. Some must be relocated for the railway station project. The Jingmen professionals reckon that local residents who stand to lose their land as a result of current plans should be (adequately) compensated. Interestingly, apart from these two generic “ideas”, very specific elements with regard to the JWRS were mentioned as source of ideas. The overall effect is that the “ideas” of the professionals are only focused on a single dimension of sustainability.

With regard to the surrounding areas of the JWRS, three ideas stand out, i.e., “arrange good affiliate facilities” (nine calls), “pay attention to plants” (seven calls) and “distribute surrounding industries rationally” (six calls). These ideas clearly pertain to improving the surrounding areas (with green plants and facilities that serve social and economic functions). In contrast to the ideas of the railway station, these ideas were more interdependent between sustainability dimensions.

*Table 3.1 Top Calls from Local Professionals Regarding Jingmen West Railway Station (JWRS) and Its Surrounding Areas **

Rank	**Sustainability Idea**	**# Total**	**# per Object**		**# per Dimension**		
			JWRS	**SA**	**SOC**	**ENV**	**ECO**
1	Pay attention to water quality/wastewater	10	10	-	-	10	-
2	Arrange good affiliate facilities	9	-	9	4	-	5
	Pay attention to plants	9	2	7	1	8	-
4	Pay attention of the compensation of land acquisition	8	7	1	8	-	-
5	Distribute surrounding “industries” rationally	7	1	6	3	-	4
	Timely clearing away trash	7	4	3	-	7	-
	Pay attention to the effects of construction to air quality	7	4	3	-	7	-
	Conserve energy	7	4	3	-	5	2
9	Pay attention to aesthetics	6	4	2	-	1	5
	Reduce noise	6	6	-	2	4	-
	Show local characteristics	6	6	-	2	-	4

** SA: surrounding areas of the JWRS; SOC: social sustainability; ENV: environmental sustainability; ECO: economic sustainability.*

3.4.2.2 Interdependence of "Sustainability Ideas" for the Jinmen West Railway Station (JWRS)

Figure 3.5 shows the "sustainability ideas" associated with the railway station. First and foremost, it can be noticed that no idea has a direct relationship with all three sustainability dimensions. However, there are a few ideas interdependent with two dimensions.

First, in the intersection between environmental and economic sustainability, five ideas were mentioned: "adopt green building", "conserve water", "conserve energy", "adopt assembly building" and "well design the station". The linkage between these dimensions seems to be oriented towards the adoption of modular and green methods for the construction of the station. Additionally, it appears that professionals recognize the conservation of resources as an environmental and economic approach to become more sustainable.

At the intersection between social and economic sustainability, three ideas were mentioned: "the station cannot be too far away from the central areas of the city", "pay attention to the services inside the station" and "show local characteristics". The interdependence between social and economic sustainability could be viewed as the social-economic function, i.e., the attractiveness of the station to people (including its location) and the services in the station.

The ideas which focused on the interdependence between the social and environmental dimensions of sustainability were only mentioned twice ("reduce noise" and "reduce consumption of basic farmland"). The professionals seemed to view the relationship between both dimensions primarily as an opportunity to reduce undesirable side-effects, like noise during the construction and operation of the railway station. The part of basic farmland, which must make way if the railway station is located further away from the city center, could be reduced. In that sense, indirectly, the location choice actually affects all aspects of sustainability, as closer to the city center would be better economically, socially (closer to social and economic activities) and environmentally (less farmland lost).

Although no idea met the full TBL, each bilateral interdependence was identified in a number of ideas. Ideas with both an environmental and an economic dimension were strongly related to resource conservation and the application of green/modular building as well as specific design techniques. Ideas which had both a social and an economic dimension addressed the importance of the social and economic functions of the station and were mainly concerned with the relative geographical location of the station within the city and the extent of services in the station. Ideas with both an environmental and a social dimension focused more on the identification of mitigation measures that could be employed to reduce negative effects like noise and loss of farmland.

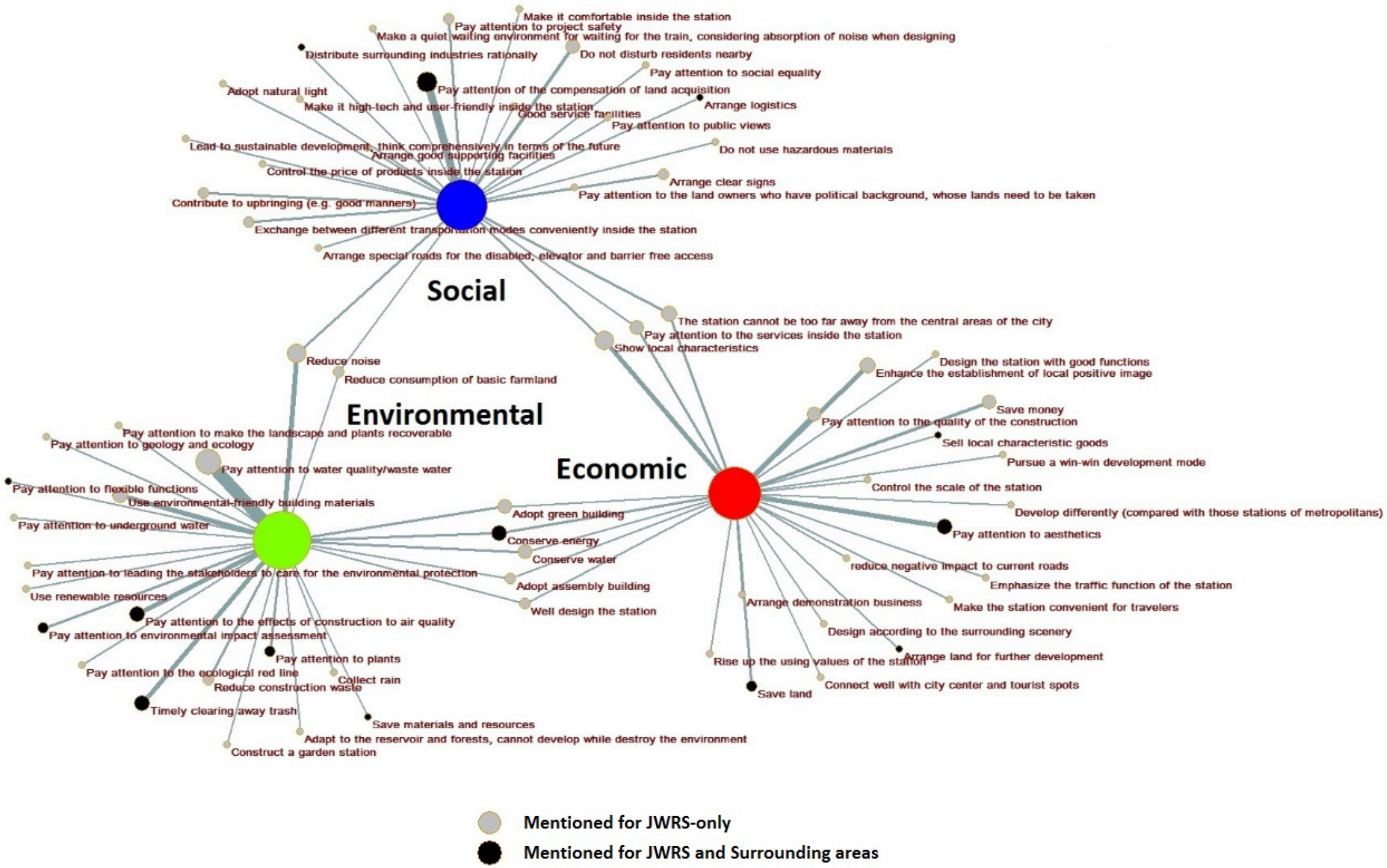


Figure 3.5 "Sustainability Ideas" Mapped in Relation to Jingmen West Railway Station (JWRS)

3.4.2.3 Interdependence of "Sustainability Ideas" for the Surrounding Areas of the Jinmen West Railway Station (JWRS)

Figure 3.6 shows the "sustainability ideas" that the interviewees mentioned with regard to the surrounding areas of the JWRS. Like the ideas about the railway station itself, only bilateral relations were found between the sustainability dimensions.

First, three ideas sought to improve social and economic sustainability: "distribute surrounding industries rationally", "arrange good affiliate facilities" and "increase employment". The professionals envision that the areas surrounding the station should be specifically allocated to businesses to increase employment and economic development. Additional facilities for the station such as parking and transportation facilities were also considered from this perspective.

Social and environmental dimensions of sustainability were connected in two ideas mentioned by the professionals ("make natural sceneries" and "pay attention to plants"). Both ideas facilitate the inclusion of natural solutions in the design of the surrounding areas (specific flora or local sceneries) for the public.

Only one idea was offered which focused on environmental and economic sustainability ("pay attention to aesthetics"). This in itself is a generic idea which stresses that the overall surrounding areas must be well designed with good appearance (building aesthetics) and ecological aesthetics in mind to attract more people and investment.

Although no idea met the full TBL again, each bilateral interdependence was at least mentioned by the professionals. The ideas which contained social and economic aspects were particularly focused on the management and "design" of businesses and facilities in the vicinity of the station to increase the attraction of the location and to attract employment for the city. At the intersection between social and environmental sustainability, the professionals focused on the greening of the environment around the station. Finally, only a very generic idea (aesthetics) could be identified at the crossroad between economic and environmental sustainability.

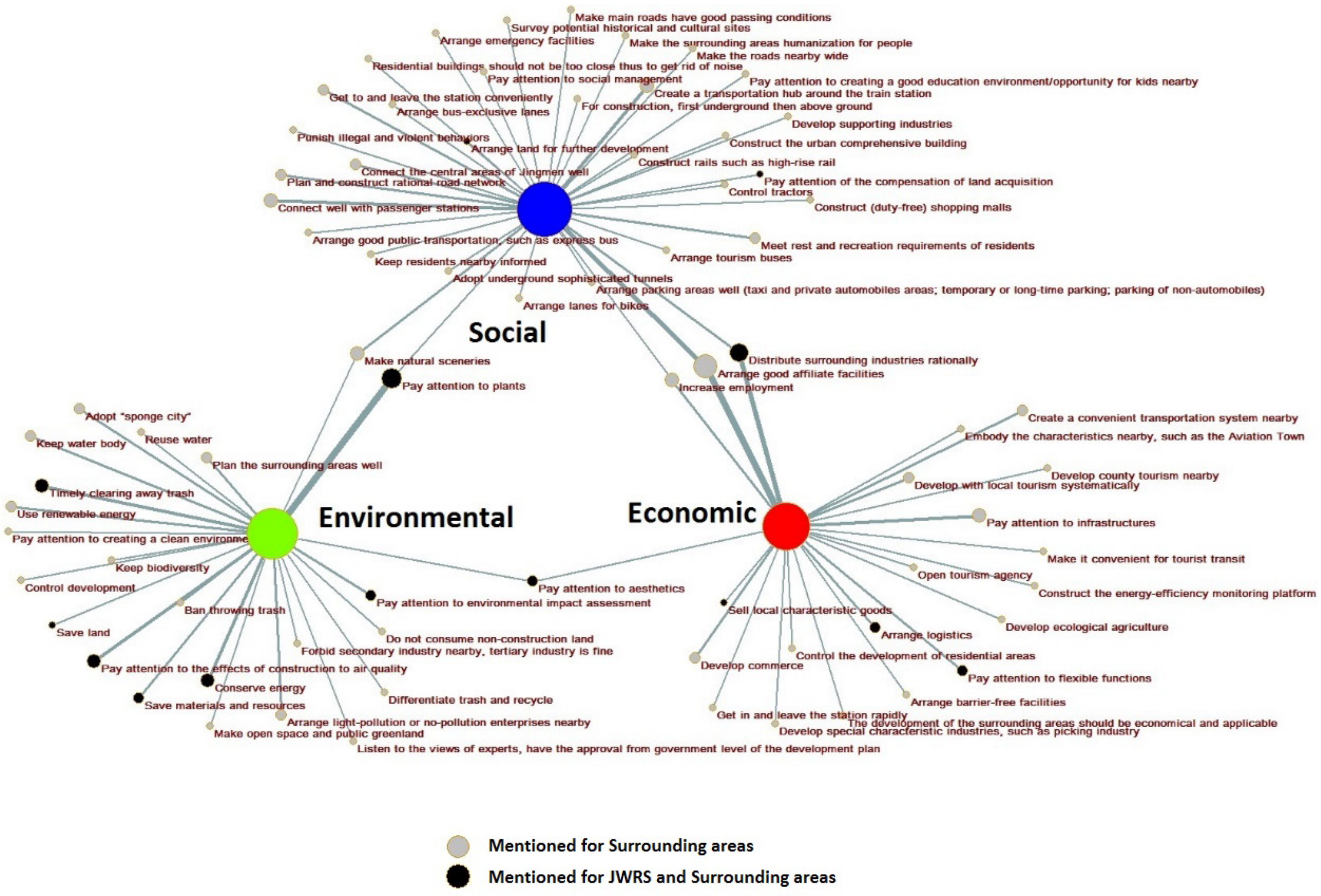


Figure 3.6 "Sustainability Ideas" Mapped in Relation to the Surrounding Areas of the JWRS

3.4.3 "Sustainability Ideas" in Relation to Circular Economy (CE) in Jingmen

The policy documents revealed that the city of Jingmen simultaneously pursues two sustainability transitions: as a CE Demonstration City and as an Eco-Civilization Construction Demonstration City/County for one of its specific counties (Jingshan). The local demonstration programs show that, besides the national and regional policies regarding SDGs, CE is considered an important element in Jingmen's sustainability transition. According to Chinese Promotion law for CE issued in 2008, CE is defined by three general types of measures, i.e., reducing, reusing and recycling (3R).

Although the policy documents on transport infrastructure do not mention CE explicitly for railway station construction, the "sustainability ideas" mentioned by the professionals in the case have generated corresponding CE measures which can be classified according to the "3R" perspective.

3.4.3.1 "Sustainability Ideas" on Reducing

Four ideas can be recognized as CE measures which seek to reduce the impact of the JWRS construction project, i.e., "reduce construction waste", "save land", "reduce consumption of basic farmland" and "collect rain". However, these types of ideas were not mentioned often by the local professionals in relation to the JWRS. The ideas were only mentioned once or twice each.

The ideas on reducing seem to have the strongest link with the environmental sustainability dimension of the railway station. The clearest example of a type of CE measure is the idea "reduce construction waste". The only CE idea that did not belong to environmental sustainability was the idea to "save land". This one was actually oriented more to economic sustainability, since saving land would save costs for acquiring this land and relocating the former residents.

3.4.3.2 "Sustainability Ideas" on Reusing

Approximately four ideas could be related to the CE measure on reusing, namely, to "conserve water", "save materials and resources", "conserve energy", and "reuse water". All these ideas were only mentioned to a limited extent by local professionals, and they were predominantly present in ideas where environmental and economic sustainability meet: the conservation and reuse of energy, water and other materials.

3.4.3.3 "Sustainability Ideas" on Recycling

Two ideas connected to the CE measure of recycling ("use renewable resources" and "differentiate trash and recycle"). Both are again associated with the environmental sustainability dimension. The connection to the concept of recycling is also not very strong, because one idea refers to renewable resources more than recycling, and the other idea is just mentioned recycling in relation to trash, without a specific reference on the type of trash.

3.5 Discussion

The Jingmen case has offered a few probing insights. First of all, we are offered a glimpse of multiple sustainability transitions that professionals are faced with. Second, we have gained valuable insights into the conceptualization and realization of sustainability ideas (or measures) in transport infrastructure construction projects, by looking at the TBL and the interdependence between the sustainability dimensions. A few key findings are discussed here.

3.5.1 The Triple Bottom Line (TBL) Principle Interdependence in Practice

The TBL forms our starting point and identifies true sustainability. The notion of achieving true sustainability appears to lie in the achievement of improvements in all three sustainability dimensions. The principle has become so dominant in scientific understanding of sustainability, that the value of the TBL is unquestioned by some as a prerequisite for implementation (Ahi and Searcy, 2015).

On this note, our case in Jingmen showed an interesting empirical feature of the TBL principle in practice. The case showed that true sustainability simply could not be envisioned by local professionals if they were conceptualizing a sustainable railway station and its surrounding areas (Figures 3.5 and 3.6). Not a single idea actually overlapped all the three dimensions of sustainability. Furthermore, only a few bilateral connections could be found. The ideas that overlapped with paired dimensions actually had quite a clear and direct set of characteristics on how these pairs were linked, for example by means of conserving resources and adopting new technologies.

3.5.2 Transitioning in Silos

China has become known as a country which invests heavily in sustainability transitions (Dieppe et al., 2018). In the case of Jingmen, we found that sustainability goals were indeed mentioned in national and regional policy documents both for SDGs and CE. The transition was recognized in the considerations of the city as well as its proposed projects and earned Jingmen a demonstration status in two sustainability programs. At the city level, it was awarded the CE Demonstration City status.

Interestingly though, the overarching national and regional policies at the local level seem to produce "precooked" silo type initiatives, and only specific sectors are expected to pitch in for the specific transition. Most notably, regional policies consider CE as a resource efficiency effort for industrial parks and agricultural applications. In addition, the regional government earmarked the transport infrastructure towards sustainability via its policy focus on SDGs. At least on paper, as a result of this singular policy, a new cognitive silo appears to be born.

This is actually corroborated by the preparation of our case and the analysis of the "sustainability ideas" in relation to the Chinese CE promotion law. First, the preparation period found Jingmen reluctant to combine CE transition with the railway station project. Interestingly, we were told by one public official that adopting CE for a transport infrastructure project was considered too revolutionary by the city policy makers. Second, the "sustainability ideas" from public professionals were relatively weakly recognized as related to CE.

These insights show that the hierarchical introduction of transition(s) as in current practice in China creates a cognitive silo for local professionals when taking on transport infrastructure projects head-on. However, when the transition focus is being laid before local professionals in more abstract terms, the integral nature of ideas makes breaking out of the silos possible. The TBL principle which stresses the interdependence among the various sustainability dimensions provides a useful analytical approach to achieve and analyze this.

3.5.3 Breaking the Silos with the Triple Bottom Line (TBL)

In literature, CE is portrayed as the explicit connection between environmental and economic sustainability dimensions (Ghisellini et al., 2016). It is also recognized strongly connected to the SDGs (Schroeder, 2018; Zhu, 2018). Especially, Schroeder (2018) identified the extent to which CE practices are relevant for the implementation of the UN's SDGs.

In contrast to the existing literature, this case study revealed that CE is quite strongly related to environmental sustainability, but only weakly related to economic sustainability in the perception of local professionals. This finding is based on the limited set of CE relations, which we identified in the "sustainability ideas" proposed by the public professionals, who predominantly focused on "reduce" and "reuse".

This study, therefore, paints a picture of CE only being relevant to achieve environmental sustainability. However, it is worth noting here the addition of costs could unravel the economic sustainability of the CE option more clearly. Explicating the cost and benefit relation more explicitly would actually help break the transition in silo, particularly by focusing on the TBL approach.

3.6 Conclusion

There is still a long way to go for infrastructure construction projects in China to fully seize the TBL principle as the case study about JWRS showed. On the one hand, the findings of our research are quite remarkable for sustainability transition, considering the volume and importance of transport infrastructure constructions. On the other hand, this research shows the institutional complexity which (partly) explains the "cognitive silo" in which local professionals find themselves in the planning of an infrastructure project. These, along with the relative rapid pace with which infrastructure projects are planned and subsequently realized in China, explain how CE does not seem to be embedded in current infrastructure construction projects. One way in which a more "open" perspective towards sustainability and in particular CE could be pursued among professionals is to understand the interdependent impact of a measure taken in a project by considering its triple effect, both intended and unintended. A more specific focus on interdependencies could actually stimulate the realization of true sustainability effects by inspiring professionals to focus on integral considerations in projects. These could be made tangible in possible trade-off relations of the triple effect of a measure via, for example, life cycle assessment (LCA) methods (environmental plus social LCA and life cycle costing) (Balanay and Halog, 2016).

In the specific circumstances of the Jingmen case, we explored the measures local practitioners considered about how to make a typical transport infrastructure project, a railway station together with its surrounding areas more sustainable. The TBL served as a framework to guide our data collection and interpret the data. Currently, CE mainly plays a role in views of professionals in terms of improvement of environmental sustainability. However, CE deserves a more important position in infrastructure projects among all sustainability dimensions: environmental sustainability, economic and also social sustainability. Furthermore, organizations and professionals could benefit from a more open attitude and more systemic way of thinking about infrastructure projects to recognize more sustainable opportunities (including technological improvements such as Building Information Modeling

(Shin et al., 2018)) during the planning, realization, and operational phase (by far the longest period) (Hertogh, 2014).

Furthermore, the various administrative and policy levels could contribute towards the realization of more sustainable outcomes by aligning or even integrating the various sustainability strategies. We suggest that the central Chinese government could stimulate CE and sustainability in infrastructure construction projects by providing more integral and clearer policy guidance to lower-level governments. At the same time, local professionals in cities like Jingmen could be challenged to broaden their perspectives and take the lead in the implementation of CE in more urban infrastructure development. For a big transport infrastructure like the JWRS, local professionals, especially policy makers, should have a strategically panoramic view to make rational decisions towards sustainability after integrated and systematic considerations.

Further research could follow up and consider the challenges for CE between the planning and realization phase of infrastructure projects. It would be interesting to reuse the list of "sustainability ideas" summarized in the current article after the construction of the JWRS as well as its surrounding areas and investigate to what extent/why local policy makers decided not to follow up on some of the "sustainability ideas" that were mentioned during the interviews.

References for Chapter 3

Ahi, P., Searcy, C., 2015. Assessing sustainability in the supply chain: A triple bottom line approach. Appl. Math. Model. 39, 2882–2896. https://doi.org/10.1016/j.apm.2014.10.055

Alessandro, S.D., Luzzati, T., Morroni, M., 2010. Energy transition towards economic and environmental sustainability: feasible paths and policy implications. J. Clean. Prod. 18, 291–298. https://doi.org/10.1016/j.jclepro.2009.10.015

Amasuomo, E., Hasnain, S.A., Osanyinlusi, A.Y., 2015. Sustainable Development in the Context of Major Infrastructure Projects in United Kingdom. J. Geosci. Environ. Prot. 3, 44–55.

Assefa, G.Ã., Frostell, B., 2007. Social sustainability and social acceptance in technology assessment: A case study of energy technologies. Technol. Soc. 29, 63–78. https://doi.org/10.1016/j.techsoc.2006.10.007

Balanay, R., Halog, A., 2016. Charting Policy Directions for Mining' s Sustainability with Circular Economy. Recycling 1, 219–231. https://doi.org/10.3390/recycling1020219

Basiago, A.D., 1999. Economic, social, and environmental sustainability in development theory and urban planning practice. Environmentalist 19, 145–161.

Borgonovi, E., Compagni, A., 2013. Sustaining Universal Health Coverage: The Interaction of Social, Political, and Economic Sustainability. Value Heal. 16, S34–S38. https://doi.org/10.1016/j.jval.2012.10.006

Bradley, T.H., Frank, A.A., 2009. Design, demonstrations and sustainability impact assessments for plug-in hybrid electric vehicles. Renew. Sustain. Energy Rev. 13, 115–128. https://doi.org/10.1016/j.rser.2007.05.003

Bueno, P.C., Vassallo, J.M., Cheung, K., 2017. Sustainability Assessment of Transport Infrastructure Projects: A Review of Existing Tools and Methods. Transp. Rev. 35, 1–28. https://doi.org/10.1080/01441647.2015.1041435

Child, M., Koskinen, O., Linnanen, L., Breyer, C., 2018. Sustainability guardrails for energy scenarios of the global energy transition. Renew. Sustain. Energy Rev. 91, 321–334. https://doi.org/10.1016/j.rser.2018.03.079

Cowan, D.M., Dopart, P., Ferracini, T., Sahmel, J., Merryman, K., Gaffney, S., Paustenbach, D.J., 2010. A cross-sectional analysis of reported corporate environmental sustainability practices. Regul. Toxicol. Pharmacol. 58, 524–538. https://doi.org/10.1016/j.yrtph.2010.09.004

Development and Reform Commission of Jingmen. [WWW Document], n.d.

Dieppe, A., Gilhooly, R., Han, J., 2018. The transition of China to sustainable growth–implications for the global economy and the euro area. Frankfurt am Main. https://doi.org/https://ssrn.com/abstract=3113109

Dubey, R., Gunasekaran, A., Childe, S.J., Papadopoulos, T., Luo, Z., Fosso, S., Roubaud, D., 2017. Can big data and predictive analytics improve social and environmental sustainability? Technol. Forecast. Soc. Chang. 144, 534–545. https://doi.org/10.1016/j.techfore.2017.06.020

Economic Sustainability. [WWW Document], n.d.

Ekins, P., 2011. Environmental sustainability: From environmental valuation to the sustainability gap. Prog. Phys. Geogr. Earth Environ. 35, 629–651. https://doi.org/10.1177/0309133311423186

Elbarkouky, M.M.G., Cairo, N., 2012. A Multi-Criteria Prioritization Framework (MCPF) to Assess Infrastructure Sustainability Objectives and Prioritize Damaged Infrastructure Assets in Developing Countries. J. Sustain. Dev. 5, 1–13. https://doi.org/10.5539/jsd.v5n9p1

Elo, S., Kääriäinen, M., Kanste, O., Pölkki, T., 2014. Qualitative Content Analysis: A Focus on Trustworthiness. SAGE Open 4, 1–10. https://doi.org/10.1177/2158244014522633

Environmental Functions. [WWW Document], n.d.

Europe moving towards a sustainable future. [WWW Document], n.d.

Exploratory Social Network Analysis with Pajek. [WWW Document], 2007. https://doi.org/10.1177/0038038506067527

Fernández-sánchez, G., Rodríguez-lópez, F., 2010. A methodology to identify sustainability indicators in construction project management—Application to infrastructure projects in Spain. Ecol. Indic. 10, 1193–1201. https://doi.org/10.1016/j.ecolind.2010.04.009

File: Sustainable development. svg. [WWW Document], n.d.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy–A new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geng, Y., Zhu, Q., Doberstein, B., Fujita, T., 2009. Implementing China's circular economy concept at the regional level: A review of progress in Dalian, China. Waste Manag. 29, 996–1002. https://doi.org/10.1016/j.wasman.2008.06.036

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Giddings, Bob, Hopwood, Bill, Brien, Geoff O, Giddings, B, Hopwood, B, Brien, G O, 2002. Environment, economy and society: fitting them together into sustainable development. Sustain. Dev. 196, 187–196.

Glaser, M., Diele, K., 2004. Asymmetric outcomes: assessing central aspects of the biological, economic and social sustainability of a mangrove crab fishery, Ucides cordatus (Ocypodidae), in North Brazil. Ecol. Econ. 49, 361–373. https://doi.org/10.1016/j.ecolecon.2004.01.017

Goh, K.C., Yang, J., 2014. Importance of Sustainability-Related Cost Components in Highway Infrastructure: Perspective of Stakeholders in Australia. J. Infrastruct. Syst. 20, 1–9. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000152.

Guo, B., Geng, Y., Ren, J., Zhu, L., Liu, Y., Sterr, T., 2017. Comparative assessment of circular economy development in China's four megacities: The case of Beijing, Chongqing, Shanghai and Urumqi. J. Clean. Prod. 162, 234–246. https://doi.org/10.1016/j.jclepro.2017.06.061

Hertogh, M.J.C.M., 2014. Opportunity framing, in: H.L.M. Bakker, J.P. de K. (Ed.), Management of Engineering Projects - People Are Key. NAP, Nijkerk, p. 102.

Hospital, H.C., Lauderdale, F., Policy, N., Affairs, U., International, F., Affairs, P., 2002. Content Analysis: Review of Methods and Their Applications. J. Nutr. Educ. Behav. 34, 224–230.

Jackson, L.P., Grinsted, A., Jevrejeva, S., 2018. 21st Century Sea-Level Rise in Line with the Paris Accord Earth's Future. Earth's Futur. 6, 213–229. https://doi.org/10.1002/eft2.284

Karaca, F., Graham, P., Machell, J., Camci, F., 2015. A comparative analysis framework for assessing the sustainability of a combined water and energy infrastructure. Technol. Forecast. Soc. Chang. 90, 456–468. https://doi.org/10.1016/j.techfore.2014.04.008

Kazamia, E., Smith, A.G., 2014. Assessing the environmental sustainability of biofuels. Trends Plant Sci. 19, 615–618. https://doi.org/10.1016/j.tplants.2014.08.001

Kern, F., Smith, A., 2008. Restructuring energy systems for sustainability? Energy transition policy in the Netherlands. Energy Policy 36, 4093–4103. https://doi.org/10.1016/j.enpol.2008.06.018

Koo, D., Ariaratnam, S.T., Jr, E.K., 2009. Development of a sustainability assessment model for underground infrastructure projects. Can. J. Civ. Eng. 776, 765–776. https://doi.org/10.1139/L09-024

Lee, Y., Huang, C., 2007. Sustainability index for Taipei. Environ. Impact Assess. Rev. 27, 505–521. https://doi.org/10.1016/j.eiar.2006.12.005

Lindner, M., Tommi, W.W., Vo, D., Valinger, E., 2012. Conducting sustainability impact assessments of forestry-wood chains : examples of ToSIA applications. Eur. J. For. Res. 21–34. https://doi.org/10.1007/s10342-011-0483-7

Lock, I., Seele, P., Lock, I., 2017. Theorizing stakeholders of sustainability in the digital age. Sustain. Sci. 12, 235–245. https://doi.org/10.1007/s11625-016-0404-2

Marsden, S., 2011. Assessment of transboundary environmental effects in the Pearl River Delta Region: Is there a role for strategic environmental assessment? Environ. Impact Assess. Rev. 31, 593–601. https://doi.org/10.1016/j.eiar.2010.03.010

Molina-moreno, V., Carlos, J., Jorge, S., 2017. Proposal to Foster Sustainability through Circular Economy-Based Engineering: A Profitable Chain from Waste Management to Tunnel Lighting. Sustainability 9, 1–9. https://doi.org/10.3390/su9122229

Morrissey, J., Iyer-raniga, U., Mclaughlin, P., Mills, A., 2012. A Strategic Project Appraisal framework for ecologically sustainable urban infrastructure. Environ. Impact Assess. Rev. 33, 55–65. https://doi.org/10.1016/j.eiar.2011.10.005

Mostafa, M.A., El-gohary, N.M., Asce, A.M., 2014. Stakeholder-Sensitive Social Welfare–Oriented Benefit Analysis for Sustainable Infrastructure Project Development. J. Constr. Eng. Manag. 140, 1–12. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000788.

Notice from Hubei Provincial Government about the Releasing of the 13th Five Year plan in 2016 for Hubei on a Comprehensive Transportation System. [WWW Document], n.d.

Notice from the State Council about the release of 13th Five Year Eco-Environment Protection Planning. [WWW Document], n.d.

Nuñez-cacho, P., Jaroslaw, G., 2018. What Gets Measured, Gets Done: Development of a Circular Economy Measurement Scale for Building Industry. Sustainability 10, 2340–2361. https://doi.org/10.3390/su10072340

Opinions from the Hubei Provincial Government about the Acceleration of CE. [WWW Document], n.d.

Pla-julián, I., 2019. Is circular economy the key to transitioning towards sustainable development? Challenges from the perspective of care ethics. Futures 105, 67–77. https://doi.org/10.1016/j.futures.2018.09.001

Reza, B., Sadiq, R., Hewage, K., 2014. Emergy-based life cycle assessment (Em-LCA) for sustainability appraisal of infrastructure systems: a case study on paved roads. Clean Technol. Environ. Policy 16, 251–266. https://doi.org/10.1007/s10098-013-0615-5

Sauvé, S., Bernard, S., Sloan, P., 2016. Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. Environ. Dev. 17, 48–56. https://doi.org/10.1016/j.envdev.2015.09.002

Schroeder, P., 2018. The Relevance of Circular Economy Practices to the Sustainable Development Goals. J. Ind. Ecol. 23, 77–95. https://doi.org/10.1111/jiec.12732

Shen, L., Asce, M., Wu, Y., Zhang, X., Ph, D., 2011. Key Assessment Indicators for the Sustainability of Infrastructure Projects. J. Constr. Eng. Manag. 137, 441–451. https://doi.org/10.1061/(ASCE)CO.1943-7862

Shin, M.H., Lee, H.K., Kim, H.Y., 2018. Benefit–Cost Analysis of Building Information Modeling (BIM) in a Railway Site. Sustainability 10, 4303–4312. https://doi.org/10.3390/su10114303

Social Sustainability. [WWW Document], n.d.

Standards Setters and Framework Providers to Support Better Reporting on the Sustainable Development Goals. [WWW Document], n.d.

The 12th Five Year Special Planning for the Development of Green Construction Technology. [WWW Document], n.d.

The National Sustainable Development Report of P. R. China. [WWW Document], n.d.

The Promotion Law of People's Republic of China (full). [WWW Document], n.d.

The Proposal of Promoting the Comprehensive and Deep Development of Green Transport from Ministry of Transport. [WWW Document], n.d.

The Sustainable Development Goals. [WWW Document], n.d.

Tsai, C.Y., Chang, A.S., 2012. Framework for developing construction sustainability items : the example of highway design. J. Clean. Prod. 20, 127–136. https://doi.org/10.1016/j.jclepro.2011.08.009

Turnheim, B., Nykvist, B., 2019. Opening up the feasibility of sustainability transitions pathways (STPs): Representations, potentials, and conditions. Res. Policy 48, 775–788. https://doi.org/10.1016/j.respol.2018.12.002

Ugwu, O.O., Haupt, T.C., 2007. Key performance indicators and assessment methods for infrastructure sustainability—a South African construction industry perspective. Build. Environ. 42, 665–680. https://doi.org/10.1016/j.buildenv.2005.10.018

Ugwu, O.O., Kumaraswamy, M.M., Wong, A., Ng, S.T., 2006a. Sustainability appraisal in infrastructure projects (SUSAIP) Part 1. Development of indicators and computational methods. Autom. Constr. 15, 239–251. https://doi.org/10.1016/j.autcon.2005.05.006

Ugwu, O.O., Kumaraswamy, M.M., Wong, A., Ng, S.T., 2006b. Sustainability appraisal in infrastructure projects (SUSAIP): Part 2: A case study in bridge design. Autom. Constr. 15, 229–238. https://doi.org/10.1016/j.autcon.2005.05.005

Webb, R., Bai, X., Smith, M.S., Costanza, R., Griggs, D., Moglia, M., Neuman, M., Newman, P., Newton, P., Norman, B., Ryan, C., Schandl, H., Steffen, W., Tapper, N., Thomson, G., 2018. Sustainable urban systems: Co-design and framing for transformation. Ambio 47, 57–77. https://doi.org/10.1007/s13280-017-0934-6

Witjes, S., Lozano, R., 2016. Towards a more Circular Economy: Proposing a framework linking sustainable public procurement and sustainable business models. Resour. Conserv. Recycl. 112, 37–44. https://doi.org/10.1016/j.resconrec.2016.04.015

Wu, X., Zhao, W., Yang, Z., 2019. Improving the Efficiency of Highway Construction Project Management Using Lean Management. Sustainability 11, 3646–3652.

Yang, W., Qi, Z., 2016. Quantification of CO_2 emissions of macro-infrastructure in China with simplified life cycle assessment. Nat. Hazards 82, 545–569. https://doi.org/10.1007/s11069-016-2197-0

Yicai. [WWW Document], n.d.

Zavrl, M.S., Zeren, M.T., 2010. Sustainability of Urban Infrastructures. Sustainability 2, 2950–2964. https://doi.org/10.3390/su2092950

Zeng, H., Chen, X., Xiao, X., Zhou, Z., 2017. Institutional pressures, sustainable supply chain management, and circular economy capability: Empirical evidence from Chinese eco-industrial park firms. J. Clean. Prod. 155, 54–65. https://doi.org/10.1016/j.jclepro.2016.10.093

Zhang, K., Wen, Z., 2008. Review and challenges of policies of environmental protection and sustainable development in China. J. Environ. Manage. 88, 1249–1261. https://doi.org/10.1016/j.jenvman.2007.06.019

Zhong, Y., Wu, P., 2015. Economic sustainability , environmental sustainability and constructability indicators related to concrete- and steel-projects. J. Clean. Prod. 108, 748–756. https://doi.org/10.1016/j.jclepro.2015.05.095

Zhu, J., 2018. Efforts for a Circular Economy in China. A Comprehensive Review of Policies. J. Ind. Ecol. 23, 110–118. https://doi.org/10.1111/jiec.12754

4. Introducing Circular Economy (CE) in the Infrastructure Construction Sector: Comparing Sectoral Innovation Systems (SIS) in China and the Netherlands[16]

4.1 Introduction

The construction sector is responsible for a significant share of energy-related carbon emissions as well as materials across the world (EIA, 2013), which threatens achieving the SDGs. At the same time, compared to other economic sectors, progress toward sustainability is particularly slow in the construction sector (Faber and Hoppe, 2013; Vermeulen and Hovens, 2006). One reason lies in the character of the sector, which is perceived as closed, fragmented, conservative, and risk-averse (Van Bueren, 2009). Within the construction sector, scholarly attention to innovation mostly focuses on buildings, like high-profile BREEAM and LEED projects (Hubbard and Hubbard, 2019), and less on infrastructures.

CE can be seen as a conceptual innovation that influences businesses and entire supply chains in economic sectors (Konietzko et al., 2020; Moraga et al., 2019; Morseletto, 2020; Tam et al., 2019; Vecchio et al., 2020; Brown et al., 2019; Trica et al., 2019), making it an intrinsic issue for sectoral innovation. As a sustainability approach with an innovative emphasis on materials, CE is gaining traction (Ranta et al., 2018). This is indicated by increasing numbers of academic publications on CE innovation studies, which particularly highlight developments in China and the European Union (EU) (Türkeli et al., 2018). In the early days of CE introduction to economic sectors, China and certain EU countries like the Netherlands were regarded as front-runners. For this reason, it is worthwhile exploring how CE was introduced in China and EU countries. Yet, they differ in the ways CE is emphasized. China adopt a broader conceptual focus that incorporates pollution and other issues alongside waste and resource concerns, whilst framing CE as a response to the environmental challenges created by rapid growth and industrialization. In contrast, the EU have adopted a narrower environmental scope to CE, focusing more on waste, resources, and business opportunities (McDowall et al., 2017, p651). These two different approaches offer the opportunity to compare how CE is achieved at the meso-scale (Ranta et al., 2018; Liu et al., 2024)), where the scale urban infrastructure construction works fall in.

Overall, the transition towards sustainability and CE in the construction sector can be considered as an innovation transition, where the CE introduction is gaining a foothold, albeit slowly (Liu et al., 2019; Schraven et al., 2019; Munaro et al., 2021). This raises questions on how CE is introduced and which conditions as well as incentives affecting conditions encourage effective introduction of CE in economic sectors. More in general, it raises attention on how to encourage sustainable innovation at the sector level. Encouraging innovation is key to sectoral economic development, both for the private sector and public sector, while

[16] This chapter is based on: **Liu, X.Y.,** Schraven, D., Hoppe, T., Wu, J., Hertogh, M. and de Jong, M. (2024) "Introducing Circular Economy in the infrastructure construction sector: Comparing sectoral innovation systems in China and the Netherlands" ***Sustainable Futures*** (under the 2nd round review)

innovation can help in meeting public policy goals like SDGs (Matatkova and Stejskal, 2013). A suitable approach to understanding the introduction of CE innovation in the construction sector is Sector(al) Innovation Systems (SIS) (e.g., Chan and Daim, 2012). Deriving from the broader body of literature on Innovation Systems (IS), SIS adopts a sociotechnical system approach to see what conditions influence the adoption of innovations, and how this can be organized at the sectoral level (Kubeczko et al., 2006). It approaches real-life events, experiences, and case studies of innovation to draw out the main barriers and drivers. This also applies to analyzing and presenting cases from championing countries, which reveals the conditions and mechanisms under which SISs emerge and contribute to the effective take-up of sustainable innovation in selected economic sectors. This also applies to observing (typical) challenges that emerge preventing SIS development, and to identify, assess, or come up with (managerial, policy) solutions to resolve these. For this reason, we adopt an SIS approach to analyze CE introduction in the infrastructure construction sector in two CE front-running countries, i.e., China and the Netherlands. To date, no attempt has been made to study CE innovation in this sector using an SIS approach.

Therefore, this paper tries to answer the question: "What are the main barriers and potential ways forward to effectively implement CE innovation in the infrastructure construction sector?" In so doing, we use SIS to study sociotechnical system conditions for CE innovation adoption, and more particularly to observe experiences in two countries with challenges firsthand, and the noticeable steps taken in coming up with solutions to make their infrastructure sectors more circular. The paper is structured as follows. First, the theoretical background of SIS (within the broader IS) literature is presented (Section 4.2). Next, Section 4.3 presents the research design and methodology, which includes a rationale for selecting the front-running cases of Jiangsu province (China) and the Netherlands (EU). Methodology includes the analysis of the context, as well as perceptions of experienced, knowledgeable stakeholders in these cases, and a multi-case comparative analysis. Section 4.4 presents results, comparing the cases, whilst discussing the main insights for implementing CE in the infrastructure sector from an SIS perspective. In Section 4.5, the results of this chapter are discussed. Section 4.6 offers concluding remarks, limitations, and future recommendations on policy and research.

4.2 Theoretical Underpinning

In this section, the theoretical underpinning of the SIS literature is provided and then used to motivate the key aspects of a circular infrastructure construction sector as an IS innovation system.

4.2.1 Innovation System (IS) Perspectives for a Circular Infrastructure Sector

IS can be referred to the statement that "systems of innovation are networks of institutions, public or private, whose activities and interactions initiate, import, modify, and diffuse new technologies" (Negro et al. (2008). An IS consists of four key components: i.e., actors, networks, institutions, and technologies. IS is an increasingly favored approach for discerning patterns of development as well as implementation of technologies as well as innovations. It is also used to study socio-technical change (Goess et al., 2015). Introducing CE to the infrastructure construction sector to get CE principles adopted can be seen as a process of socio-technical, even transformative, change.

Since its conception in 1991 (Carlsson and Stankiewicz, 1991), the IS literature has spawned various concepts proposing ways to organize innovation among multiple organizations. This has been conceived for different geographical levels, like the national level (e.g., Fagerberg et al., 2018; Gray, 2011; Intarakumnerd et al., 2002; Lee and Park, 2006; Mowery, 2011, 1998, 1992; Sun and Liu, 2010) and the regional level (e.g., Belussi et al., 2010; Doloreux and Parto, 2005; Liu and Chen, 2003). For the infrastructure sector, these levels serve as a context for the innovation system.

In addition, different conceptual approaches to IS have been conceived with different foci regarding innovation, pertaining to technology, the economic sector, and missions (Hekkert et al., 2020). Concerning CE, it can be argued that an IS targets the uptake of sustainable technologies, like bio-based or recycling technologies. Furthermore, intentional transformative change from traditional (unsustainable) to circular infrastructure implicitly also means changing key economic processes in the sector, like procurement and demolition. More recently, missions were also conceived as a new version of IS: Mission-oriented Innovation Systems (MIS) (Hekkert et al., 2020), even in infrastructure (Coenen et al., 2023). However, missions are not always clear, particularly in CE. Recent insights reveal that the role of missions themselves is not yet clear for a broad phenomenon with many facets like CE (Coenen et al., 2023).

4.2.2 Sector Innovation Systems (SIS) as an Analytical Approach

SIS was developed as an analytical framework to analyze and understand innovation dynamics within and across various sectors (Malerba, 2002; Hansen et al., 2018) by analyzing actors, networks, institutions, and technologies. To understand the analytical approach to SIS a bit more in-depth, first a brief understanding must be provided about the functions of an IS system.

In essence, for an IS to be successful, certain conditions must be present and processes need to be functioning well. Determinants can be identified as processes that influence the development, diffusion, and application of a given innovation. These so-called system functions are related to the character of, and the interactions among the components of an innovation system, i.e., agents (e.g., firms and other organizations), networks, technological regime(s), and institutions (Negro et al., 2008). The notion of "function" creates insight into the dynamics as well as possible patterns of (socio)technological change and related innovation processes (Hekkert et al., 2007).

SIS has been applied to analyze innovation dynamics in several sectors. A handful of examples includes, amongst many others, healthcare services (Savory and Fortune, 2014), forestry in the Czech Republic (Jarský, 2015), the sustainable built environment in the Netherlands (Faber and Hoppe, 2013), green buildings in Singapore (Siva et al., 2017), the transportation sector in China (Chan and Daim, 2012), and power generation technologies (Rogge and Hoffmann, 2010). From these studies, it becomes clear that the SIS approach can be used to analyze a given sector surrounding a specific technology or (other types of) innovation, with an analytical focus at a country or regional level.

An SIS approach can help to identify system failures and deadlocks within/across certain sectors (Faber and Hoppe, 2013). Among the multiple innovation system concepts, SIS has a strong analytical focus on describing collective emergent outcomes of co-evolutionary interactions among the core building blocks of a system or sectoral market (Malerba, 2002; Siva et al., 2017). Besides the reasons mentioned, similar to Siva et al. (2017)'s research, the focus of the present study is on a single economic sector (i.e., infrastructure construction). However, to date, there is no scholarly attention to applying SIS to cases addressing the introduction of CE to economic sectors[17].

Any sectoral system analysis involves an overview of the main agents in the sector, including their interactions, formal and informal networks (Faber and Hoppe, 2013). Among SIS used in previous studies (e.g., (Rho et al., 2015; Savory and Fortune, 2014)), Siva et al. (2017) presented the most specific conceptualization of SIS, which contains the four key components: technological regime, market demand, actor interactions and networks, as well as institutional framework (See Fig. 4.1).

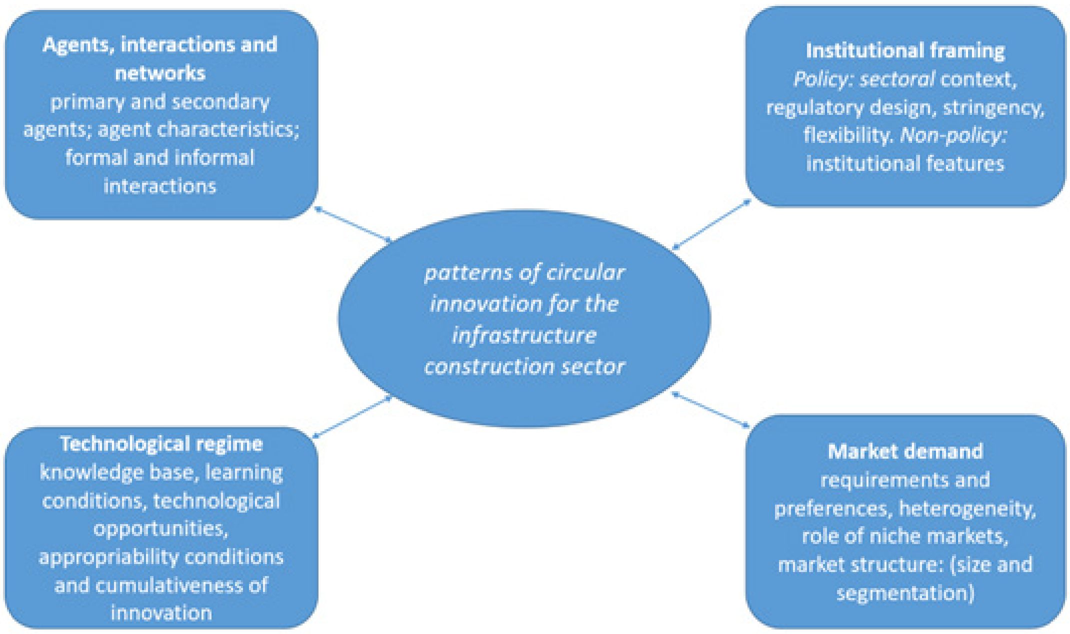


Figure 4.1 Dimensions of patterns of innovation and their interaction in the infrastructure construction sector (adapted from (Faber and Hoppe, 2013))

Technological Regime: Innovations are developed and eventually introduced in a specific socio-technical context made up of tacit and explicit knowledge, sunk costs, learning conditions, complementarities, and interdependencies (Malerba, 2002). In SIS this has been elaborated into four main aspects (Siva et al., 2017): 1) Technology: refers to novel technologies, the economic feasibility of these new technologies, and the extent to which these new technologies are implemented; 2) Complementarities and interdependencies: refers to whether new technologies complement or replace existing technologies, and whether a technology is interdependent on other technologies; 3) Knowledge base: refers to

[17] There are no relevant results when using the query "(TITLE-ABS-KEY (circular AND economy) AND TITLE-ABS-KEY ("sector* innovation system" OR "SIS"))" to search in Scopus on Jun. 20, 2023.

the extent crucial knowledge is available, and to methods by which this knowledge is disseminated and communicated; 4) Learning conditions: refer to both internal and external learning processes as well as opportunities to learn.

Market Demand: Demand stems from the preferences of end-consumers, mostly revealed by actual consumer choices. It is important to encourage understanding of the role of end-users in the innovation process by considering their perceptions and practices concerning adopting a given innovation, and how this translates into demand (Siva et al., 2017).

Agents, Interactions, and Networks: Agents include individuals and organizations, which interact through processes of communication, exchange, cooperation, competition, and command (Malerba, 2004). The level of formal and informal interactions among the agents is also considered; such interactions can take place for example through platforms for networking and knowledge-sharing (Siva et al., 2017).

Institutional Framework: Institutions include various formal and non-formal rules; formal rules stem from government legislation, regulation, policies, and initiatives; while informal rules refer to routines, common habits, established practices, and standards (Siva et al., 2017). All of these shape agents' cognitions and actions, and influence inter-agent interactions (Malerba, 2004, 2002).

4.3 Methods and Materials

In this section, it is explained how the SIS framework is applied to the multi-case study of CE introduction in the infrastructure construction sectors in the Chinese Jiangsu Province and the Netherlands using surveys. This study aims to cover and analyze all four SIS components of the infrastructure construction sector. It does so by adopting a survey and multi-case research design. First operationalization is discussed and then comes case selection as well as research methods.

4.3.1 Case selection

As mentioned in Section 4.1 cases are selected from China and the EU because both are considered to have regions/provinces or countries that are considered front runners in CE introduction. However, the cases also have to be fairly comparable in terms of several socio-demographic and economic indicators.

In the EU, the Netherlands is considered to be one of the European pioneers of CE-related initiatives (Mazur-Wierzbicka, 2021). Here, high-reaching ambitions for CE are created by the Dutch government and public organizations for the infrastructure industry (Kupers, 2021). Considering China is a large country (compared to the Netherlands), Jiangsu Province (one of the first pilot areas of CE in China) was selected as a representative area of China. It was partly because all the 13 cities in Jiangsu Province are "circular cities"[18]. Thus Jiangsu can be recognized as a pioneering CE province in China.

Considering CE as an innovation transition to the infrastructure construction sector, the use of an SIS perspective can help compare the CE implementation in the infrastructure

[18] http://www.stats.gov.cn/ztjc/ztfx/fxbg/200512/t20051201_15892.html (accessed on Oct. 22, 2021)

construction sector in China's Jiangsu (as a decentralized jurisdiction of China) and the Netherlands (as a local context of the EU) as well as make comparisons between these two distinct geographic areas (for example among aspects such as market structures, institution and ways to transit to CE). Fig. 4.2 presents a geographical depiction of the locations of Jiangsu in China and the Netherlands in the EU.

Table 4.1 Some socio-demographic and economic indicators of Jiangsu Province and the Netherlands

	Population	**Area**	**GDP**
Jiangsu Province	85.15 million (by the end of 2022)[19]	107.2 thousand km^2 [20]	12.29 trillion RMB[21] (2022)[22]
the Netherlands	17.40 million (2020)[23]	4.15 thousand km^2	0.99 trillion USD (2022)[24]

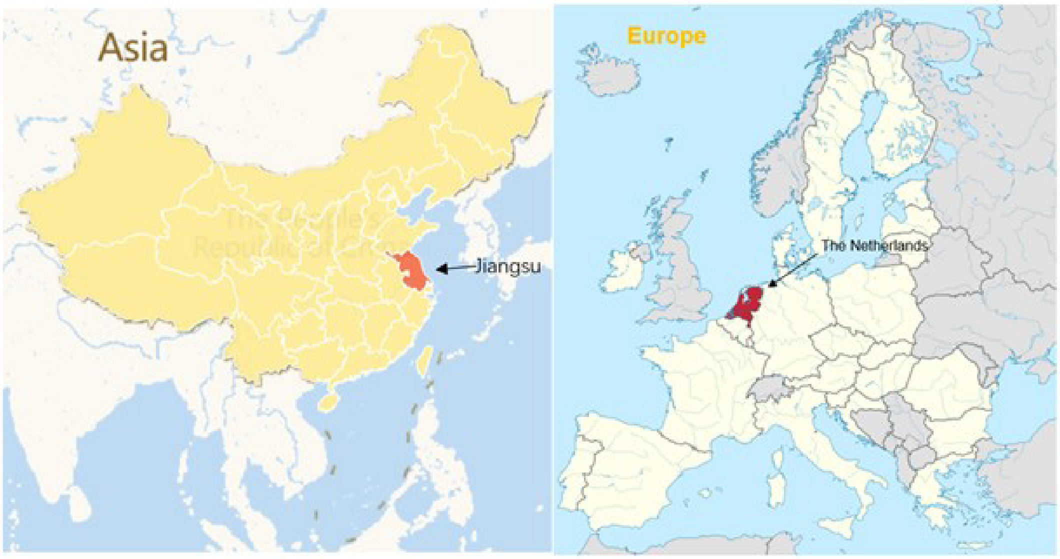


Figure 4.2 Jiangsu Province (left) and the Netherlands (right) (own figure)

4.3.2 Data Collection, Processing and Analysis

To analyze and compare SIS uniformly, an online survey was conducted. A questionnaire

[19] https://www.jiangsu.gov.cn/col/col88749/index.html (accessed on Oct. 31, 2023)

[20] https://www.jiangsu.gov.cn/col/col88747/index.html (accessed on Oct. 31, 2023)

[21] RMB: Chinese currency, 100 RMB equals about 12.92 EUR.

[22] http://jswx.gov.cn/yw/202302/t20230201_3154811.shtml (accessed on Oct. 31, 2023)

[23] http://nl.china-embassy.gov.cn/zhgx/zzgx/201410/t20141022_2887221.htm (accessed on Oct. 31, 2023)

[24] https://www.163.com/dy/article/HTL885HT0517BT3G.html (accessed on Oct. 31, 2023)

(see the Appendix C) was used covering the main components of SIS and their sub-items (See Fig. 4.1). Using a survey for an SIS study has been done before (e.g., (Kubeczko et al., 2006)). The questionnaire contains a mix of open questions (e.g., Which actors are more influential than others? Please provide arguments.), single/multiple choice questions (e.g., Please select your role in the infrastructure construction sector.), and rating questions (e.g., Please rate the level of your participation in these platforms).

In the infrastructure construction sector, economic processes are often guided through projects, where stakeholders participate (so-called primary agents). In this regard, stakeholders are defined as "persons and organizations such as customers, sponsors, the performing organization, and the public that are actively involved in the project, or whose interests may be positively or negatively affected by the execution or completion of the project" (PMI, 2014, p. 246). In addition, there are more general (or secondary) stakeholders for the whole economic sector since it lumps a portfolio of projects. The views of primary and secondary stakeholder lists can be quite diverse (Di Maddaloni and Davis, 2017; Safapour et al., 2019). Often, different stakeholder lists can be found (e.g., (Xie et al., 2014)).

For purposes of this study, it is considered that there are different characteristics between projects and the sector at large. Therefore, a purposive sampling approach is used. As part of this sampling, primary stakeholders are considered as those that are pivotal in the sector, i.e., without which a project cannot be finished. Based on relevant literature (Di Maddaloni and Davis, 2017; Safapour et al., 2019), the list of primary stakeholders for the infrastructure construction sector includes clients, designers, material suppliers, engineering/technical consultants, government officials, investors, and contractors. Secondary stakeholders refer to those who serve more supportive roles and are not always needed for realizing projects. A list of secondary stakeholders includes financing parties, finance consultants, law consultants, the general public and community residents, academic researchers, and the media. Stakeholders were selected to provide a valid representation of the infrastructure construction sector stakeholder ecosystem and to avoid selection bias.

For both cases, for each primary stakeholder role, at least two respondents were targeted for this study; while for each secondary stakeholder role, at least one respondent was required. Next to the general questions, respondents were asked to answer an additional number of tailored questions, based on the characteristics and role of different stakeholders as well as their position in the infrastructure construction sector sociotechnical system. These questions were assigned to roles based on the expected relevance of their knowledge and experience. The order of questions was programmed with Microsoft Forms, and the survey was prepared as well as translated into Chinese for the Chinese respondents. English and Dutch versions were offered for the Dutch respondents. The survey links are shown in Appendix D. The questions and how they were set to different stakeholder roles are listed in Appendix C and E respectively. In total, 23 Chinese respondents and 27 Dutch respondents completed the survey. The list of respondents is shown in Appendix F. In total 23, respondents completed the survey for the Jiangsu case and 27 for the Dutch case.

After the respondents completed the survey, the survey data were downloaded and arranged in a database based on the SIS framework. The roles of all the respondents in the infrastructure construction sector are known to the first author and their answers were checked by the first author for confirmation that they chose the correct stakeholder roles to ensure validity.

Besides survey data, relevant documents, websites, and articles, were also collected and analyzed. This information was also organized following the SIS framework.

The comparative study involves a confrontation of responses offered by parties from both cases. The type of data was both qualitative and quantitative based on elements of the SIS framework. Comparison between the cases was done by comparing relative and raw frequencies of items deriving from the four key components of the SIS theoretical framework.

4.4 Results

In this section, we show the results of the two cases. First, we provide a brief discussion of the context for each case. Then a comparison is made concerning the four parts of the SIS framework.

4.4.1 Context of Cases

In China, CE has been adopted by the central government as a national development strategy for pursuing SD (Guo et al., 2017). *The Promotion Law of Circular Economy in China* is the first CE law in the world, and it is also one of the quickly issued laws in China. Different lower levels of government within China also launched regional CE regulations. The policy "*Several Opinions of the State Council on Accelerating the Development of Circular Economy"* makes the development directions and the key tasks of Chinese CE clear, and provides the organizing, coordinating, and leading role of the National Development and Reform Commission for the promotion and development of CE. *Opinions on Accelerating the Construction of Ecological Civilization* further makes it clear to "adhere to green, circular and low-carbon development and hold CE as the basic way for the construction of ecological civilization". Other national CE policies include *Measures for the Administration of Recycling of Renewable Resources, Circular Development Leading Actions*, and so on. The resource output ratio (in terms of GDP created with the consumption of unit resources) is the key indicator of CE in China. The Ministry of Finance as well as the National Development and Reform Commission set special funds for CE development, supporting the construction of key CE projects. Central government departments such as The People's Bank as well as the National Development and Reform Commission issued the "*Notice on Opinions on Investment and Financing Policies" and "Measures to Support the Development of Circular Economy"*. The Chinese central government has devoted financial funds of over 10 billion RMB (roughly 1.3 billion euros) to effectively motivate business enterprises to construct CE projects, causing social investment of more than 100 billion RMB. There are also local policy instruments such as the *Jiangsu Province Circular Economy Pilot Implementation Plan*[25].

The EU is in the process of transformation towards a CE model, which was announced in 2014 (Smol et al., 2020). With the introduction of The Roadmap to a Resource Efficient Europe (2011) and the later commitment of The Action Plan towards the Circular Economy (2015), the European Commission (EC) has expressed its fundamental interest to substantially improve the resource efficiency of the European economy and enable the transition towards

[25] http://www.js.gov.cn/art/2007/10/22/art_47048_2682145.html (accessed on Jun. 1, 2021)

CE (Domenech and Bahn-Walkowiak, 2017). European Environment Agency (EEA) survey results indicate that 21 out of 32 responding EEA member countries already support CE initiatives, including the Netherlands. Once a year, the Ministry of Infrastructure and Water Management (IenW) in the Netherlands organizes the National Circular Economy Conference (in Dutch), and every other year the Netherlands Environmental Assessment Agency (PBL) publishes a monitoring progress report. In the next sections, the results of the survey are presented and discussed.

4.4.2 Technological Regime

4.4.2.1 Technologies

The technology categories that were considered by the Chinese and Dutch respondents (9 and 11 respectively for this question) that are dominantly used to implement CE in their respective infrastructure construction sectors are shown in Fig. 4.3. It shows that re-use and renewable energy technologies are considered to be used most in both cases, while biological processes, bio-materials, and digital technologies are considered to be used least. Whereas Jiangsu respondents were more positive about re-use technologies than Dutch respondents, the latter are more positive about digital technologies than the former.

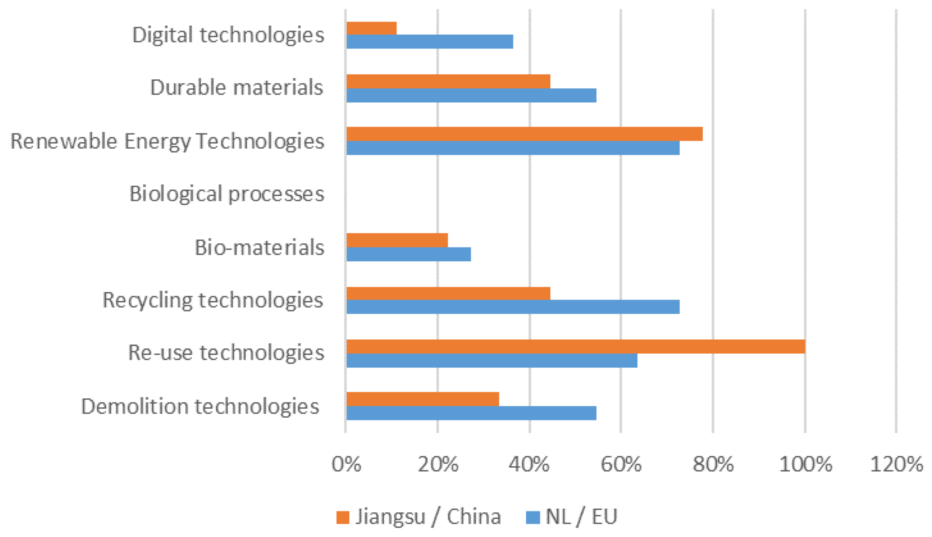
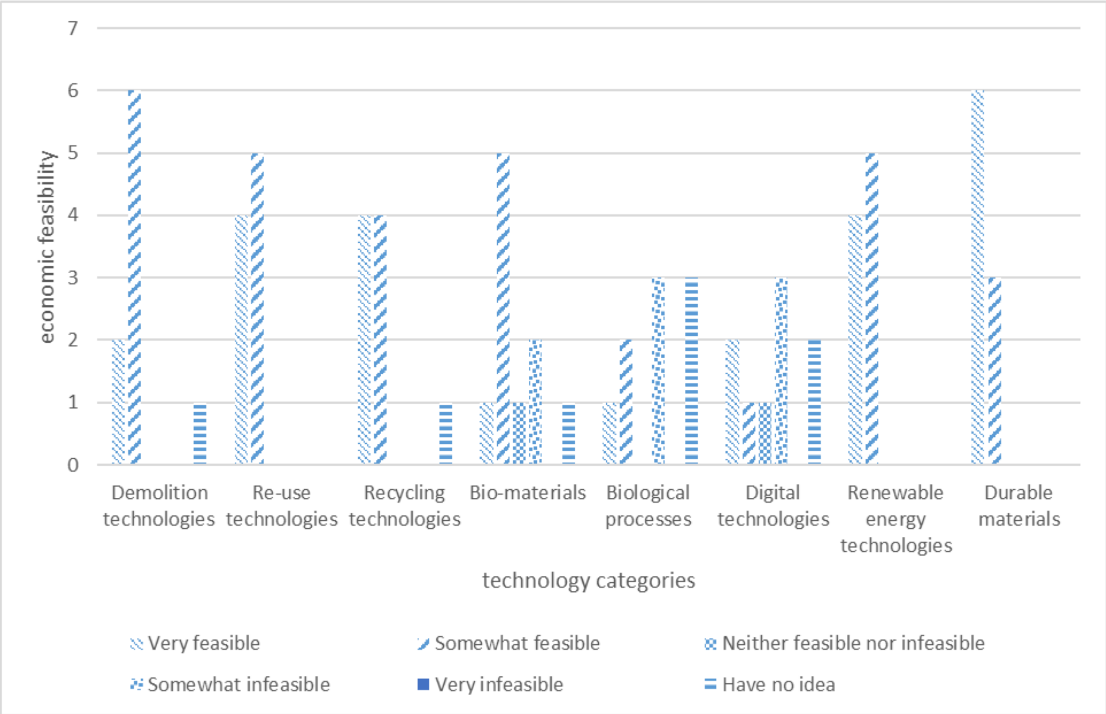
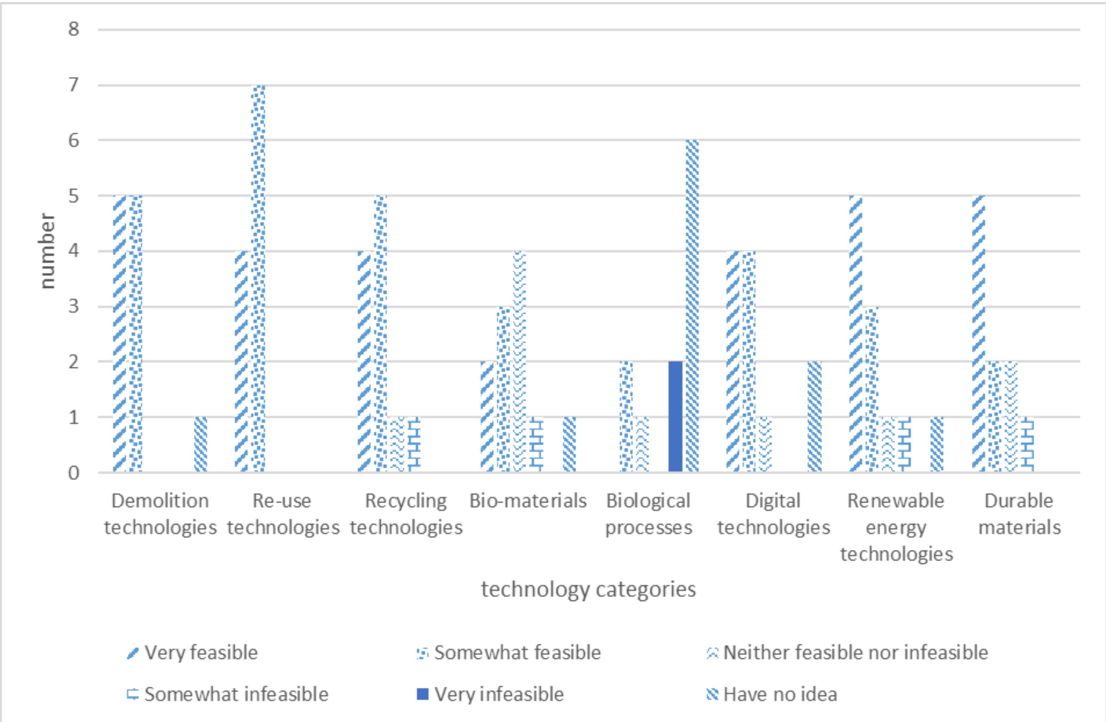


Figure 4.3 Technology categories considered mostly used to implement CE in the infrastructure construction sector (own figure; EU, European Union)

Views from the respondents about the economic feasibility of implementing each of these technology categories are shown in Fig. 4.4.



(a)



(b)

Figure 4.4 Perceived economic feasibility of implementing each of the technology categories according to respondents from the Jiangsu case (a) and the Dutch case (b) (own figure)

From Fig. 4.4 (a), demolition, re-use, recycling, renewable energy technologies, and durable materials are considered economically feasible. Most Jiangsu case respondents argued that the eight technology categories have been implemented successfully in China, except for Academic researcher CN1 (hereafter AR-CN1), who expressed that biological technology is relatively expensive. Engineering/Technical consultant CN1 (E/TC-CN1) provided several examples of using recycled aggregate concrete (RAC), solar photovoltaic and wind power generation, high-strength steel bars, and concrete. Similarly, besides the last three, Material supplier CN1 (MS-CN1) added geothermal energy. However, Designer CN1 (D-CN1) also pointed out that the implementation scope should be broadened further in the future.

Somewhat similar to the Jiangsu case, demolition, reuse, recycling, renewable energy technologies, durable materials, and digital technologies are generally considered economically feasible by the Dutch respondents (Fig. 4.4 (b)).

Most Dutch respondents were positive about the already successful implementation of certain technology categories. Academic researcher NL1 (hereafter AR-NL1) specifically pointed out that asphalt recycling is widely used. Engineering/Technical consultant NL2 (E/TC-NL2) argued that (whether these technology categories have been implemented successfully in the Dutch infrastructure construction sector) demolition technologies are considered very feasible. Reuse of elements and/or objects is also considered very feasible given the focus on value retention, certification, and demonstrability. In addition, digital technologies are considered promising and scalable because they are easy to reproduce.

AR-NL2 and E/TC-NL1 generally held different views compared with the former respondents. AR-NL2 considered that all the technology categories have already been technically applied, but they will only become economically profitable when they are scaled up. E/TC-NL1's opinions were even further: for reuse technologies, he saw there is a lack of storage capacity; for recycling technologies, he thought a lot of recycling is already done in civil engineering, but this is not always high-quality and there is downcycling.

In sum, in both cases bio-materials, biological processes, and digital technologies are still considered rather underdeveloped, infeasible, and in need of further development.

4.4.2.2 Complementarity and Interdependencies

Respondents held different views about whether CE is aligned to or at odds with existing technologies in the Jiangsu infrastructure construction sector. Contractor CN2 (C-CN2), for example, argued that although CE is ahead of existing technologies, it should still be introduced to the infrastructure construction sector. On the contrary, E/TC-CN1 considered CE to align well with existing technologies in the sector, as quite some CE technologies are considered mature and are already used. Material supplier CN1 (MS-CN1) argued that since traditional construction modes waste large amounts of natural resources, CE is urgently needed in the sector; and quite some technology categories can be applied to infrastructure construction. However, this will only likely take place once (compulsory) promotion (i.e., regulation) at the national level is applied. Even though the respondents did not reach a consensus about this question, a majority of the respondents advocated that CE is needed in the sector. In the Dutch case, a majority of the respondents held that CE currently complements existing technologies in the Dutch infrastructure construction sector rather well.

4.4.2.3 Knowledge Base

For the Jiangsu case, most respondents argue that the general knowledge level of CE in the infrastructure construction sector needs further improvement. C-CN2 (and D-CN2) considered that CE is a new "concept" in the Chinese infrastructure construction sector still.

E/TC-CN1 argued that green building and endurance/sustainability/long-lasting are becoming the main characteristics of Chinese infrastructure. For the Dutch case, most respondents argued that the existing pool of knowledge on CE in the infrastructure construction sector is not good enough. Client NL2 (hereafter CI-NL2) stated that "(the knowledge base) is under development, but it is not equipped for realizing a CE in 2050". E/TC-NL1 expressed "There is much to be learned about the theory of CE and how to apply it". E/TC-NL2 mentioned two levels: "At a strategic level, a lot has been devised and CE is used as a buzzword. The implementation could be much better. At the tactical level, tools and processes are needed". D-NL1's opinion was "Recycling takes place on a large scale in the Netherlands. But beyond that, the knowledge about CE is still very limitedly concentrated among a small group of enthusiasts". According to AR-NL2, "many initiatives and demonstrators underway that mainly demonstrate the technical feasibility, but not yet/hardly the economic feasibility". While MS-NL2 considered that there are already various platforms available that provide good information, such as "circularebouweconomie"[26], platform CB'23[27] and https://decirculaireweg.nl/.

4.4.2.4 Learning

Examples of ways by which relevant learning outcomes of CE implementation in Jiangsu are shared include seminars, presentations, workshops, and articles (Client CN1, hereafter CI-CN1); media promotion (AR-CN1); demonstration promotion and technology communication (E/TC-CN1); forum communication and demonstration project promotion (AR-CN2); new technology promotion (MS-CN1); promotion of technology companies (D-CN1); technology communication conferences (C-CN1); school learning and online post (D-CN2).

Besides the ways the Chinese respondents proposed, there are also academic CE journals in China, such as *Environmental Protection and Circular Economy*, *China Circular Economy*, and *Renewable Resources and Circular Economy* (all in Chinese).

According to the *Regulations of Jiangsu Province on the Promotion of Circular Economy*[28], local governments and related departments should organize the publicity and education of CE, promoting green, low-carbon, and circular development modes; encourage and support enterprises, research institutions and universities to conduct research, development, promotion and application of CE; middle and primary schools, universities, and vocational schools/training institutions should educate students about CE ideas and knowledge; efforts should be made to encourage and support social organizations such as intermediary agencies and industry associations to conduct CE dissemination, and services such as CE technology guidance and consultancy.

Most respondents in the Dutch case provided examples of how relevant learning

[26] https://circularebouweconomie.nl (accessed on Jun. 1, 2021)

[27] https://platformcb23.nl/. Platform CB'23 wants to connect construction-wide parties with circular ambitions, both in the civil engineering sector and in residential and non-residential construction. The aim is to draw up national, construction sector-wide agreements on circular construction before 2023. (https://platformcb23.nl/over-platform-cb-23 accessed on Aug. 19, 2021)

[28] http://www.jsrd.gov.cn/zyfb/sjfg/201511/t20151127_268872.shtml (accessed on Jun. 1, 2021)

outcomes are shared. CI-NL1 mentioned trade press, internal company communication, and seminars; AR-NL1 mentioned pilots, media publications, and conferences; and E/TC-NL1 mentioned pilot programs or professional media (Cobouw[29]). D-NL2 expressed "Incidentally, learning results are shared in our own company during lunch lectures, etc., but online platforms are also used for this, including LinkedIn". C-NL3 mentioned working groups (in large companies). E/TC-NL2 mentioned learning from experimentation: "Circular road is an interesting testing ground, includes a program that is decentralized where each project takes a circular aspect and unites these findings at a strategic level, and is based on network functioning principles. It will be decisive for the transition to a CE".

4.4.3 Market Demand Creation

For the Jiangsu case, several issues were mentioned as being considered important to create more market demand for civil infrastructures, i.e.: "high-quality, align and in harmony with the environment, assure good revenue" (C-CN1); "long-lasting and low costs of operation and maintenance" (MS-CN1); "safe and nice" (C-CN1); "the balance of functions and costs" (D-CN2); "low-cost, high-quality and durable". CI-CN2 argued that infrastructures should provide benefits to citizens and also offer sustainable benefits. However, respondents have different opinions. In sum, respondents hold that it is important that CE meet certain expectations Chinese clients have in terms of traditional project aspects such as quality and cost, as these are considered crucial to realize successful projects.

In the Dutch case, respondents presented similar answers. GO-NL1 mentioned safety, availability (with minimal time loss due to maintenance activities), and low cost (from the taxpayers' perspective); AR-NL1 mentioned technical reliability, long life, limited maintenance costs, environmentally friendly and cost-effectiveness; and according to AR-NL2, customers expect good quality at a low price. E/TC-NL1 mentioned "minimal costs in realization, management and maintenance"; GO-NL2 thought that "Infrastructure fulfils a social need. This is often a need for mobility, driven by economic motives like accessibility, speed, and efficiency"; E/TC-NL2 argued "Infrastructure is a public good, having an important social and economic function. MS-NL2 argued that "Sustainability (i.e., CE) means having a long infrastructure technical life span, low environmental impact whilst operating energy neutral". Most of the respondents did not think these expectations go hand in hand with implementing CE. GO-NL1 wrote, "Low-cost perspective and risk aversion do not always work well with innovation and new approaches". CI-NL1 expressed, "There is the impression that a lot is already happening, but it is becoming difficult to make progress, to have an impact".

Similar to the Jiangsu case, it can be concluded that it is important that CE implementation sufficiently pays attention to matching the expectations of clients, particularly in terms of aspects such as quality and cost.

4.4.4 Agents, Interaction and Networks

4.4.4.1 Actors

Fig. 5 presents the stakeholders that are considered involved in developing CE in the

[29] https://www.cobouw.nl/ (accessed on Aug. 19, 2021)

infrastructure construction sector.

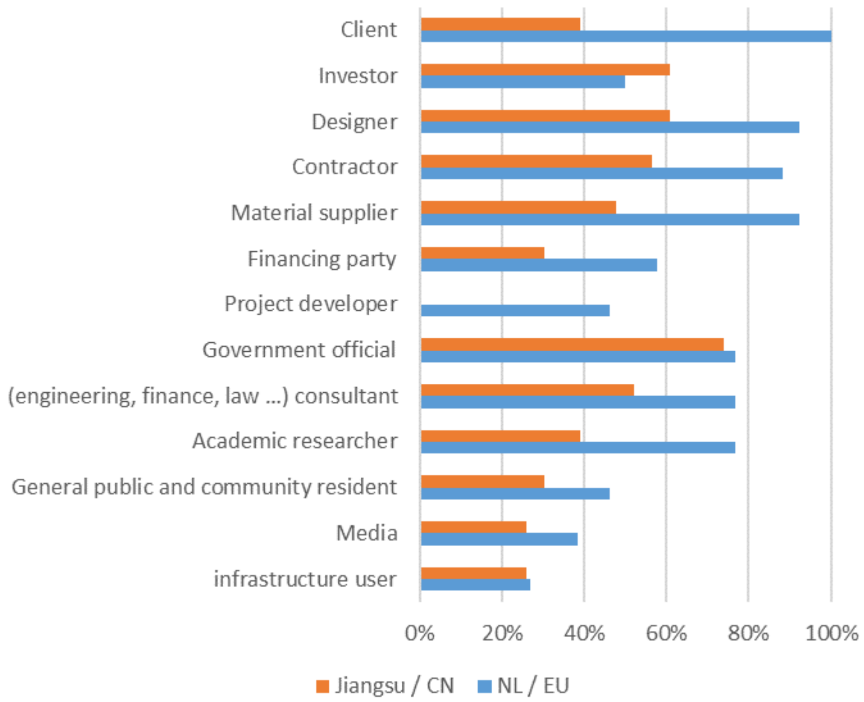


Figure 4.5 Actors considered to be involved in introducing CE to the infrastructure construction sector (own figure)

In the Jiangsu case, demand side actors are considered less involved. Respondents argued that government officials are the actors considered most involved with CE. There is little surprise as the Chinese government is important in infrastructure development.

As for which actors are most influential, AR-CN1 mentioned that decisions made by contractors are most influential. However, MS-CN1 held that investors and technical consultants are more influential. D-CN1 argued that investors and governments are the most important because they can provide requests, and C-CN1 offered designers and contractors directly.

Contrary to the Jiangsu case respondents, the Dutch case respondents held that clients have a more important role than investors. CI-NL2 proposed "Clients, because they have to create space for pilots and more sustainable (validated) alternatives; contractors and suppliers, as they must develop more sustainable alternatives"; AR-NL1 wrote, "The client has the greatest influence; he ultimately determines how sustainable the road will be through the commissioning and specifications". As for which actors are more influential than others, GO-NL1 mentioned the Ministry of the Interior (full name: The Ministry of the Interior and Kingdom Relations, BZK), RWS and ProRail[30]. D-NL1 argued RWS as they are the largest client

[30] ProRail, as an independent party is a railway manager. This means that it is responsible for the maintenance, renewal, expansion and safety of the Dutch railway network. (https://www.prorail.nl/over-ons accessed on Aug. 19, 2021)

for infrastructure in the Netherlands; they determine the rules of the game. General public and community resident NL1 (GPCR-NL1) considered clients and the government as important actors as they send money, draw up the rules and agreements regarding construction works, and can also do so in a binding manner. GPCR-NL2 held that “Clients have the most influence as they have a virtual monopoly on the awarding of infrastructure assignments; they are again mainly influenced by politics”. In sum, respondent preferences regarding the importance of certain actors vary among the two cases, but in general, the government was considered as a very important actor, and in the Dutch case, the clients were also considered to have an influential role.

4.4.4.2 Interactions and Networks

For the Jiangsu case, 5 out of 23 respondents argued that there are platforms where knowledge is shared and actors are interacting regarding CE in the Chinese infrastructure construction sector. On the contrary, seven respondents disagreed. Table 4.2 presents an overview of the platforms mentioned with respondents rating their involvement in these platforms.

Table 4.2 Platforms where knowledge is shared and actors interact regarding CE (the Jiangsu case)

Respondent	the 1st platform	the 2nd platform	the 3rd platform	the 4th platform
Client CN1	Sector associations and forums ****			
Academic researcher CN2	Forum of China Construction Industry Association ***	Construction and Solid Waste Treatment Forum ****	Green Construction Forum ****	Green Building Conference ***
Material supplier CN1	Designers’ Society *****	Construction Units’ Association ****	New Technology Promotion Station *****	
Contractor CN1	Academic Associations *****			
Designer CN2	Gooood (https://www.gooood.cn/) ****	Archdaily (https://www.archdaily.com; https://www.archdaily.cn/) ****	Archcollege (http://www.archcollege.com/) ***	

“*****” means “Very active”, “****” means “Somewhat active”, “***” means “Neither active nor inactive”, “**” means “Somewhat inactive”, “*” means “Very inactive”

“Gooood” is considered a top-ranked website in the field of architecture (including landscape and interior design) which has the highest traffic in China (one of the top 5 architecture sites in the world; ranks 1st in top architecture sites in both China and Asia)[31]; "Archdaily" is a weblog covering architectural news, projects, products, events, interviews, competitions, opinion pieces, etc., catering to architects, designers, and other interested parties[32]; "Archcollege" is a high-quality platform for architects. The respondents thought generally the platforms support innovations and diffusion of CE in the sector well (D-CN2).

Most respondents argued that these platforms are supported or facilitated by the government. For example, according to CI-CN1, government officials often take part in the activities organized by the associations, and some retired officials would join such associations and be leaders. Only three respondents attended any networking sessions regarding CE in the Chinese infrastructure construction sector (nine respondents did not).

In China, there is a national CE association, i.e., China Association of Circular Economy[33], and it organizes the China Circular Economy Development Forum every year. Locally, there are Jiangsu Association of Circular Economy[34], Circular Economy Public Service Platform of Jiangsu Province[35] and Circular Economy Public Service Platform of Nanjing[36].

For the Dutch case, thirteen respondents considered platforms as venues where useful knowledge is shared with actors interacting regarding CE. Table 4.3 presents platforms for the Dutch case.

Table 4.3 The platforms where knowledge is shared and actors are interacting regarding CE (the Dutch case)

No.	the 1st platform	the 2nd platform	the 3rd platform	the 4th platform	the 5th platform
Government official NL1	transition agenda circular construction industry	platform CB'23 (www.platformcb23.nl/english)	Cirkelstad (www.cirkelstad.nl)	Circo[37]	

[31] https://www.gooood.cn/aboutus (accessed on Aug. 18, 2021)

[32] https://en.wikipedia.org/wiki/ArchDaily (accessed on Aug. 18, 2021)

[33] https://www.chinacace.org/ (accessed on Jun. 1, 2021)

[34] http://www.jsace.org/ (accessed on Jun. 1, 2021)

[35] http://www.jsxhjj.com/ (accessed on Jun. 1, 2021)

[36] Nanjing is the capital city of Jiangsu; http://www.njxhjj.com/ (accessed on Jun. 1, 2021)

[37] CIRCO activates production companies and creative professionals to get started with circular design, receiving support from IenW. (https://www.circonl.nl/over-ons/ accessed on Aug. 19, 2021)

	(www.circulairebouweconomie.nl/english)				
	*****	*****	****	***	
Client NL2	CB'23	Buyergroups (PIANOo)	Asfaltimpuls (CROW)	betonakkoord[38]	
	****		**	*****	
Academic researcher NL2	CB'23	CBE[39] (Circular Built Environment Hub)			
	**				
Government official NL2	Bouwcampus[40]	CROW			
	****	***			
Engineering/ Technical consultant NL1	CB'23	Cirkelstad			
	****	****			
Engineering/ Technical consultant NL2	bouwcirculair[41]	CB'23	platform bruggen[42]	bouwcampus	BTIC[43] (The Construction and Technology Innovation Center)

[38] Betonakkoord offers an interesting proposition for BV Netherlands: cost-effectively achieving a significant positive social impact through innovations, knowledge, and the will to collaborate. (https://www.betonakkoord.nl/ accessed on Aug. 19, 2021)

[39] CBE is a platform for researchers of the Faculty of Architecture and the Built Environment at Delft University of Technology (TU Delft) to promote the development of knowledge towards a circular built environment that enables the design of future buildings, cities, and infrastructures. (https://www.tudelft.nl/bk/onderzoek/onderzoeksthemas/circular-built-environment accessed on Aug. 19, 2021)

[40] The Bouwcampus is an initiative of RWS, Rijksvastgoedbedrijf, Bouwend Nederland, TU Delft and the municipalities of Rotterdam and Delft (on behalf of the G4 and G32 municipalities). It wants to increase the social added value of the construction world. (https://debouwcampus.nl/over-ons/missie accessed on Aug. 19, 2021)

[41] BouwCirculair strives for sustainable materials in construction projects. (https://bouwcirculair.nl/ accessed on Aug. 19, 2021)

[42] Platform Bruggen combines forces, initiatives, and knowledge of all parties in the bridge sector (https://www.crow.nl/thema-s/infratechniek/platform-bruggen accessed on Aug. 19, 2021); we can see it is a part of CROW.

[43] BTIC is the flywheel for construction, design, and technology innovation. (https://btic.nu/over-btic/ accessed on Aug. 19, 2021)

	*****	**	*****	*****	*****
Designer NL1	Bouwcampus ****				
Contractor NL2	Cirkelstad ***	Circulair Friesland ***			
Material supplier NL1	CROW *				
Material supplier NL2	https://circulairebouweconomie.nl/ ***	CB'23: https://platformcb23.nl/ ****	https://decirculaireweg.nl/ *		
Designer NL2	Duurzaam GWW[44] ****	Circulair Bouwen ****			

"*****" means "Very active", "****" means "Somewhat active", "***" means "Neither active nor inactive", "**" means "Somewhat inactive", "*" means "Very inactive"

Compared with the Jiangsu case, the Dutch respondents mentioned more detailed platforms. There are more of these kinds of platforms in the Netherlands than in China at large. The Dutch platforms are considered good sources for making knowledge and information available. Respondents in the Dutch case indicate being active on the platforms they mentioned.

For how well these platforms are supported or facilitated by the government or other actors, GO-NL1 described that "Support (for circulairebouweconomie) is paid for by ministries; platform CB'23 is financed by ministries, RWS and RVB (The Central Government Real Estate Agency); Cirklestad receives contribution from ministry BZK; Circo receives contribution from ministry IenW and provinces (project-basis); betonakkoord receives contribution from ministry IenW"; AR-NL1 wrote "Both the Bouwcampus and CROW (Asfaltimpuls) are supported by many public and private parties"; D-NL1 provided public clients are part of Bouwcampus; E/TC-NL1 presented "Cirkelstad is self-sufficient, and CB'23 is entirely facilitated by the government"; E/TC-NL2 wrote all the platforms presented by him are supported by governments; D-NL2 stated that governments, knowledge institutes, suppliers and contractors work together in the platforms he mentioned.

Seven respondents (GO-NL1, CI-NL1, AR-NL2, E/TC-NL1, E/TC-NL2, D-NL1, and D-NL2) facilitated or attended networking sessions regarding CE in the Dutch infrastructure construction sector. GO-NL1 wrote there are even numerous networking events, too many to specify (also international); CI-NL1 mentioned company internal networking sessions.

Besides the Dutch examples, there are also platforms facilitated or financed by the EU,

[44] https://www.duurzaamgww.nl/over-ons/ (accessed on Aug. 19, 2021)

for instance, CEC4Europe (Circular Economy Coalition for Europe)[45] and European Circular Economy Stakeholders Platform (ECESP). Such circular platforms and knowledge networks are considered to accelerate the realization of the CE by sharing knowledge, highlighting case studies, and by facilitating collaboration[46].

4.4.5 Institutional Framework

4.4.5.1 Policy

Fig. 4.6 presents an overview of the opinions respondents had about the perceived effectiveness of six policies to promote the transition to CE in the infrastructure construction sector.

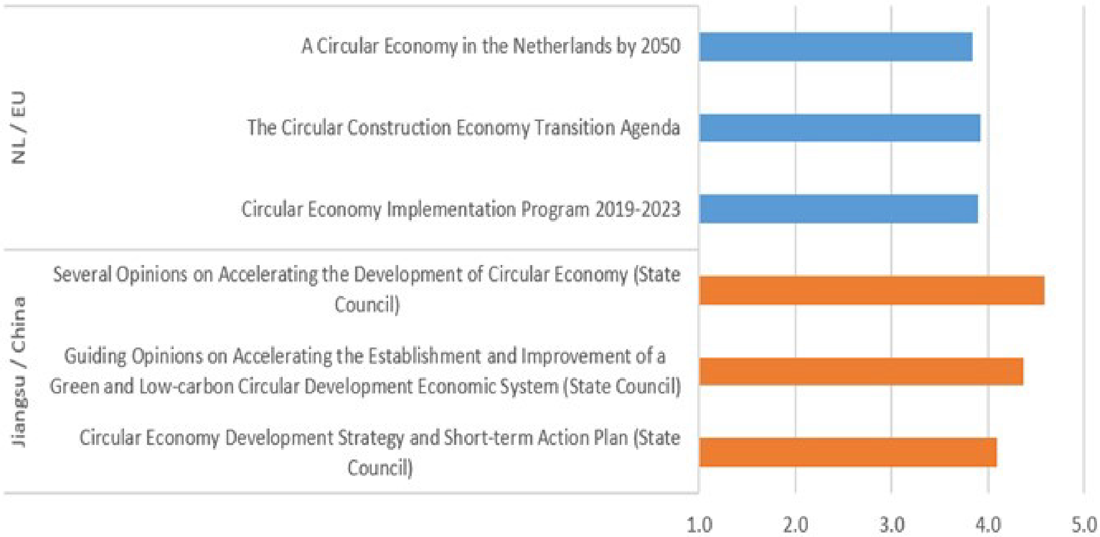


Figure 4.6 Perceived effectiveness of policies to promote the transition to CE in the infrastructure construction sectors respectively (5 means "Very effective"; 1 means "Very ineffective"; own figure)

For the Jiangsu case, almost all of the respondents rated all three policy instruments as "very effective" (5) or "somewhat effective" (4). Investor CN1 (hereafter In-CN1) argued that the policies were issued and updated by the State Council, which indicates a willingness to act by the central government. However, AR-CN2 expressed that the directions are embodied generally in policy, but the "down to earth" ways, i.e., how policy is implemented are determined locally, whilst D-CN1 did not observe any local implementation of CE policy. MS-CN1 considered that the national policies correctly and effectively target the key points of CE, but that relevant national departments need to fully promote CE. As for policy instruments to promote CE in the sector, In-CN1 mentioned setting up CE pilot programs, whilst AR-CN2 emphasized the importance of *Technical Guidelines for Green Construction*, issued by the Ministry of Housing and Urban-Rural Development.

Nearly all respondents in the Jiangsu case thought there is support from both the central

[45] https://www.cec4europe.eu/?cn-reloaded=1 (accessed on Jun. 1, 2021)

[46] https://kenniskaarten.hetgroenebrein.nl/en/knowledge-map-circular-economy/circular-knowledge-networks-platforms/ (accessed on Jun. 1, 2021)

and local governments for CE implementation in the sector. However, firm implementation is still needed. CI-CN1 stated that "There are some policies but these are not fully implemented locally". Similarly, AR-CN2 considered that a series of relevant real "down to the earth" measures are still needed to incentivize implementation processes. MS-CN1 argued that "Policy and funding support from the governments are relatively sufficient, but when implemented, the goal should not be distracted or weakened".

As for how stringent or flexible these policies are to develop CE in the Chinese infrastructure construction sector, respondents held different views. In-CN1 mentioned the two policies (*Several Opinions on Accelerating the Development of Circular Economy* and *Circular Economy Development Strategy and Short-term Action Plan*) are from the central government, but different cities may implement them quite differently. LC-CN1 argued that the first policy is about the development of vision direction of CE, and the second is more convenient for operations. A Representative from media CN1 (RM-CN1) reckoned that currently CE is not well implemented, which is indicated by poor clarity of responsibilities. The General public and community resident CN1 (GPCR-CN1) suggested that during the formulation of CE regulations and laws, the infrastructure construction sector should cooperate with other economic sectors, i.e., forging inter-sectoral coordination.

The Dutch case respondents provided several arguments. E/TC-NL1 argued that all the policy documents provide direction, which helps to get moving, and they also work towards concretization in clear steps.

E/TC-NL2 was not aware of any Dutch CE policies for the infrastructure sector. He had only heard about *A Circular Economy in the Netherlands by 2050*, and he had hardly ever heard of the *Circular Construction Economy Transition Agenda* and *Circular Economy Implementation Program 2019-2023*. D-NL1 argued, "At the moment there is reasonable development in ambitions and policy, but it is not yet reflected in projects; there is a gap between policy and implementation". Project developer NL1 (PD-NL1) wrote, "As project developers of real estate projects, we look at each project in which way we can contribute to the CE; this is independent of government policy documents".

As for other policy instruments to promote CE in the Dutch infrastructure construction sector, GO-NL1 mentioned Taskforce "herijking afvalstoffen"[47] (THA, task force recalibration of waste products). Actually since 2011, more than 200 Green Deals[48] have been concluded in the Netherlands, many of which relate to CE, for example:

Netherlands Hotspot for Circular Economy: This Green Deal aims to accelerate the transition to a CE by carrying out scalable circular projects;

"Circulaire Stad" (Circular City): This Green Deal aims to support the transition to a circular and inclusive economy regarding material cycles in the construction sector by realizing a similar approach in at least five cities other than Rotterdam.

---

[47] https://www.rijksoverheid.nl/documenten/kamerstukken/2021/03/01/opvolging-verkenningen-taskforce-herijking-afvalstoffen (accessed on Aug. 19, 2021)

[48] Green Deal is a growth strategy to transform the EU into a climate-neutral and circular economy, while preserving Europe's competitiveness (https://www.government.nl/topics/climate-change/eu-policy, accessed on Nov. 1, 2023)

The central government has also set up the "Versnellingshuis Nederland Circulair", concluded several Green Deals, and launched the programs "Van Afval Naar Grondstof" (VANG) and the "Ruimte in Regels voor Groene Groei" (Space in Rules for Green Growth). A detailed overview of the central government's policy from 2018 is given in the Cabinet's response to the transition agendas for the CE[49]. In the EU, there is the EU Construction and Demolition Waste Protocol and Guidelines[50].

Policymakers in China indicate they would like to learn from EU or Dutch policy documents, just like this is done for other CE policy domains and Zero Waste Cities (Ma et al., 2022). Compared to China, there are more different government departments involved in CE in the Netherlands.

Eight respondents considered that there is sufficient support from central and local government for CE implementation in the Dutch infrastructure construction sector while eight others thought there is not. E/TC-NL2 argued that "The government would like to move towards CE. Both in administration and in politics a lot of attention is paid to it. In addition, there are currently an awful lot of pilots, platforms, and covenants that trying to induce transformative change. However, the elaboration (scaling up/implementation) is still somewhat problematic. The solution is considered to lie with developing a policy mix of steering policy (ambitions) and decentralized thematic programs". C-NL2 expressed there is certainly support, especially at RWS; however, financial support is insufficient.

GO-NL1 argued that "The focus of the government (policy, financing) is mainly on climate change/CO_2 reduction. In terms of policy and regulations, a lot more could be facilitated. Local governments, especially smaller councils often do not have enough knowledge, capacity, and capabilities to implement CE". In a similar vein, D-NL1 argued that support from the government is still very limited, purely looking at the outcome of recent projects. FC-NL1 argued that the policies indicate direction and ambitions; they do not give a narrow bandwidth on how to achieve those ambitions. CE and sustainable investments consultant NL1 (CESIC-NL1) considered, "There is an increasing need for 'guiding principles', clarity of performance indicators, criteria, and benchmarks. The agendas are by definition process-oriented and stimulate collaboration as well as innovation. However, they often remain too abstract for the sector". Investor-NL1 (In-NL1) thought the national policies were apparently not strict enough; in his practice, he still sees a lot of power in the existing parties that prevent necessary changes (for instance, the cement industry is very powerful). According to AR-NL2, "Everything is still without obligation, which doesn't work. If we want to make a major transition to CE, there must be mandatory regulation". In sum, local implementation of CE in the infrastructure construction sector is insufficient in both the Jiangsu case and the Dutch case.

4.4.5.2 Non-policy aspects

For the Jiangsu case, three respondents considered informal institutions to fully support

[49] https://kenniskaarten.hetgroenebrein.nl/en/knowledge-map-circular-economy/ce-policies-support-ambitions/ (accessed on Jun. 1, 2021)

[50] https://ec.europa.eu/growth/content/eu-construction-and-demolition-waste-protocol-0_en (accessed on Jun. 1, 2021)

the development of CE in the infrastructure construction sector. Five others partially supported this statement.

FC-CN1 reckoned that informal institutions (such as behavioral habits) can sometimes be more influential than formal institutions. As a complement to formal institutions in developing CE, RM-CN1 believed that informal institutions are currently overlooked as a driving force. She added that "Informal institutions tend to exist unconsciously and in people's habits. They can be more powerful in terms of durability". In the "*Several Opinions on Accelerating the Development of Circular Economy" program*, there is also content about institutions, i.e., "Make technological innovation and institutional innovation propulsive; adhere to enterprises as the main part, combining government adjustment, market leadership, and public participation, therefore forging policy system and social institution that can contribute the development of CE."[51]

As for non-policy ways used for promoting CE in the sector, In-CN1 mentioned the use of knowledge-sharing platforms, private sector projects, market-based certification schemes/competitions, and community projects. LC-CN1 argued that citizen initiatives and community projects can promote CE; while knowledge-sharing platforms and NGO projects can be used to disseminate CE. IU-CN1 claimed that in the Chinese economic environment, policy and non-policy function hand-in-hand. RM-CN1 stated that, "(non-policy ways) can deeply change the action modes of people by changing the sense of value and ways of thinking".

For the Dutch case, nine respondents believed that informal institutions partially support the development of CE in the infrastructure construction sector. RM-NL1 wrote, "In general, the media plays an important role in the announcement and promotion of innovative methods of CE, and early adopters influence how society embrace or disapprove of new developments. In-NL1 argued that informal institutions do provide support, but play a limited role of significance. PD-NL1's opinion was that "There is little knowledge among the general public about the possibilities of being circular in infrastructure; however, this is generally supported by the general public".

As for how informal institutions and non-public instrumentation are used for promoting CE, RM-NL1 considered that social media can play an important role in promoting CE, preferably bottom-up instead of top-down. Another idea was to implement a "materials passport" (LC-NL1). GPCR-NL2 mentioned "meetings, highlighting inspiring examples, working groups, developing tools (see bouwcirculair, CB 23, etc.)". To In-NL1 the "market-based certification scheme" sounds like a good incentive, noticing that there are many "technology-based" initiatives in the field of CE, adding that, "We need to think about how we give these parties a good chance to overcome (imposed) barriers and to continue, which often also comes down to making subsidies available to enable bringing technologies to the market".

4.6 Summary of the Results

The main results of the two cases are presented in Table 4.4.

[51] http://www.shanghai.gov.cn/nw15540/20200820/0001-15540_4686.html (accessed on Jun 1, 2021)

Table 4.4 The main results of the Jiangsu and the Netherlands cases based on the framework of Fig. 4.1

	Jiangsu	**The Netherlands**
Technological regime	Bio-materials, biological processes, and digital technologies not commonly used	Bio-materials, digital technologies, especially biological processes not commonly used
	Knowledge of CE needs development in both countries	
Market demand	CE can better meet the expectations clients have, in terms of e.g., quality and cost	
Agents, interactions, and networks	Government, designers, investors, contractors, different consultants, and researchers are important	Government, clients, researchers, and financing parties are important; More CE platforms were provided
Institutional framing	There are national and regional policy instruments in both cases, but effective and large-scale local CE implementation is hardly seen	

As for the Technological regime, the Jiangsu case respondents generally tended to think that bio-materials, biological processes, and digital technologies are not commonly used to implement CE (in contrast to the other five categories). Those technology categories still need further development to implement CE in the sector, partly in terms of economic feasibility. The Dutch respondents generally tended to think that bio-materials, digital technologies, and especially biological processes are not commonly used to implement CE (in contrast to the other five categories). Biomaterials and biological processes still need further development to implement CE in the sector, partly in terms of economic feasibility. Besides, the knowledge of CE in the infrastructure construction sector in both countries still needs further development. The concerns of technologies and knowledge can be seen as barriers to CE implementation in the sector.

As for Market demand creation, the respondents had similar answers about the criteria (expectations) clients have for infrastructures, and CE can better match those criteria (expectations), in terms of aspects such as quality and cost, since quality is of utmost importance and costs should not be too high.

Concerning Agents, interaction, and networks, the Chinese government is essential for the infrastructure construction sector. Besides the government, most of the supply-side stakeholder roles (i.e., designers, investors, contractors, and different sorts of consultants) were also considered important and relatively more influential than others for the implementation of CE in the sector (it is the same for the Netherlands). From the secondary stakeholders, academic researchers were considered as being involved most in developing CE in the sector according to the Chinese respondents (the same frequency as clients). The Dutch government and clients are essential for the Dutch infrastructure construction sector. From the secondary stakeholders, academic researchers and financing parties were considered as being involved most in developing CE in the sector in the Netherlands. As for CE platforms and knowledge networks, the Dutch respondents mentioned more specific examples than the Chinese respondents.

As for the Institutional framework, local implementation of CE in the sector is insufficient in China and the Netherlands. There are national and regional policy instruments in China and the Netherlands for CE in the infrastructure construction sector, however, real, effective and large-scale local policy implementation in local contexts is hardly observed for both cases.

4.5 Discussion

Bio-materials, biological processes, and digital technologies are hardly observed from literature about CE in infrastructure (compared to demolition technologies (Bao et al., 2019; Lederer et al., 2020), re-use technologies (Lederer et al., 2020), recycling technologies (Jensen et al., 2020), renewable energy technologies (Jensen et al., 2020; Mutezo and Mulopo, 2021) and durable materials (Mantalovas et al., 2020; Sansom, 2014)). In addition to technologies, the knowledge of CE in both the Chinese and Dutch infrastructure construction sectors can be enriched; both national and international knowledge exchange are beneficial. Platforms where knowledge can be shared and actors can interact regarding CE in the sector should be further encouraged, which can also benefit interactive learning. From the data-gathering process of this study, it is believed that there are more such platforms in the Dutch infrastructure sector than on the Chinese side. Quite some such platforms in the Netherlands are supported by the government. Even when there are extensive knowledge base and networks, they should be sufficiently utilized (van Alphen et al., 2010). In addition, intergovernmental communication, coordination and collaboration are also encouraged to be a lever for CE implementation in the sector.

In both countries, the governments are essential to the sector. One reason that the Dutch respondents selected "client" more frequently than "investor" in terms of actors that are involved in developing CE in the infrastructure construction sector is RWS is a client in the Netherlands, with public procurement. While in China, there tend to be more private investors (compared to the situation in the Netherlands).

Insufficient local implementation of CE in the infrastructure construction sector in China and the Netherlands is partly because CE philosophy is easy to understand but very complex to put into practice (Alonso-Almeida et al., 2021). Kirchherr et al. (2018) found that cultural barriers, particularly a lack of consumer interest and awareness as well as a hesitant company culture, are considered the main CE barriers by businesses and policy-makers.

It is suggested by us that for CE implementation in China, the infrastructure construction sector should be stressed more (thus catching up with other key leading economic sectors for CE, such as agriculture and plastics), further encouraged, and related laws as well as regulations to be rationally stricter. If implementing CE in the sector is an aim set by the central government, it is promising that the sector will be more circular. Additionally, relevant assessment criteria can also be made to promote CE implementation in Chinese infrastructure constructions. Recently, the "Utilization of Construction Waste as Resources" policy has been listed as one of the five demonstration projects in *The 14th Five-Year Plan for Circular*

Economy Development issued by the National Development and Reform Commission[52]. To achieve the goals of the policy, 50 Demonstration Cities of the “Utilization of Construction Waste as Resources” policy will be selected and key enterprises of utilizing construction waste as resources will be fostered. Unlike the existing 101 CE Demonstration Cities in China, the selection of the future 50 Demonstration Cities will focus more on the utilization of construction waste. Such promotions from the Chinese national government are essential since the government plays a key role in the implementation of CE in the Chinese infrastructure construction sector. Similarly, the Singaporean national government plays a central role in Singapore’s Green Building innovation system (Siva et al., 2017); and the Dutch government takes a central role in innovation systems in the Dutch residential construction (Bossink, 2009). For these sectors with relatively big assets, the impetus for innovation is mainly implemented with a top-down approach, contrary to that of small entities like solar water heaters (Goess et al., 2015) of certain sectors. On the other hand, the lower-level innovation in China is less than that in the Netherlands, which can be explained partly by the different political systems; but such more prosperous innovation can also be made in different directions without clear guidance from the upper level.

4.6 Conclusion

This article used SIS as a framework to evaluate the current situation of CE applications in the Chinese and Dutch infrastructure construction sectors as an innovative trial, which serves as a piece of academic contribution. The SIS framework offers a lens and works well. Via a survey covering a complete set of stakeholder roles in the sector, key barriers and future directions for CE implementation in the sector are identified, especially for policymakers. Results show that these pertain to all four dimensions of the SIS framework. The main reasons for insufficient local implementation of CE in the Chinese infrastructure construction sector include 1) underdeveloped technologies, and lack of CE knowledge (in terms of Technological regime); 2) insufficient interacting platforms (in terms of Agents, interaction, and networks); 3) lack of attention in related laws and regulations (in terms of Institutional framework). Besides, the implementation of CE in the sector should better meet the market demand, e.g., reach the expectations of clients and owners in aspects such as cost and quality. In the Netherlands, local implementation of CE in the infrastructure construction sector is not enough either, with underdeveloped technologies and a lack of CE knowledge. The Dutch government wants to use legislation to advance the transition to a CE[53]. Provided the Dutch government can take a more powerful leading role to promote CE in the sector, CE innovations will be more prosperous within the sector to propel the circular transition from bottom-up.

Even though the authors believe almost all the stakeholders of the Chinese and Dutch infrastructure sectors are included and enough insights are acquired from the respondents, a

---

[52] http://www.gov.cn/zhengce/zhengceku/2021-07/07/5623077/files/34f0a690e98643119774252f4f671720.pdf (accessed on Oct. 22, 2021)

[53] https://www.government.nl/topics/circular-economy/accelerating-the-transition-to-a-circular-economy (accessed on Nov. 3, 2021)

larger distribution of some easy, simple-click questions from the survey can be done in the future. A study covering more provinces or regions within China can also be more comprehensive compared to the present study of one representative province.

Based on the results of our study it is suggested that 1) CE technologies (especially Bio-materials, biological processes, and digital technologies) and knowledge should be further developed; 2) platforms for knowledge sharing and actor interactions regarding CE in the Chinese infrastructure construction sector should be further encouraged; 3) related laws and regulations can be stricter in China if necessary; 4) CE can be put into legislation in the Netherlands. Implementing CE in the infrastructure construction sector is a systematic process, which needs promotion from governments, technology development, market demand, and even public participation.

References for Chapter 4

Alonso-Almeida, M. del M., Rodriguez-Anton, J.M., Bagur-Femenías, L., Perramon, J., 2021. Institutional entrepreneurship enablers to promote circular economy in the European Union: Impacts on transition towards a more circular economy. J. Clean. Prod. 281. https://doi.org/10.1016/j.jclepro.2020.124841

Bao, Z., Lu, W., Chi, B., Yuan, H., Hao, J., 2019. Procurement innovation for a circular economy of construction and demolition waste: Lessons learnt from Suzhou, China. Waste Manag. 99, 12–21. https://doi.org/10.1016/j.wasman.2019.08.031

Belussi, F., Sammarra, A., Sedita, S.R., 2010. Learning at the boundaries in an "Open regional innovation system": A focus on firms' innovation strategies in the Emilia Romagna life science industry. Res. Policy 39, 710–721. https://doi.org/10.1016/j.respol.2010.01.014

Bossink, B.A.G., 2009. Assessment of a national system of sustainable innovation in residential construction: a case study from The Netherlands. Int. J. Environ. Technol. Manag. 10, 371–381.

Brown, P., Bocken, N., Balkenende, R., 2019. Why do companies pursue collaborative circular oriented innovation? Sustain. 11, 1–23. https://doi.org/10.3390/su11030635

Carlsson, B., Stankiewicz, R., 1991. On the nature, function and composition of technological systems. J. Evol. Econ. 1, 93-118.

Chan, L., Daim, T., 2012. Sectoral innovation system and technology policy development in China. J. Technol. Manag. China 7, 117–135. https://doi.org/10.1108/17468771211242827

Coenen, T.B.J., Visscher, K., Volker, L., 2023. A systemic perspective on transition barriers to a circular infrastructure sector. Constr. Manag. Econ. 41, 22–43. https://doi.org/10.1080/01446193.2022.2151024

Di Maddaloni, F., Davis, K., 2017. The influence of local community stakeholders in megaprojects: Rethinking their inclusiveness to improve project performance. Int. J. Proj. Manag. 35, 1537–1556. https://doi.org/10.1016/j.ijproman.2017.08.011

Doloreux, D., Parto, S., 2005. Regional innovation systems: Current discourse and unresolved issues. Technol. Soc. 27, 133–153. https://doi.org/10.1016/j.techsoc.2005.01.002

Domenech, T., Bahn-Walkowiak, B., 2017. Transition Towards a Resource Efficient Circular Economy in Europe: Policy Lessons From the EU and the Member States. Ecol. Econ. https://doi.org/10.1016/j.ecolecon.2017.11.001

EIA, 2013. Energy Information Administration—EIA—Independent Statistics and Analysis. Washington, DC.

Faber, A., Hoppe, T., 2013. Co-constructing a sustainable built environment in the Netherlands-Dynamics and opportunities in an environmental sectoral innovation system. Energy Policy 52, 628–638. https://doi.org/10.1016/j.enpol.2012.10.022

Fagerberg, J., Mowery, D.C., Verspagen, B., 2018. The evolution of Norway's national innovation system. Innov. Econ. Dev. Policy Sel. Essays 36, 316–329. https://doi.org/10.3152/030234209X460944

Goess, S., de Jong, M., Ravesteijn, W., 2015. What makes renewable energy successful in China? The case of the Shandong province solar water heater innovation system. Energy Policy 86, 684–696. https://doi.org/10.1016/j.enpol.2015.08.018

Gray, D.O., 2011. Cross-sector research collaboration in the USA: A national innovation system perspective. Sci. Public Policy 38, 123–133. https://doi.org/10.3152/030234211X12960315267417

Guo, B., Geng, Y., Sterr, T., Zhu, Q., Liu, Y., 2017. Investigating public awareness on circular economy in western China: A case of Urumqi Midong. J. Clean. Prod. 142, 2177–2186. https://doi.org/10.1016/j.jclepro.2016.11.063

Hekkert, M.P., Janssen, M.J., Wesseling, J.H., Negro, S.O., 2020. Mission-oriented innovation systems. Environ. Innov. Soc. Transitions 34, 76–79. https://doi.org/10.1016/j.eist.2019.11.011

Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: A new approach for analysing technological change. Technol. Forecast. Soc. Change 74, 413–432. https://doi.org/10.1016/j.techfore.2006.03.002

Hubbard, S.M.L., Hubbard, B., 2019. A review of sustainability metrics for the construction and operation of airport and roadway infrastructure. Front. Eng. Manag. 6, 433–452. https://doi.org/10.1007/s42524-019-0052-1

Intarakumnerd, P., Chairatana, P.A., Tangchitpiboon, T., 2002. National innovation system in less successful developing countries: The case of Thailand. Res. Policy 31, 1445–1457. https://doi.org/10.1016/S0048-7333(02)00074-4

Jarský, V., 2015. Analysis of the sectoral innovation system for forestry of the Czech Republic. Does it even exist? For. Policy Econ. 59, 56–65. https://doi.org/10.1016/j.forpol.2015.05.012

Jensen, P.D., Purnell, P., Velenturf, A.P.M., 2020. Highlighting the need to embed circular economy in low carbon infrastructure decommissioning: The case of offshore wind. Sustain. Prod. Consum. 24, 266–280. https://doi.org/10.1016/j.spc.2020.07.012

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., Hekkert, M., 2018. Barriers to the Circular Economy: Evidence From the European Union (EU). Ecol. Econ. 150, 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028

Konietzko, J., Bocken, N., Hultink, E.J., 2020. A tool to analyze, ideate and develop circular innovation ecosystems. Sustain. 12, 14–17. https://doi.org/10.3390/SU12010417

Kubeczko, K., Rametsteiner, E., Weiss, G., 2006. The role of sectoral and regional innovation systems in supporting innovations in forestry. For. Policy Econ. 8, 704–715. https://doi.org/10.1016/j.forpol.2005.06.011

Kupers, L., 2021. Strategizing organisational ambitions in infrastructure projects. Delft

University of Technology.
Lederer, J., Gassner, A., Kleemann, F., Fellner, J., 2020. Potentials for a circular economy of mineral construction materials and demolition waste in urban areas: a case study from Vienna. Resour. Conserv. Recycl. 161, 104942. https://doi.org/10.1016/j.resconrec.2020.104942
Lee, J. dong, Park, C., 2006. Research and development linkages in a national innovation system: Factors affecting success and failure in Korea. Technovation 26, 1045–1054. https://doi.org/10.1016/j.technovation.2005.09.004
Liu, S.G., Chen, C., 2003. Regional innovation system: Theoretical approach and empirical study of China. Chinese Geogr. Sci. 13, 193–198. https://doi.org/10.1007/s11769-003-0016-5
Liu, X., Schraven, D., Bruijne, M. de, Jong, M. de, Hertogh, M., 2019. Navigating Transitions for Sustainable Infrastructures — The Case of a New High-Speed Railway Station in Jingmen , China. Sustainability 11, 4197. https://doi.org/10.3390/su11154197
Liu, X., Schraven, D., Ma, W., De Jong, M., Hertogh, M., 2024. Achieving a framework of the circular economy in urban transport infrastructure projects: a meso-scale perspective. Front. Sustain. 5, 1475155. https://doi.org/10.3389/frsus.2024.1475155
Ma, W., Hoppe, T., de Jong, M., 2022. Policy Accumulation in China: A Longitudinal Analysis of Circular Economy Initiatives. Sustain. Prod. Consum. 34, 490-504.
Malerba, F., 2004. Sectoral Systems of Innovation: Concepts, Issues and Analyses of Six Major Sectors in Europe. Cambridge University Press, Cambridge.
Malerba, F., 2002. Sectoral systems of innovation and production. Res. Policy 31, 247–264.
Mantalovas, K., Di Mino, G., Del Barco Carrion, A.J., Keijzer, E., Kalman, B., Parry, T., Presti, D. Lo, 2020. European national road authorities and circular economy: An insight into their approaches. Sustain. 12, 1–19. https://doi.org/10.3390/su12177160
Matatkova, K., Stejskal, J., 2013. Descriptive analysis of the regional innovation system - novel method for public administration authorities. Transylvanian Rev. Adm. Sci. 91–107.
Mazur-Wierzbicka, E., 2021. Circular economy: advancement of European Union countries. Environ. Sci. Eur. 33. https://doi.org/10.1186/s12302-021-00549-0
McDowall, W., Geng, Y., Huang, B., Barteková, E., Bleischwitz, R., Türkeli, S., Kemp, R., Doménech, T., 2017. Circular Economy Policies in China and Europe. J. Ind. Ecol. 21, 651–661. https://doi.org/10.1111/jiec.12597
Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., de Meester, S., Dewulf, J., 2019. Circular economy indicators: What do they measure? Resour. Conserv. Recycl. 146, 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045
Morseletto, P., 2020. Targets for a circular economy. Resour. Conserv. Recycl. 153, 104553. https://doi.org/10.1016/j.resconrec.2019.104553
Mowery, D.C., 2011. Nanotechnology and the US national innovation system: Continuity and change. J. Technol. Transf. 36, 697–711. https://doi.org/10.1007/s10961-011-9210-2
Mowery, D.C., 1998. The changing structure of the US national innovation system: Implications for international conflict and cooperation in R & D policy. Res. Policy 27, 639–654. https://doi.org/10.1016/S0048-7333(98)00060-2
Mowery, D.C., 1992. The U.S. national innovation system: Origins and prospects for change. Res. Policy 21, 125–144. https://doi.org/10.1016/0048-7333(92)90037-5

Munaro, M.R., Freitas, M. do C.D., Tavares, S.F., Bragança, L., 2021. Circular Business Models: Current State and Framework to Achieve Sustainable Buildings. J. Constr. Eng. Manag. 147. https://doi.org/10.1061/(asce)co.1943-7862.0002184

Mutezo, G., Mulopo, J., 2021. A review of Africa's transition from fossil fuels to renewable energy using circular economy principles. Renew. Sustain. Energy Rev. 137, 110609. https://doi.org/10.1016/j.rser.2020.110609

Negro, S.O., Suurs, R.A.A., Hekkert, M.P., 2008. The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system. Technol. Forecast. Soc. Change 75, 57–77. https://doi.org/10.1016/j.techfore.2006.08.006

Ranta, V., Aarikka-Stenroos, L., Ritala, P., Mäkinen, S.J., 2018. Exploring institutional drivers and barriers of the circular economy: A cross-regional comparison of China, the US, and Europe. Resour. Conserv. Recycl. 135, 70–82. https://doi.org/10.1016/j.resconrec.2017.08.017

Rho, S., Lee, K., Kim, S.H., 2015. Limited catch-up in China's semiconductor industry: A sectoral innovation system perspective. Millenn. Asia 6, 147–175. https://doi.org/10.1177/0976399615590514

Rogge, K.S., Hoffmann, V.H., 2010. The impact of the EU ETS on the sectoral innovation system for power generation technologies - Findings for Germany. Energy Policy 38, 7639–7652. https://doi.org/10.1016/j.enpol.2010.07.047

Safapour, E., Kermanshachi, S., Kamalirad, S., Tran, D., 2019. Identifying Effective Project-Based Communication Indicators within Primary and Secondary Stakeholders in Construction Projects. J. Leg. Aff. Disput. Resolut. Eng. Constr. 11, 04519028. https://doi.org/10.1061/(asce)la.1943-4170.0000332

Sansom, M., 2014. Briefing: Reuse and recycling rates of UK steel demolition arisings. Proc. Inst. Civ. Eng. Eng. Sustain. 167, 89–94.

Savory, C., Fortune, J., 2014. An emergent sectoral innovation system for healthcare services. Int. J. Public Sect. Manag. 27, 512–529. https://doi.org/10.1108/IJPSM-03-2014-0036

Schraven, D., Maio, F. Di, Hertogh, M., 2019. Resources, Conservation & Recycling Circular transition : Changes and responsibilities in the Dutch stony material supply chain 150. https://doi.org/10.1016/j.resconrec.2019.05.035

Siva, V., Hoppe, T., Jain, M., 2017. Green buildings in Singapore; Analyzing a frontrunner's sectoral innovation system. Sustain. 9, 1–23. https://doi.org/10.3390/su9060919

Smol, M., Marcinek, P., Duda, J., Szołdrowska, D., 2020. Correction: Smol, m., et al. importance of sustainable mineral resource management in implementing the circular economy (ce) model and the european green deal strategy. (Resource 2020, 9, 55). Resources 9, 1–3. https://doi.org/10.3390/resources9060078

Sun, Y., Liu, F., 2010. A regional perspective on the structural transformation of China's national innovation system since 1999. Technol. Forecast. Soc. Change 77, 1311–1321. https://doi.org/10.1016/j.techfore.2010.04.012

Tam, E., Soulliere, K., Sawyer-Beaulieu, S., 2019. Managing complex products to support the circular economy. Resour. Conserv. Recycl. 145, 124–125. https://doi.org/10.1016/j.resconrec.2018.12.030

Trica, C.L., Banacu, C.S., Busu, M., 2019. Environmental factors and sustainability of the circular economy model at the European union level. Sustain. 11.

https://doi.org/10.3390/su11041114
Türkeli, S., Kemp, R., Huang, B., Bleischwitz, R., McDowall, W., 2018. Circular economy scientific knowledge in the European Union and China: A bibliometric, network and survey analysis (2006–2016). J. Clean. Prod. 197, 1244–1261. https://doi.org/10.1016/j.jclepro.2018.06.118
van Alphen, K., Hekkert, M.P., Turkenburg, W.C., 2010. Accelerating the deployment of carbon capture and storage technologies by strengthening the innovation system. Int. J. Greenh. Gas Control 4, 396–409. https://doi.org/10.1016/j.ijggc.2009.09.019
Van Bueren, E., 2009. Greening Governance. An Evolutionary Approach to Policy Making for a Sustainable Built Environment. Delft University of Technology.
Vecchio, P.D.., Passiante, G.. B., Arberio, G.., Innella, C., 2020. Digital innovation ecosystems for circular economy: The case of ICESP, the Italian circular economy stakeholder platform. Int. J. Innov. Technol. Manag. 18, 2050053.
Vermeulen, W.J.V., Hovens, J., 2006. Competing explanations for adopting energy innovations for new office buildings. Energy Policy 34, 2719–2735. https://doi.org/10.1016/j.enpol.2005.04.009
Xie, L.L., Yang, Y., Hu, Y., Chan, A.P.C., 2014. Understanding project stakeholders' perceptions of public participation in China's infrastructure and construction projects: Social effects, benefits, forms, and barriers. Eng. Constr. Archit. Manag. 21, 224–240. https://doi.org/10.1108/ECAM-12-2012-0115

5. Towards an Analytical Framework of Circular Economy (CE) in Urban Transport Infrastructure Projects: a Meso-scale Perspective[54]

5.1 Introduction

Surfacing environmental concerns have made both public and private organizations look towards and embrace CE within their material-related practices (Han et al., 2017; Jedelhauser and Binder, 2018; Veleva and Bodkin, 2018). With so much widespread attention, it could be reasonably assumed that different sectors are keen to follow up on the changes that the CE aspires to. Surprisingly though, one critical sector, the urban transport infrastructure sector, has been scarcely observed in the CE arena (Mantalovas et al., 2020). The urgency for this sector is certainly not trivial, since urban infrastructure projects have high environmental impacts due to the long lifespans and lengthy periods of influence on the surrounding environment (Malekpour et al., 2015). Ambition and action on this front would entail significant opportunities such as reducing energy use, GHG emissions, and waste production.

Two explorative studies into the meaning of the CE have opened up a possible way to understand and address the observed inactivity of the CE in the urban infrastructure sector. Both Pomponi and Moncaster (2017) and Kirchherr et al. (2017) have elaborated that the CE can be studied at three systemic scales (levels), namely: micro, meso, and macro. Yet, these scales are hierarchical in nature and undefined in scope. For example, Pomponi and Moncaster (2017) seem to disagree with Kirchherr et al. (2017) on whether eco-industrial parks are part of the meso-scale. Irrespective of this ambiguity, it seems that the outer extreme examples in "micro" or "macro" are receiving more attention than the middle stream, i.e., "meso" of this division (Pomponi and Moncaster, 2017). Kirchherr et al. (2017)'s views are similar to Heshmati (2015)'s and Su et al. (2013)'s, and they provided examples for the three scales respectively: a single object (micro-scale), a symbiosis association (meso-scale), and a city (macro-scale). In this research, it is considered the meso-scale falls into the range between object level and city/region level. It is assumed that most urban transport infrastructure projects belong to the meso-scale.

In this chapter, we take the view that the underdevelopment of the CE at the meso-scale helps to contextualize why the urban transport infrastructure sector has not picked up on the changes instigated by the CE. At the heart of this argument lies the observation that the urban transport infrastructure sector is a very hierarchically operating business environment, in which projects are made up of contracts among clients, contractors, and subcontractors. These dependencies and the complexity of the construction value chain complicate any motion of changes in projects, including the implementation of circular principles (Munaro and Tavares, 2023). In this setting, it is also difficult for the private sector to invest in innovations if there is little certainty about potential benefits within this system. Therefore, this chapter stresses the unattended meso-scale for urban transport infrastructure projects

[54] This chapter has been published as: **Liu, X.Y.,** Schraven, D., Ma, W.T., de Jong, M. and Hertogh, M. (2024) "Achieving a framework of the circular economy in urban transport infrastructure projects: a meso-scale perspective" ***Frontiers in Sustainability*** 5, doi: 10.3389/frsus.2024.1475155

to be more circular.

The research question of this paper is: "How can CE be made actionable for urban transport infrastructure projects?"

To answer this research question, the focus of this paper is to build an analytical framework, through which we would be empirically empowered to comprehend how the CE changes must occur in the context of urban transport infrastructure projects. The framework also includes an analysis of some impacts caused by CE changes. As a prerequisite of economic development, transport infrastructure is the backbone of global trade and globalization, representing a key facilitator of economic growth and welfare, and providing crucial services, both shaping and supporting urban development (Tsamboulas et al., 2007; Achour and Belloumi, 2016; Schuckmann et al., 2012; Efthymiou and Antoniou, 2013).

We build the analytical framework through two steps: firstly, we uncover the currently available well-established CE "frameworks"[55] that have been described to comprehend CE and assess their potential for studying the CE in the urban transport infrastructure context with a set of criteria; secondly, after selecting one "framework", we propose contextually driven modifications (including CE activity impact analysis) to make it better suited and more useful to studying real-life CE practices in the context of urban transport infrastructure projects. The proposed framework is specifically designed to figure out the potential areas where CE principles could be embedded during the main lifecycle phases of urban transport infrastructure projects. The framework aims for the meso-scale, and with such novelty, it can not only be used to inspire CE activities for specific project stakeholders, guiding locations of the activities; but also to learn finished projects, which is the case of this chapter, showing the applicability of the framework.

5.2 Literature Review

At the project level, CE has been implemented in, for example energy infrastructure projects (Invernizzi et al., 2020; Mignacca and Locatelli, 2021) and water infrastructure (Vera-Puerto et al., 2020). For construction projects, some studies use frameworks such as a CE evaluation framework (Dams et al., 2021), a CE index for the built environment (O'Grady et al., 2021), circular environmental impact indicators (Foster et al., 2020), and CE in buildings (adaptive reuse of building components) (Sanchez et al., 2020).

As for both buildings and infrastructures in the construction sector, Wuni and Shen (2022) revealed twenty-one significant success factors for integrating CE principles into modular construction projects in Hong Kong. Kooter et al. (2021)'s aim was to understand the dynamics of circular construction projects and how these inter-organizational projects contribute to the transition toward a CE. Both studies are from a project management perspective.

Urban transport infrastructure projects typically involve diverse stakeholders (e.g., agencies/clients, consultants, contractors, and suppliers), with contracts signing typically for the design, construction, and maintenance, often separate contracts for each stage. Therefore, all the stakeholders (during the whole life cycle phases of projects) need to realize the importance of CE and collaborate. Additionally, because of the long lifespan of most transport infrastructures, CE should be considered not only during the construction phase, but also

[55] More details in Section 5.2

during the operation/maintenance phase and decommissioning/demolition phase.

Winans et al. (2017) reviewed the history of the CE concept to provide a context for a critical examination of how it is applied currently. They studied specifically three thematic categories. First, they considered policy instruments and approaches that mainly cover eco-industrial parks, eco-industrial networks, and industrial symbiosis. Second, they considered value chains, material flows, and products, which include wood, paper, plastics, metals, phosphorus and other chemicals, agricultural products and waste, water, as well as land. Third, they looked into technological, organizational, and social innovations, like biological and technical product and material innovations, economic and business models, and enabling conditions and systems for the energy sector. It is noticeable that there is no CE implementation in urban transport infrastructure projects in Winans et al. (2017)'s review.

In a more general sense, since 2017 there have been various notable attempts to develop a framing of the CE concept as a whole. For purposes of this study, we depart from an overview of viable candidates for this framing, to set the contours for an urban transport infrastructure relevant conception of CE. Therefore, we developed four critical criteria for identifying the right elements befitting the infrastructure context. These include:

1) The framework should embody diverse CE aspects (such as reduce, reuse, recycle, etc.), to be able to comprehensively capture CE principles;

2) In terms of the CE dimension, it can be applied to the scope of urban transport infrastructure projects, rather than macro- or micro-scales;

3) It should contain enough information for implementation, rather than being too simple or not suitable for implementation;

4) Concerning the potential CE application areas, it can be related to infrastructure projects, which means it is not specifically and exclusively designed for application to the food or agriculture sector, for instance.

The four criteria can be supported by Wisse (2016)'s thesis, which included "Relevant", "Applicable to scope", and "Useable and easily interpreted". The four criteria are used in Appendix G.

In making sure that the CE frameworks are reviewed comprehensively, we performed the review in a systematic stepwise approach. Figure 5.1 shows the process of this systematic literature review. First, the Scopus database was used to search peer-reviewed journals because it has long-term, worldwide coverage. By searching Scopus with a query[56], 2551 articles could be seen for CE "frameworks"[57]. However, these still needed to be filtered. Some articles describe CE itself as the "framework", e.g. Mesa et al. (2018), Masullo (2017), Chen et al. (2017), Hu et al. (2011). After a process of proactive reading, 1596 articles were obtained. These were then further reduced in case articles did not have clearly identifiable names for

[56] (TITLE ("circular economy") OR AUTHKEY ("circular economy")) AND (TITLE ("approach" OR "frame" OR "framework" OR "instrument" OR "method" OR "methodology" OR "model" OR "tool") OR AUTHKEY ("approach" OR "frame" OR "framework" OR "instrument" OR "method" OR "methodology" OR "model" OR "tool") AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English"))).

[57] This was done on Jun 16, 2023.

the framework that they proposed. This led to a final selection of 18 articles (see Appendix G).

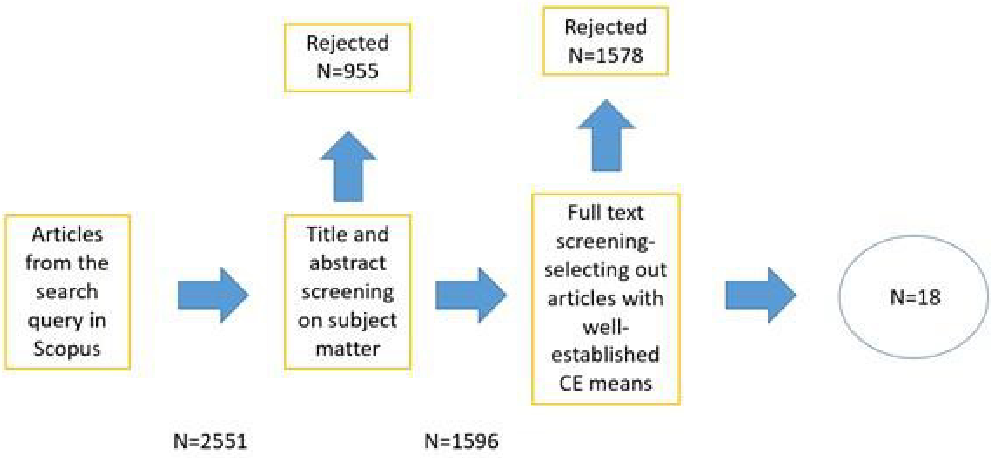


Figure 5.1 Schematic diagram showing the literature review process (own figure)

The "frameworks" of the 18 articles can be sometimes referred to as models, instruments, or tools, but still contain a framing of the CE concept before a study uses them as an instrument, model, or tool. Therefore, the review labels all of these as frameworks for consistency hereafter. The frameworks are presented in detail for overview in Appendix G.

After comparing the thirteen "frameworks", three frameworks were found to meet all four criteria. This meant that in terms of the CE and urban transport infrastructure projects, the BECE (Backcasting and Eco-design for CE) framework, the CEIMA (Circular Economy Interface Matrix Analysis) framework, and the ReSOLVE (implement, Regenerate, Share, Optimize, Loop, Virtualize, Exchange) framework are regarded as the most suitable cornerstones to be further developed into the targeted analytical framework. From their pros and cons, it can be seen that the three frameworks can complement each other. Therefore, the three frameworks are studied more and compared in the next section.

5.3 Analytical Framework for CE in Urban Transport Infrastructure Projects

In this section, the analytical framework is developed step by step. The right ingredients and building blocks have been found in the three previous frameworks. These are reviewed in more detail in the following section, and the useful building blocks are extracted. Next, the framework's contours and building blocks are synthesized as the analytical framework. Finally, the case contours are sketched for a relevant application, including justification.

5.3.1 Building Blocks for a CE Analytical Framework for Transport Infrastructure Projects

5.3.1.1 BECE/iReSOLVE/ReSOLVE

Mendoza et al. (2017) presented the BECE framework to ensure that businesses can implement the CE requirements more readily. BECE empowers organizations to tackle the CE holistically by embedding the concept into corporate decision-making and by bringing operational as well as systems thinking together, thus increasing the likelihood of successful implementation. In their paper, four categories correspond to key strategies that can contribute to building the CE business models, including sustainable business model innovation (SBMI); sustainable product design (SPD); closed-loop systems (CLS); and product-service systems (PSS). The BECE framework embodies diverse CE, can be applied to the scope of urban transport infrastructure projects, contains enough information for implementation, and can be related to infrastructure projects. As a leading CE tool used by businesses for building CE business models, the ReSOLVE checklist proposed by the Ellen MacArthur Foundation (EMF) was used in Mendoza et al. (2017)'s paper.

The BECE framework was informed and described after Mendoza et al. (2017) conducted a literature review of existing CE frameworks to examine their congruence with the CE principles, actions, and requirements. Mendoza et al. (2017)'s analysis of existing CE frameworks raises questions on how the CE can be brought about effectively, given that implementation aspects are often missing and that few of the frameworks consider innovation at a systems level. Thus, they coupled Backcasting (a way to reach a common understanding of successful futures and the steps required to achieve them) (Circular Academy, 2023) and Eco-Design to propose the BECE framework.

There are ten steps in the BECE framework, from which steps 1 to 3 belong to the application of Backcasting; steps 4 to 7 belong to the application of an eco-design analysis; and steps 8 to 10 are the implementation of the vision by defining and validating scenarios as well as action plans. As a case study, the BECE framework was tested in a pilot workshop in preparation for a real-life application at a later stage in collaboration with a major retailer (Mendoza et al., 2017). However, the BECE framework is still company-oriented, not project-oriented. This has a downside that the overarching deployment of the model is not focused on multiple actors but just one business.

On the basis, the BECE framework originated from the ReSOLVE checklist (or the ReSOLVE framework, as cited by Lewandowski (2016), proposed by EMF). As ReSOLVE lacks guidance on the implementation of the ideas in business practice, Mendoza et al. (2017) added the action IMPLEMENT (it has several underpinning requirements taken from project management) to ReSOLVE, resulting in the "iReSOLVE" checklist (contained in Appendix H).

The iReSOLVE framework has a pro. First, it is compatible with using stakeholders and big data to accomplish CE (Virmani et al., 2022; Jabbour et al., 2019; Alonso-Almeida et al., 2021). It allows, for example to help track and manage materials such that the collection as well as return of products and waste can be improved (Nascimento et al., 2018; Nobre and Tavares, 2020; Muller et al., 2022). The ReSOLVE framework is a well-known theoretical framework for CE (Lejardi et al., 2021) and has been used often (Dev et al., 2020; Heyes et al., 2018; Jabbour et al., 2019; Mastos et al., 2021; Mhatre et al., 2021; Pizzi et al., 2021; Tu et al., 2020).

The iReSOLVE framework also has several cons. The problem lies in the scope definition, the interrelation of the CE strategies, and the implementation path could strongly vary depending on the sector or product in which the strategy is applied (Lejardi et al., 2021).

5.3.1.2 CEIMA/9Rs

Coenen et al. (2020) developed the CEIMA framework following a Design Science Research-based approach, linking a bottom-up asset stakeholder perspective to the existing top-down conceptualizations of CE. With the CEIMA framework, identified interfaces between stakeholders and circular actions reveal key opportunities for stakeholders within the infrastructure sector to start with the implementation of circular actions (Coenen et al., 2020). It covers the whole lifecycle of assets, which is a useful building block for the framework to be proposed in this chapter. The CEIMA framework is designed for urban transport infrastructure projects; it also embodies diverse CE aspects, and contains enough information for implementation.

It consists of 23 CE actions based on the operationalization of the 9Rs. The 9R concepts underlie a circular economic framework that examines how materials can be used and reused at their highest value while minimizing waste and environmental destruction (Potting et al., 2017). This signifies that the 23 actions identified by Coenen et al. (2020) are particularly focused on strategies related to handling materials or products.

Coen et al. (2020) focused on the identification of actions, when people are following the referencing structure as the researchers have prepared it. In pursuance of identifying contextually driven actions, such a fixed CE action list is user-friendly for non-CE experts, but it restricts potential CE innovation actions or new ideas; while with a heuristic format, the focus on 9Rs may therefore narrow the innovation focus to only the particular referencing frame of 9Rs, and disallow for more indirect circular innovations to be recognized.

There are some pros to the CEIMA framework, as it refers to its usefulness. First, CEIMA makes an interface possible between stakeholders and circular actions, and it uses a bottom-up approach to associate linkage among CE practices and actions (Virmani et al., 2022). Second, Coenen et al. (2020) discussed that a broad, unified, clear perspective is needed to generate a better understanding of how organizations can implement CE in practice (Muller et al., 2022).

There are also some cons to the CEIMA framework. Coenen et al. (2020) in their study took the view that professionals without expertise can use frameworks to arrive at the same outcome without having to understand the multitude of circular principles and approaches (Lejardi et al., 2021). It thereby assumes that it is beneficial to arrive at the same actionable outcome when it comes to CE. This, however, restricts potential CE innovation actions or new ideas.

5.3.1.3 Building Blocks: CEIMA and iReSOLVE Inspirations

As the building blocks are selected for CEIMA and iReSOLVE, a few reasons can be named. First, both frameworks consider multiple lifecycle phases and different stakeholders of the project or asset; they both do not constrain to a certain lifecycle phase or one stakeholder. Second, 9Rs, which underlies CEIMA, missed a broader category range to identify circular strategies; iReSOLVE takes a broader set of categories into view, as it transcends the mere focus on material or product choices (Okorie et al., 2018) by also encompassing supporting and systemic actions. The 9R strategies were developed for assessing CE levels of materials in a product. It thereby tries to understand the CE system and determine the extent to which a product or structure contributes to the CE (Dişli and Ankaralıgil, 2023). The ReSOLVE framework has six business actions to aid organizations in the principles of CE (Okorie et al., 2018).

Taking these reasons into account, the analytical framework needs a combination of building blocks from both sides. In the original “iReSOLVE” checklist, there are “iReSOLVE actions" and "iReSOLVE requirements" (each "iReSOLVE requirement" can have one or more corresponding CE activities, which can be viewed as "What"). Next to that, CEIMA illustrated that certain additional characteristics need to be considered for urban transport infrastructure projects. These include most notably multiple stakeholders ("Who"), lifecycle stages ("When"), and spatial dispersion ("Where").

In addition, as it can be easily figured out that all the "frameworks" reviewed do not consider the impacts of CE practices in a project, therefore, for the analysis of impacts these activities can induce, an added part of "iReSOLVE requirement (CE) activities Impact analysis" after the four "*Wh*"s part is forged.

Taken together, this helps to enhance the framework as 4Wh-iReSOLVE in Figure 5.2. The framework hosts three main categories. First, it offers space to specify the generic situation of the urban infrastructure project that is analyzed with categories signifying the "Who", "What", and "Where". Second, the action categories are listed based on the iReSOLVE structure. Finally, in order to analyze the proper impact that these actions help accomplish, three impact categories are formulated along the lines of the sustainability dimensions (environmental, economic, and social).

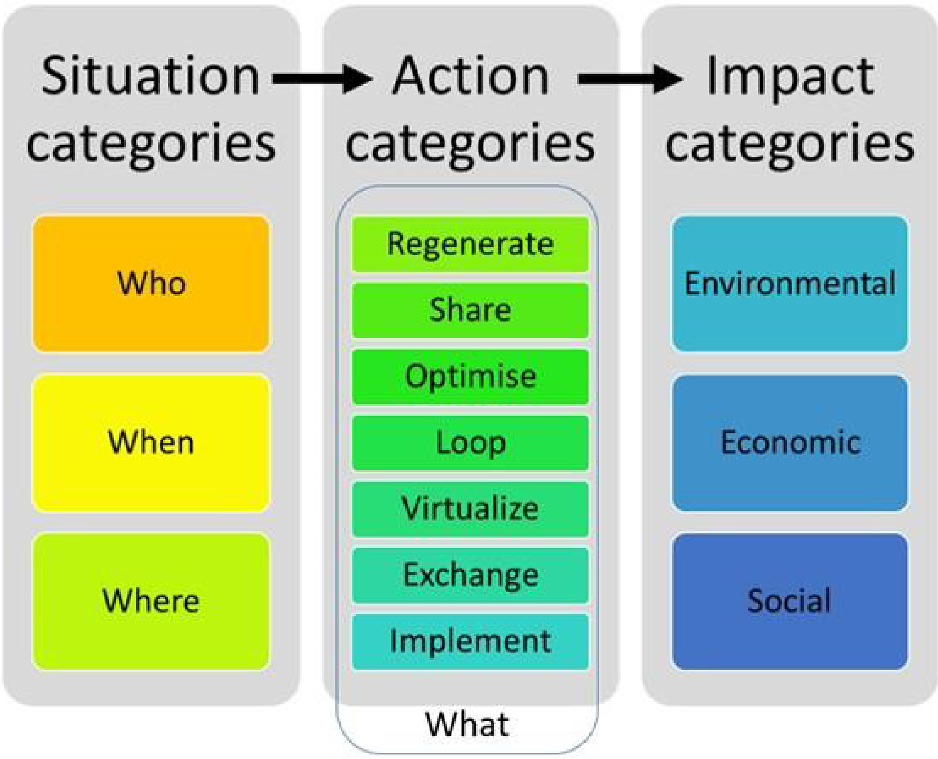


Figure 5.2 Schematic representation of the 4Wh-iReSOLVE framework

5.3.2 Analytical Function of the Framework

The situation categories show that for a certain urban transport infrastructure project, "*Wh*en", "*Wh*ere", and "*Wh*o" can do "iReSOLVE actions" to implement CE. As the current "iReSOLVE requirements" are comprehensive, due to reasons such as technology, for typical urban transport infrastructure projects, not all the "iReSOLVE requirements" are likely to be analyzed (e.g., digest anaerobically). Also, in practice, each "iReSOLVE requirement" can have diverse forms of activities. Additionally, the actions can bring about certain impacts.

To use the analytical framework, all the "iReSOLVE requirements" are analyzed for the project. The purpose of this is to find out whether certain CE actions apply to the involved stakeholders as well as to the different lifecycle phases of a project, and if so, the specific locations for executing these CE activities are further identified.

To facilitate this goal, the framework has been operationalized in Appendix H. On the top left, the generic situation can be described about the project, in terms of the "Who", "When", and "Where". In the bottom left, the seven action categories are outlined, with a total of 23 activities formulated as examples. This is the part where the results of finding the relevant CE actions in a project can be specified. In the bottom right, for each action, the expected impact on the environmental, economic, or social aspects can be described. In Appendix G, some examples are written about the long or short-term impact of an action. But this acts simply as an example, and may include actual metrics, or LCA output. Finally, at the top right corner, the total noted impact of the activities can be summarized or accumulated to the project level if needed.

In essence, the outcome of applying the analytical framework to an urban transport infrastructure project is a detailed table that shows what "iReSOLVE requirement activities" different stakeholders of the project can conduct during which project phase(s) and where to conduct. Particularly, the impact analysis can show the impacts (benefits) after the executions of the CE activities.

5.3.3 Case Analysis with the Framework

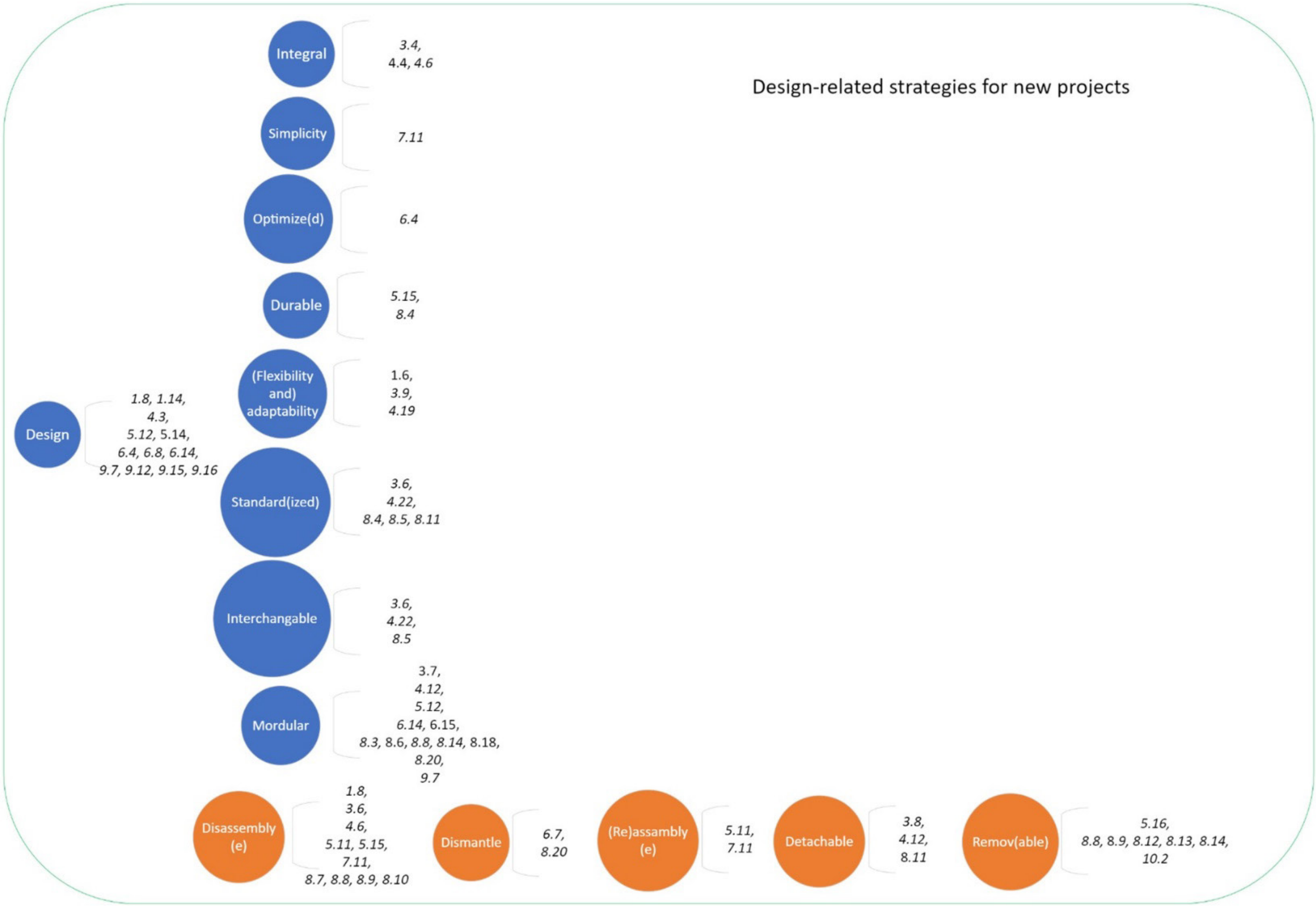
The framework is used to analyze ten innovation cases in the Netherlands as part of open-ended innovation efforts for designing circular viaducts. In 2020, Rijkswaterstaat (RWS, the executive agency of the Ministry of Infrastructure and Water Management) in the Netherlands launched an SBIR (Strategic Business Innovation Research) call, challenging entrepreneurs to present innovative solutions for circular viaducts. Based on impact, feasibility, and economic perspective, RWS selected ten (out of more than 30 offers) for further feasibility studies (prototypes are being developed) (RWS, 2022).

The feasibility studies of all ten consortia were retrieved from public sources (Circulaire viaducten, 2022). The documents have been read and studied by me. Afterward, the 4Wh-iReSOLVE framework was used to analyze the ten consortia. The contact persons of the ten project initiatives have been contacted, and they are asked: 1) whether they think our analysis covers all the CE activities of their projects; 2) whether the CE activities are attributed to the correct lifecycle phases; and 3) their overall views about the framework (including the impact analysis, if applicable).

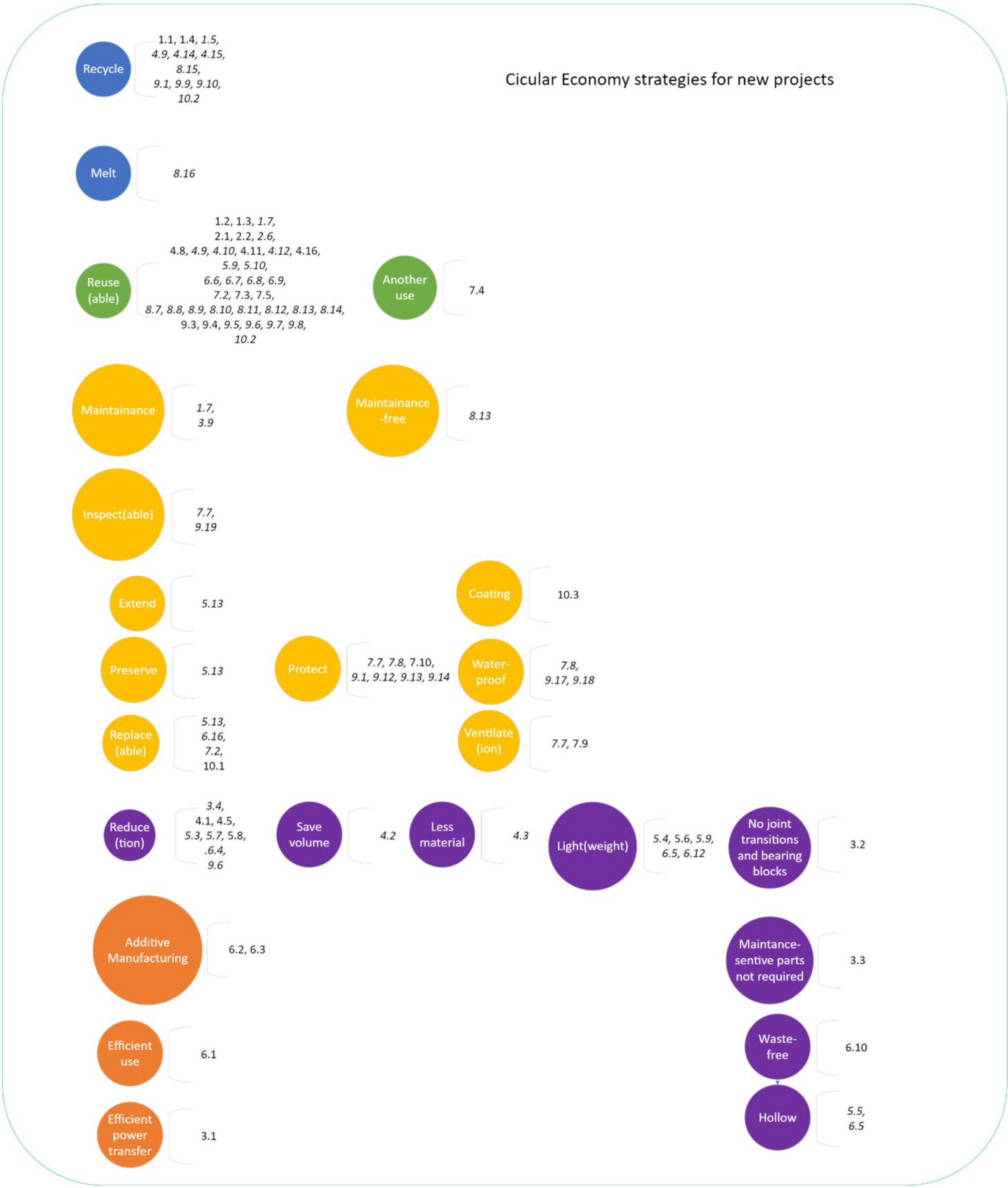
After the identification of CE activities, we requested feedback from the responsible circular viaduct design. Four of these project initiatives responded and offered feedback. Specifically, as mentioned, these participants were asked whether the CE activities are attributed to the right positions in the framework; and the third author of the article also did the judgement of the analysis from me for validation. Finally, it turns out that the analysis of the four project initiatives by me was found to be robust.

5.4 Results of CE Actions in the Ten Circular Viaduct Designs

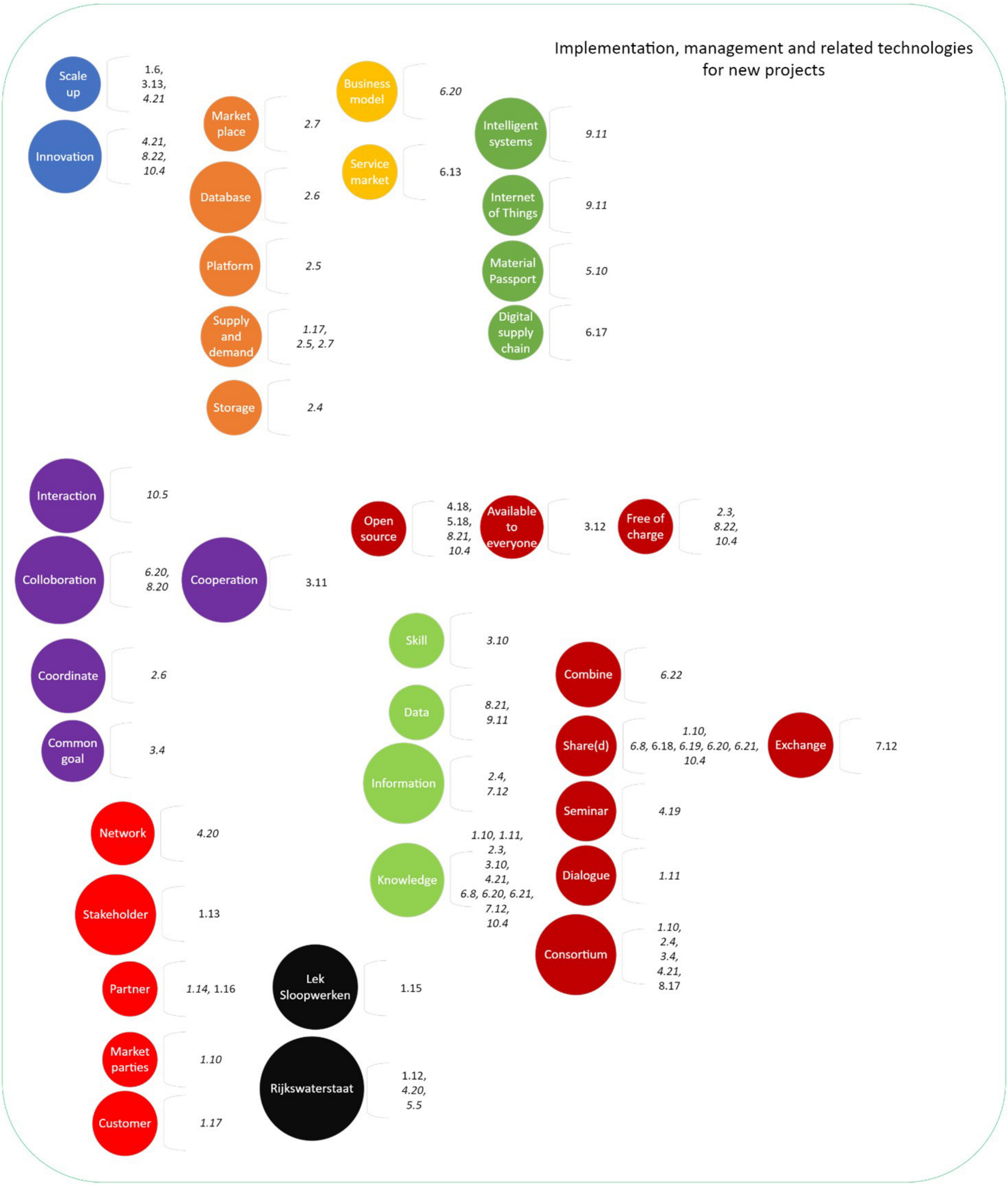
The results of all ten projects are presented in the following sub-sections. To be concise, these projects are briefly introduced, following impact analysis (if applicable), and the overall main results of all ten projects are summarized in Figure 5.3 (more details in Section 5.4.6). All the CE activities of the ten projects can be seen in Appendix I, with lifecycle phases presented for each CE activity. For the ten projects, the companies can be seen as designers and builders.



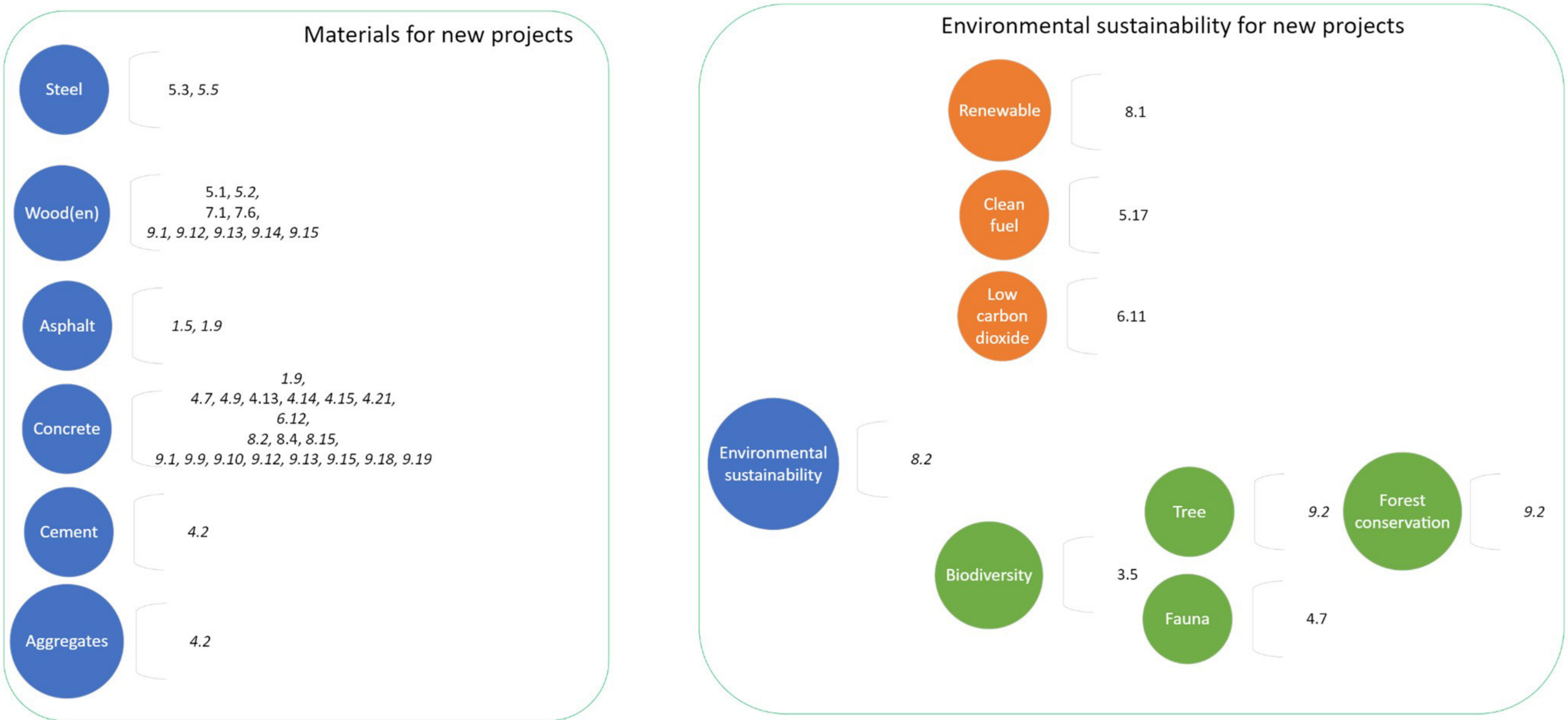
(a). Group 1. Design-related strategies for new projects



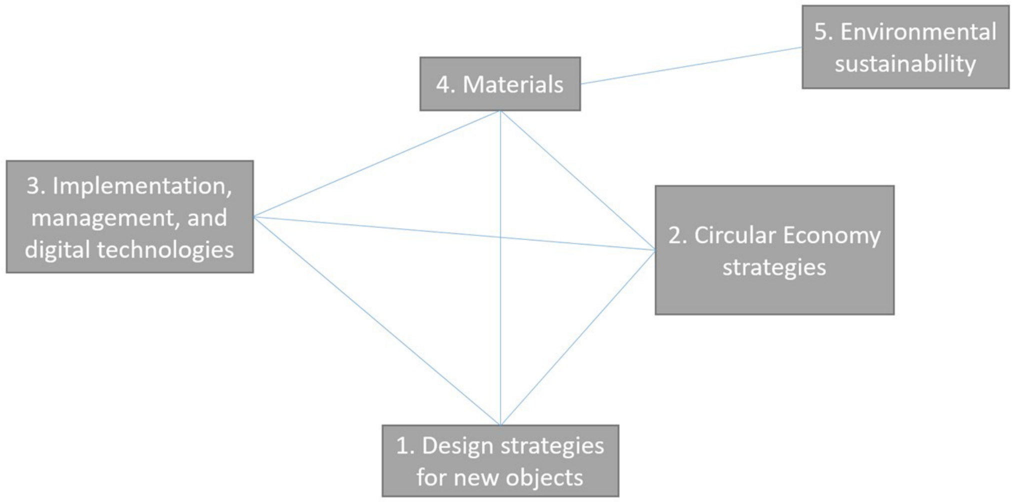
(b). Group 2. Circular Economy strategies



(c). Group 3. Implementation, management and related digital technologies



(d). Group 4 and Group 5. Materials and Environmental sustainability respectively



(e). Connectivity among the five groups

Figure 5.3 Group analysis of all the CE activities of Project 1–10[58] (own figure)

5.4.1 Projects 1-3

Project 1 is about closing the circle for the high-quality reuse of existing viaducts, which is technically feasible, constructively safe, and economically attractive. Project 2 is mainly about the reuse of physically unaltered inverted T-beams prefab girders. The design innovation of Project 3 offers a total solution for a circular construction system for viaducts. The system consists of a fully recoverable, modular arch construction and substructure. The solution is demountable and reusable at the element level.

5.4.2 Project 4

Project 4 is Circular Arch Viaduct, which means:

Substantial material reduction by applying Ultra High Strength Fiber Reinforced Concrete (UHSVB) in the ultimate bend-free shape, the pressure arc.;

A modular, demountable, and reusable viaduct of UHSVB elements with a service life of up to 200 years and reusable foundation piles;

Abutments of circular and cementless geopolymer concrete where granulate from old viaducts as 100% recycled building materials are reused.

Table 5.1 shows the iReSOLVE requirement activities impact analysis of Project 4.

[58] The numbers are in correspondence with those in Appendix I; the numbers in italics mean the corresponding CE statements contain more than one core word, and in such cases, if the core words belong to different groups, we call the groups are "connected," thus forging (e)

Table 5.1 iReSOLVE requirement activities impact analysis of Project 4

<table>
<tr><td>Specific locations (Where)</td><td colspan="4">(for activity No. 4.17): pile foundation;</td></tr>
<tr><td rowspan="4">iReSOLVE requirement activities impact analysis</td><td rowspan="2">(for activity No. 4.8, 4.9, 4.10, 4.11, 4.12, 4.16)</td><td>Environmental impact (En): The Circular Arch Viaduct reduces the environmental impact (in EMI) by 52% compared to a conventional concrete viaduct</td><td>Economic impact (Ec): The Circular Arch Viaduct will save up to 90% in cement and up to 95% in newly mined gravel and sand over 200 years; Because elements are reused during the rebuilding of the viaduct, the Circular Arc Viaduct will be up to 15% cheaper over a period of 200 years</td><td>Social impact (So): N/A</td></tr>
<tr><td>Long-term impact (L)</td><td>(L)</td><td>N/A</td></tr>
<tr><td rowspan="2">(for activity No. 4.1, 4.2, 4.3, 4.4, 4.5, 4.6)</td><td>(En): N/A</td><td>(Ec): The UHSVB arch girders as a corrugated arch prove to be constructively feasible and more material efficient than the originally devised sandwich system; It can be molded into complex shapes and is able to withstand tensile forces and very high compressive forces, without the need for additional reinforcement</td><td>(So): N/A</td></tr>
<tr><td>N/A</td><td>(L)</td><td>N/A</td></tr>
</table>

Activities numbers can be referred to Appendix I.

5.4.3 Projects 5-7

Project 5 is about the development of Variaduct into a preliminary design with the following innovative and distinctive elements: slim steel deck sections; foundation without piles; columns with jacking facility; substructure of prefab concrete elements; application of wood; reduction of the construction height.

Table 5.2 shows the iReSOLVE requirement activities impact analysis of Project 5.

Table 5.2 iReSOLVE requirement activities impact analysis of Project 5

<table>
<tr><td rowspan="5">iReSOLVE requirement activities impact analysis</td><td colspan="4">/</td></tr>
<tr><td rowspan="2">(for activity No. 5.3, 5.4, 5.5, 5.6, 5.7, 5.8)</td><td>Environmental impact (En): A construction height that can be 10% lower than with a traditional viaduct, which leads to a saving in fuel consumption</td><td>Economic impact (Ec): This saves fuel costs. A reduction in the construction height of our innovation also leads to a lower environmental impact and lower construction costs</td><td>Social impact (So): N/A</td></tr>
<tr><td>Long-term impact (L)</td><td>(L)</td><td>N/A</td></tr>
<tr><td rowspan="2">(for activity No. 5.17, 5.18)</td><td>(En): A CO_2 and nitrogen reduction of at least 75% to 90% when realizing the Variaduct through the use of electrical equipment, clean fuel (HVO 100), and use of NO_x filters</td><td>(Ec): N/A</td><td>(So): N/A</td></tr>
<tr><td>Short-term impact (S)</td><td>N/A</td><td>N/A</td></tr>
</table>

Activities numbers can be referred to Appendix I.

The proposal of Project 6 for the circular viaduct, like the honeycomb, consists of an efficient light spatial structure of 3D-printed concrete.

Table 5.3 shows the iReSOLVE requirement activities impact analysis of Project 6.

Table 5.3 iReSOLVE requirement activities and impact analysis of Project 6

<table>
<tr><td rowspan="3">iReSOLVE requirement activities impact analysis</td><td colspan="4">/</td></tr>
<tr><td rowspan="2">(for activity No. 6.2, 6.3, 6.4)</td><td>Environmental impact (En):</td><td>Economic impact (Ec): a prestressed, curved and printed deck works efficiently and leads to a 60% material reduction over traditional reinforced decks</td><td>Social impact (So): N/A</td></tr>
<tr><td>N/A</td><td>Long-term impact (L)</td><td>N/A</td></tr>
</table>

Activities numbers can be referred to Appendix I.

Project 7 demonstrates that the BoLT design (viaduct with a span of 25m consisting of wooden decking on wooden beams) is technically feasible, reduces CO_2 emissions, and provides a sound business case within the existing (or modified) design standards.

5.4.4 Projects 8-10

The goal of Project 8 is to show that: 1) all the viaduct components are modular and circular with reduced CO_2 emissions and minimal material consumption; 2) the viaduct can be built following current standards and guidelines; 3) the viaduct satisfies all set safety factors; 4) the business case becomes feasible, in collaboration with RWS.

Table 5.4 shows the iReSOLVE requirement activities impact analysis of Project 8.

Table 5.4 iReSOLVE requirement activities impact analysis of Project 8

iReSOLVE requirement activities impact analysis	/			
	(for activity No. 8.18, 8.19, 8.20)	Environmental impact (En): 70% lower CO_2 emissions and minimized material consumption	Economic impact (Ec): N/A	Social impact (So): N/A
		Long-term impact (L)	N/A	N/A
	(for activity No. 8.2, 8.3)	(En): UBB is an environmentally friendly, cement-free and low-CO_2 concrete	(Ec): N/A	(So): N/A
		Short-term impact (S)	N/A	N/A

Activities numbers can be referred to Appendix I.

The viaduct of Project 9 consists of a prefab wood-concrete girder system with a maximum span of 15-35 meters and a deck width of approximately 26 meters. The prefab beam has a width of 1.6 meters and consists of ¼ part of recycled concrete and ¾ part of European spruce. The wood is protected against weather influence by the concrete. As a result, the system has a lifespan of at least 100 years.

Table 5.5 shows the iReSOLVE requirement activities impact analysis of Project 9.

Table 5.5 iReSOLVE requirement activities impact analysis of Project 9

iReSOLVE requirement activities impact analysis	/			
	(for activity No. 9.1)	Environmental impact (En): This combination provides an enormous weight saving: the type of wood used is 5 times lighter than concrete. This has a positive effect on CO_2 emissions during transport and assembly with lighter material; The production and processing of glued timber constructions costs little energy. The adhesives used are environmentally friendly	Economic impact (Ec): N/A	Social impact (So): N/A
		Long-term impact (L)	N/A	N/A

Activities numbers can be referred to Appendix I.

The aim of Project 10 is to demonstrate the financial and technical feasibility of a traffic viaduct in the material biocomposite.

Table 5.6 shows the iReSOLVE requirement activities impact analysis of Project 10.

Table 5.6 iReSOLVE requirement activities impact analysis of Project 10

iReSOLVE requirement activities impact analysis	/			
	(for activity No. 10.1)	Environmental impact (En): it is a natural material that requires less energy for production and its own weight is only half that of glass fibers	Economic impact (Ec): N/A	Social impact (So): N/A
		Long-term impact (L)	N/A	N/A
	(for activity No. 10.6)	Environmental impact (En): It's light and less heavy equipment needs to be used, the elements can be placed really quickly, which results in less hindrance of the traffic (and stationary traffic causes more emissions).	Economic impact (Ec): N/A	Social impact (So): N/A
		Long-term impact (L)	N/A	N/A

5.4.5 iReSOLVE Requirement (CE) Activities of Project 1-10 Based on Different iReSOLVE Action Categories

The results of CE activities of Project 1-10 based on different iReSOLVE action categories are shown in Appendix J. In terms of action categories, different projects vary a lot. It can be noted that about half of the CE activities of Project 1 belong to the "Implement" category. The contact person of Project 1 expressed that certain quotes to life cycle phases depend on how to approach it. For example, the following quote can be perceived as the Design/Preparation phase for the ''new'' circular viaduct as well as the demolition phase of the old viaduct: "Harvest all materials from the viaducts to be demolished in the A76". For Project 2, five out of the total seven CE activities were attributed to the "Implement" category. Unlike Project 1 and Project 2, the CE activities of Project 8 cover more categories, and twelve activities were ascribed to "Share". The numbers 10.3 and 10.4 of Appendix I are in brackets because the contact person of Project 10 doesn't think activities 10.3 and 10.4 are CE activities but are ways to cooperate in the market.

Generally for Appendix J, R3, S1, L1, L3, L4, and V2 are the sub-categories that are not covered, half of which (R3, L3, and L4) are about biology, while S1, L1, and V2 are potential areas for viaducts to be more circular. On the contrary, S2, S3, and I3 are the most "popular" sub-categories, as "Reuse" as well as "Prolong product" are both common CE strategies, and most of the ten projects are conscious of stakeholder engagement.

5.4.6 Group Analysis of All the CE Activities of Project 1-10

To have a different perspective besides the iRESOLVE framework, a group analysis of all the CE activities of Project 1-10 was also conducted. To do so, the core words of all the CE activities in Appendix I were extracted to stand for those CE activity statements; then all the core words were written in notes and grouped in a workshop; finally, the groups were summarized based on their main characteristics. The results of the group analysis can be seen in Figure 5.3.

In Figure 5.3 (a)-(d), closely related core words were positioned close to each other. It can be seen from Figure 5.3 (e) that the five groups form a “kite” shape, in which the first four groups form a diamond-like shape, as each of them is connected with the other three. Group 5 (Environmental sustainability), as a small group, is only connected to Group 4; therefore Group 4 (Materials) can be viewed as the central group. The biggest group is Group 3, which aligns with the “Implement” category in Appendix J. In Group 4, concrete and wood are the materials that attracted the most attention from the ten viaduct projects. This is linked back to Chapter 2. Figure 5.3 offers us a clear map of the different strategy groups of circular viaducts from the ten projects studied. The group analysis can support the analysis of projects based on the iRESOLVE framework, and it is also possible to do the group analysis with certain software.

5.5 Discussion

With the 4Wh-iReSOLVE framework, there are more CE activities obtained from, for example Projects 1 and 8 than from, for instance Projects 2 and 10, since Projects 2 and 10 are about a certain kind of component and material respectively, not covering CE principles broadly. According to the framework, there is still quite a large potential for projects to be more circular. This is shown by Appendix I, as even if all the ten projects were summarized in this table, not all iReSOLVE action categories were covered (e.g., S1 Share assets, L1 Remanufacture products or components, V2 Dematerialize indirectly, etc.). The original “iReSOLVE requirements” are comprehensive, currently a certain project probably cannot meet all the “requirements”, since some action categories of Appendix H belong to the biological loop (i.e., R3 Return recovered biological resources to biosphere, L3 Digest anaerobically, and L4 Extract biochemical from organic waste). With more bio-based materials used in the future, it is potential that the action categories R3, L3, and L4 will be achieved by transport infrastructure projects. As circular viaduct projects, the CE activities of the ten projects analyzed also present five different CE streams (groups): Design-related strategies for new objects, high-level CE strategies, Implementation, management and related digital technologies, as well as Materials and Environmental sustainability. This part of analysis is similar to Munaro and Tavares (2023)’s categorization of barriers and drivers to CE in the construction sector. The five CE streams direct applicable CE implementation directions for (viaduct) infrastructure projects. However, as the five CE streams were extracted from only the ten projects in the Netherlands, there can be more implementation directions.

As for the impacts of CE activities, it can happen that sometimes “Environmental impact” resonates with “Economic impact”. For instance, if a certain kind of energy consumption is lower, not only the corresponding energy cost decreases, but also related CO_2 emissions would become less. Besides, the three kinds of impacts correspond to the TBL of “Sustainability”. From the analysis of the ten projects, no social impacts were found from the project documents. The impact analysis (which is an innovation point) can also make practitioners pay more attention to the long-term impacts and the corresponding activities. One limitation of this chapter is the data of the cases were from the contractors only. Further application of the enlightening 4Wh-iReSOLVE analytical framework should contain all the main stakeholders (each stakeholder with a resultant table), and there are possible overlaps as well as collaborations of certain “iReSOLVE requirement activities” among multiple stakeholders.

5.6 Conclusions

The research question of this chapter has been answered by forging and using the 4Wh-iReSOLVE framework, via literature review and case study. With the 4Wh-iReSOLVE analytical framework, a comprehensive view can be drawn of where to implement CE for different stakeholders during which lifecycle phases of a certain urban transport infrastructure project. After a systematic analysis, the framework can offer project stakeholders directions for embedding CE principles into their projects. In addition, it is flexible enough to be applied to different stages of a project. The outcomes can also be compared to draw lessons if the framework is applied to different projects in various contexts (such as with geographical variability). With the CE activities impact analysis part, stakeholders of a certain project can grasp the benefits that CE practices can bring. The analysis of the ten circular viaduct projects offers practitioners circular initiatives of viaduct design and construction in the Netherlands, and such initiatives can be valuable experiences for different stakeholders (e.g., policymakers) of the sector from other countries.

Theoretically, this research work tries to extend CE at the meso-scale, specifically for urban infrastructure projects; from the perspective of practice, the 4Wh-iReSOLVE framework stimulates CE principles awareness and guides CE implementation in urban infrastructure projects. The CE activities of the ten circular viaducts in the Netherlands were shown systematically, offering reference to the usage of the framework and future circular viaduct projects.

References for Chapter 5

Achour, H., Belloumi, M., 2016. Investigating the causal relationship between transport infrastructure, transport energy consumption and economic growth in Tunisia. Renew. Sustain. Energy Rev. 56, 988–998. https://doi.org/10.1016/j.rser.2015.12.023

Alonso-Almeida, M., Rodriguez-Anton, J.M., Bagur-Femenías, L., Perramon, J., 2021. Institutional entrepreneurship enablers to promote circular economy in the European Union: Impacts on transition towards a more circular economy. J. Clean. Prod. 281, 124841.

Álvarez, R., Ruiz-Puente, C., 2017. Development of the Tool SymbioSyS to Support the Transition Towards a Circular Economy Based on Industrial Symbiosis Strategies. Waste and Biomass Valorization 8, 1521–1530. https://doi.org/10.1007/s12649-016-9748-1

Ang, K.L., Saw, E.T., He, W., Dong, X., Ramakrishna, S., 2021. Sustainability framework for pharmaceutical manufacturing (PM): A review of research landscape and implementation barriers for circular economy transition. J. Clean. Prod. 280, 124264. https://doi.org/10.1016/j.jclepro.2020.124264

Çetin, S., De Wolf, C., Bocken, N., 2021. Circular digital built environment: An emerging framework. Sustain. 13 (11), 6348. https://doi.org/10.3390/su13116348

Chen, L., Cong, R.G., Shu, B., Mi, Z.F., 2017. A sustainable biogas model in China: The case study of Beijing Deqingyuan biogas project. Renew. Sustain. Energy Rev. 78, 773–779. https://doi.org/10.1016/j.rser.2017.05.027

Circulaire viaducten. (2022, September 24). The RWS website. Retrieved Sept. 24, 2022 from https://www.circulaireviaducten.nl/documenten-binnen-sbir/7-

haalbaarheidsonderzoeken
Circular Academy. (2023, October 17). Backcasting. The Circular Academy website. Retrieved Oct. 17, 2023 from https://www.circular.academy/portfolio/backcasting/
Coenen, T.B.J., Haanstra, W., Jan Braaksma, A.J.J., Santos, J., 2020. CEIMA: A framework for identifying critical interfaces between the Circular Economy and stakeholders in the lifecycle of infrastructure assets. Resour. Conserv. Recycl. 155, 104552. https://doi.org/10.1016/j.resconrec.2019.104552
Dams, B., Maskell, D., Shea, A., Allen, S., Driesser, M., Kretschmann, T., et al., 2021. A circular construction evaluation framework to promote designing for disassembly and adaptability. J. Clean. Prod. 316, 128122. https://doi.org/10.1016/j.jclepro.2021.128122
Dev, N.K., Shankar, R., Qaiser, F.H., 2020. Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance. Resour. Conserv. Recycl. 153, 104583. https://doi.org/10.1016/j.resconrec.2019.104583
Diacono, S., Baldacchino, L., 2023. Identifying entrepreneurial opportunities in the circular economy. J. Manag. Organ. 30 (1),165-187. https://doi.org/10.1017/jmo.2023.47
Dis¸li, G., Ankaralıgil, B., 2023. Circular economy in the heritage conservation sector: An analysis of circularity degree in existing buildings. Sustain. Energy Technol. Assessments. 56, 103126.
Domenech, T., Bahn-Walkowiak, B., 2019. Transition Towards a Resource Efficient Circular Economy in Europe: Policy Lessons From the EU and the Member States. Ecol. Econ. 155, 7-19. https://doi.org/10.1016/j.ecolecon.2017.11.001
D’Urzo, M., Campagnaro, C., 2023. Design-led repair & reuse: An approach for an equitable, bottom-up, innovation-driven circular economy. J. Clean. Prod. 387, 135724. https://doi.org/10.1016/j.jclepro.2022.135724
Efthymiou, D., Antoniou, C., 2013. How do transport infrastructure and policies affect house prices and rents? Evidence from Athens, Greece. Transp. Res. Part A Policy Pract. 52, 1–22. https://doi.org/10.1016/j.tra.2013.04.002
Ferronato, N., 2021. Integrated analysis for supporting solid waste management development projects in low to middle income countries: The NAVA-CE approach. Environ. Dev. 39, 100643. https://doi.org/10.1016/j.envdev.2021.100643
Foster, G., Kreinin, H., Stagl, S., 2020. The future of circular environmental impact indicators for cultural heritage buildings in Europe. Environ. Sci. Eur. 32, 141. https://doi.org/10.1186/s12302-020-00411-9
Han, F., Liu, Y., Liu, W., Cui, Z., 2017. Circular economy measures that boost the upgrade of an aluminum industrial park. J. Clean. Prod. 168, 1289–1296. https://doi.org/10.1016/j.jclepro.2017.09.115
Heshmati, A., 2015. A Review of the Circular Economy and its Implementation. IZA Discuss. Pap. No. 9611, 63. https://doi.org/10.1504/IJGE.2017.089856
Heyes, G., Sharmina, M., Mendoza, J.M.F., Gallego-Schmid, A., Azapagic, A., 2018. Developing and implementing circular economy business models in service-oriented technology companies. J. Clean. Prod. 177, 621–632. https://doi.org/10.1016/j.jclepro.2017.12.168
Hu, J., Xiao, Z., Zhou, R., Deng, W., Wang, M., Ma, S., 2011. Ecological utilization of leather tannery waste with circular economy model. J. Clean. Prod. 19, 221–228. https://doi.org/10.1016/j.jclepro.2010.09.018

Iacovidou, E., Millward-Hopkins, J., Busch, J., Purnell, P., Velis, C.A., Hahladakis, J.N., et al., 2017. A pathway to circular economy: Developing a conceptual framework for complex value assessment of resources recovered from waste. J. Clean. Prod. 168, 1279–1288. https://doi.org/10.1016/j.jclepro.2017.09.002

Invernizzi, D.C., Locatelli, G., Velenturf, A., Love, P.ED., Purnell, P., Brookes, N.J., 2020. Developing policies for the end-of-life of energy infrastructure: Coming to terms with the challenges of decommissioning. Energy Policy. 144, 111677.

Jabbour, C.J.C., Jabbour, A.B.L. de S., Sarkis, J., Filho, M.G., 2019. Unlocking the circular economy through new business models based on large-scale data: An integrative framework and research agenda. Technol. Forecast. Soc. Change 144, 546–552. https://doi.org/10.1016/j.techfore.2017.09.010

Jedelhauser, M., Binder, C.R., 2018. The spatial impact of socio-technical transitions – The case of phosphorus recycling as a pilot of the circular economy. J. Clean. Prod. 197, 856–869. https://doi.org/10.1016/j.jclepro.2018.06.241

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kooter, E., van Uden, M., van Marrewijk, A., Wamelink, H., van Bueren, E., Heurkens, E., 2021. Sustainability transition through dynamics of circular construction projects. Sustain. 13, 1–19. https://doi.org/10.3390/su132112101

Lauten-Weiss, J., Ramesohl, S., 2021. The circular business framework for building, developing and steering businesses in the circular economy. Sustain. 13, 1–14. https://doi.org/10.3390/su13020963

Lejardi, E.S., Franke, M., Deng, Q., Rial, R.M., 2021. Circularity Protocols for Extending the Useful Lifetime of Obsolete Large Industrial Equipment and Assets. 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Vasteras, Sweden. 1-8. https://doi.org/10.1109/ETFA45728.2021.9613234

Lewandowski, M., 2016. Designing the business models for circular economy-towards the conceptual framework. Sustain. 8 (1): 1-28. https://doi.org/10.3390/su8010043

Malekpour, S., Brown, R.R., de Haan, F.J., 2015. Strategic planning of urban infrastructure for environmental sustainability: Understanding the past to intervene for the future. Cities 46, 67–75. https://doi.org/10.1016/j.cities.2015.05.003

Mantalovas, K., Di Mino, G., Del Barco Carrion, A.J., Keijzer, E., Kalman, B., Parry, T., et al., 2020. European national road authorities and circular economy: An insight into their approaches. Sustain. 12, 1–19. https://doi.org/10.3390/su12177160

Mastos, T.D., Nizamis, A., Terzi, S., Gkortzis, D., Papadopoulos, A., Tsagkalidis, N., et al., 2021. Introducing an application of an industry 4.0 solution for circular supply chain management. J. Clean. Prod. 300, 126886. https://doi.org/10.1016/j.jclepro.2021.126886

Masullo, A., 2017. Organic wastes management in a circular economy approach: Rebuilding the link between urban and rural areas. Ecol. Eng. 101, 84–90. https://doi.org/10.1016/j.ecoleng.2017.01.005

Mendoza, J.M.F., Sharmina, M., Gallego-Schmid, A., Heyes, G., Azapagic, A., 2017. Integrating Backcasting and Eco-Design for the Circular Economy: The BECE Framework. J. Ind. Ecol. 21, 526–544. https://doi.org/10.1111/jiec.12590

Mesa, J., Esparragoza, I., Maury, H., 2018. Developing a set of sustainability indicators for product families based on the circular economy model. J. Clean. Prod. 196, 1429–1442. https://doi.org/10.1016/j.jclepro.2018.06.131

Mhatre, P., Panchal, R., Singh, A., Bibyan, S., 2021. A systematic literature review on the circular economy initiatives in the European Union. Sustain. Prod. Consum. 26, 187–202. https://doi.org/10.1016/j.spc.2020.09.008

Mignacca, B., Locatelli, G., 2021. Modular circular economy in energy infrastructure projects: Enabling factors and barriers. J. Manag. Eng. 37 (5), 04021053. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000949

Muller, L., Delai, I., Alcantara, R.L.C., 2022. Circular value chain practices for developing resource value retention options. J. Clean. Prod. 359, 131925.

Munaro, M.R., Tavares, S.F., 2023. A review on barriers, drivers, and stakeholders towards the circular economy: The construction sector perspective. Clean. Respons. Consum. 8, 100107. https://doi.org/10.1016/j.clrc.2023.100107

Muranko, Z., Andrews, D., Newton, E.J., Chaer, I., Proudman, P., 2018. The Pro-Circular Change Model (P-CCM): Proposing a framework facilitating behavioural change towards a Circular Economy. Resour. Conserv. Recycl. 135, 132–140. https://doi.org/10.1016/j.resconrec.2017.12.017

Nascimento, D. L. M., Alencastro, V., Quelhas, O. L. G., Caiado, R. G. G., Garza-Reyes, J. A., Rocha-Lona, L., et al., 2019. Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal. J. Manuf. Technol. Manag., 30 (3), 607-627.

Nobre, G.C., Tavares, E., 2017. Scientific literature analysis on big data and internet of things applications on circular economy: a bibliometric study. Scientometrics 111, 463–492. https://doi.org/10.1007/s11192-017-2281-6

Okorie, O., Salonitis, K., Charnley, F., Moreno, M., Turner, C., & Tiwari, A., 2018. Digitisation and the circular economy: A review of current research and future trends. Energies, 11 (11), 3009.

O'Grady, T., Minunno, R., Chong. H., Morrison, G.M., 2021. Design for disassembly, deconstruction and resilience: A circular economy index for the built environment. Resour. Conserv. Recycl. 175, 105847. https://doi.org/10.1016/j.resconrec.2021.105847

Pizzi, S., Corbo, L., Caputo, A., 2021. Fintech and SMEs sustainable business models: Reflections and considerations for a circular economy. J. Clean. Prod. 281, 125217. https://doi.org/10.1016/j.jclepro.2020.125217

Pomponi, F., Moncaster, A., 2017. Circular economy for the built environment: A research framework. J. Clean. Prod. 143, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A. 2017. Circular Economy: Measuring Innovation in the Product Chain. PBL, Den Haag

RWS. (2022, September 22). Circulaire viaducten. The RWS website. Retrieved Sept. 22, 2022 from https://www.circulaireviaducten.nl/ (in Dutch)

Sadeghi, M., Mahmoudi, A., Deng, X., Luo, X., 2023. Prioritizing requirements for implementing blockchain technology in construction supply chain based on circular economy: Fuzzy Ordinal Priority Approach. Int. J. Environ. Sci. Technol. 20, 4991–5012https://doi.org/10.1007/s13762-022-04298-2

Sanchez, B., Rausch, C., Haas C., Saari, R., 2020. A selective disassembly multi-objective optimization approach for adaptive reuse of building components. Resour. Conserv. Recycl. 154, 104605.
Schuckmann, S.W., Gnatzy, T., Darkow, I.L., von der Gracht, H.A., 2012. Analysis of factors influencing the development of transport infrastructure until the year 2030 - A Delphi based scenario study. Technol. Forecast. Soc. Change 79, 1373–1387. https://doi.org/10.1016/j.techfore.2012.05.008
Sinclair, M., Sheldrick, L., Moreno, M., Dewberry, E., 2018. Consumer intervention mapping-A tool for designing future product strategies within circular product service systems. Sustain. 10 (6), 2088. https://doi.org/10.3390/su10062088
Su, B., Heshmati, A., Geng, Y., Yu, X., 2013. A review of the circular economy in China: Moving from rhetoric to implementation. J. Clean. Prod. 42, 215–227. https://doi.org/10.1016/j.jclepro.2012.11.020
Tsamboulas, D.A., Yiotis, G., Mikroudis, G., 2007. A method for multi-criteria analysis in transportation infrastructure investments. Int. J. Transp. Econ. 34, 113–131. https://doi.org/10.1016/j.tranpol.2006.06.001
Tu, J.C., Chan, H.C., Chen, C.H., 2020. Establishing circular model and management benefits of enterprise from the circular economy standpoint: A case study of Chyhjiun Jewelry in Taiwan. Sustain. 12 (10), 4146. https://doi.org/10.3390/su12104146
van Bueren, B.J.A., Argus, K., Iyer-Raniga, U., Leenders, M.A.A.M, 2023. The circular economy operating and stakeholder model “eco-5HM” to avoid circular fallacies that prevent sustainability. J. Clean. Prod. 391, 136096. https://doi.org/10.1016/j.jclepro.2023.136096
van Stijn, A., Malabi Eberhardt, L.C., Wouterszoon Jansen, B., Meijer, A., 2021. A Circular Economy Life Cycle Assessment (CE-LCA) model for building components. Resour. Conserv. Recycl. 174, 105683. https://doi.org/10.1016/j.resconrec.2021.105683
Veleva, V., Bodkin, G., 2018. Corporate-entrepreneur collaborations to advance a circular economy. J. Clean. Prod. 188, 20–37. https://doi.org/10.1016/j.jclepro.2018.03.196
Vera-Puerto, I., Valdes, H., Correa, C., Agredano, R., Vidal, G., Belmonte, M., et al., 2020. Proposal of competencies for engineering education to develop water infrastructure based on “Nature-Based Solutions” in the urban context. J. Clean. Prod. 265, 121717.
Virmani, N., Saxena, P., Raut, R.D., 2022. Examining the roadblocks of circular economy adoption in micro, small, and medium enterprises (MSME) through sustainable development goals. Bus. Strat. Env. 31, 2908–2930.
Winans, K., Kendall, A., Deng, H., 2017. The history and current applications of the circular economy concept. Renew. Sustain. Energy Rev. 68, 825–833. https://doi.org/10.1016/j.rser.2016.09.123
Winning, M., Calzadilla, A., Bleischwitz, R., Nechifor, V., 2017. Towards a circular economy: insights based on the development of the global ENGAGE-materials model and evidence for the iron and steel industry. Int. Econ. Econ. Policy 14, 383–407. https://doi.org/10.1007/s10368-017-0385-3
Wiprächtiger, M., Haupt, M., Froemelt, A., Klotz, M., Beretta, C., Osterwalder, D., et al., 2023. Combining industrial ecology tools to assess potential greenhouse gas reductions of a circular economy. J. Ind. Ecol. 27:254–271.
Wisse, E., 2016. Assessment of indicators for Circular Economy: The case for the Metropole

Region of Amsterdam. Master Thesis, Utrecht University, Utrecht, the Netherlands.

Witjes, S., Lozano, R., 2016. Towards a more Circular Economy: Proposing a framework linking sustainable public procurement and sustainable business models. Resour. Conserv. Recycl. 112, 37–44. https://doi.org/10.1016/j.resconrec.2016.04.015

Wuni, I.Y., Shen, G.Q., 2022. Developing critical success factors for integrating circular economy into modular construction projects in Hong Kong. Sustain. Prod. Consum. 29, 574–587. https://doi.org/10.1016/j.spc.2021.11.010

6. Conclusions

The overall aim of this thesis is to contribute to the implementation of CE in the transport infrastructure sector. In this chapter, the main findings of this research are provided in Section 6.1, including the exploratory findings (from Chapters 2 and 3) and practical findings (from Chapters 4 and 5). Section 6.2 deals with the scientific and practical contributions. The limitations and recommendations for future research are discussed in Section 6.3.

6.1 Main findings

In this section, we first present the exploratory results of the bibliometric analysis and in-depth review of relevant literature concerning assets, building/construction materials, CE, and sustainability in Section 6.1.1; then show the preliminary findings from a real world case study, JWRS in Section 6.1.2; in Section 6.1.3, we describe how we approach the problems found in the sector perspective and the directions to tackle those problems; finally in Section 6.1.4, the framework to help implement CE in transport infrastructure projects and the results of the application of the framework are given. Together, the CRQ of this thesis is answered.

6.1.1 Review of Literature about Achieving Sustainability via Circular Economy (CE) in Assets and Construction Materials Context and Broader Bibliometric Analysis

A bibliometric analysis and further literature review were conducted to answer the first SRQ: What research studies contribute to achieving sustainability in the construction sector through circular activities at the interface between assets in the built environment and construction (building) materials?

Understanding related literature is the first step in understanding the problem this study intends to solve. Bibliometric analysis and literature review are good ways, as these two levels of analysis offer different perspectives to look at literature. With the construction/building materials list and the assets list we presented, the literature review results show there are 33 different construction materials and 12 different specific assets mentioned. In terms of CE-related R strategies, “Reduce”, “Reuse” and “Recycle” are the three most prominent, which is the 3R can be commonly seen. Higher order strategies like “Remanufacture”, “Rethink”, “Refuse” are mostly neglected. This shows in terms of the R strategies, CE transitions generally tend to start from the lower level, e.g., with laboratory tests; it is proposed that higher level strategies need more attention, probably starting from mind change, which is not complex and can be simple. “Environmental(ly)” (mainly seen as environmental impact or environmental sustainability) is the most studied dimension of the three sustainability dimensions; in contrast, “Social” is less paid heed to currently. One reason for this is that compared with the other two, social impacts are more difficult to evaluate quantitatively. In terms of assets, buildings are studied more than infrastructures, underscoring the need for more attention on integrating sustainability and CE into infrastructures. Such an advocacy to infrastructure is not only a takeaway from Chapter 2, but also from the whole thesis. Chapter 2 lays an anchor for the following three chapters, which all center around infrastructure.

6.1.2 The Case Study of a New High-speed Railway Station in China

A case study of JWRS was conducted to answer the second SRQ: How do local professionals envision sustainability ideas in pursuit of addressing multiple sustainability transitions in a (transport) infrastructure construction project?

Initial interviews conducted with local practitioners in the case study area, Jingmen, informed us that in their view, CE is still too revolutionary to be implemented for transport infrastructures. This is in line with what we found in literature. Therefore, the focus of this piece of research was redirected to sustainability (at a more general level than CE) with semi-structured interviews as the main data gathering approach. The analysis reveals opportunities for improvement towards sustainability and the interdependence between the dimensions in the TBL framework for the railway station and its surrounding areas. The case shows that local professionals identify ample opportunities for improvement (presented as "sustainability ideas" in Fig. 3.5 and Fig. 3.6), but none belongs to environmental, economic and social sustainability simultaneously (two out of the three the most). It is suggested that for such projects in the future, all the three aspects of sustainability require to be considered, and ideas that can be linked to them simultaneously are encouraged.

6.1.3 The Sectoral Innovation Systems Approach to Compare Circular Economy (CE) in the Chinese and Dutch Construction Sectors

An online survey was conducted with different stakeholder roles of the construction sector in both China and the Netherlands as the main approach to answer the third SRQ: Taking an SIS perspective, what are the main barriers blocking the implementation of CE in the Chinese and Dutch infrastructure construction sectors and the possible directions to overcome these barriers?

A survey was conducted among 50 different stakeholders of the sector in China and the Netherlands. The main results of the study include: underdeveloped technologies (i.e., bio-materials, biological processes and digital technologies), lack of knowledge and interacting platforms, and under emphasis of CE by related laws and regulations are the main reasons for insufficient implementation of CE in the Chinese infrastructure construction sector; for the Dutch infrastructure construction sector, the main reasons are underdeveloped technologies, a lack of knowledge and the absence of a CE law. These areas are also future directions for China and the Netherlands to better implement CE in the construction sector. The underdevelopment of technologies, represented by bio-materials and biological processes, is in concert with the lack of application concerning biology from the iReSOLVE framework (Chapter 5) currently. Compared with the Netherlands, for the Chinese infrastructure construction sector, the transition tends to be triggered by the higher level governance from the government; while lower level innovative initiatives at the lower level (e.g., individual companies) tend to be more prosperous in the Dutch infrastructure construction sector. Both levels are necessary for the transition to CE. **Only with the whole sector as the contextualized condition, CE can then be well implemented at the project level.**

6.1.4 The Framework for Implementing Circular Economy (CE) in Transport Infrastructure Projects and its Application in Ten Viaduct Projects

A case study of ten viaduct projects was done along with answering the fourth SRQ: What is the approach to learn and inspire CE for transport infrastructure projects?

The final piece of the whole research which is concerning the project level landed in the Netherlands. After the review of existing well-developed CE "frameworks", based on the iRESOLVE framework, we proposed the 4Wh-iRESOLVE framework to learn and inspire CE for transport infrastructure projects. The framework has been used to ten different innovative pioneer viaduct projects as case studies. Although the ten different viaduct projects "performed" quite differently (as some may focus on a single material or design, some were more comprehensive in terms of CE), the case study shows the usefulness of the framework. It can potentially be a suggested guideline in future policy documents.

6.2 Discussion

The CRQ has been answered collectively in terms of the sector and the project, i.e., creating the SIS for CE and using an appropriate approach such as the 4Wh-iReSOLVE framework for CE implementation in transport infrastructure projects. In this section, we discuss the scientific and practical contributions of this research in Sections 6.2.1 and 6.2.2, respectively.

6.2.1 Scientific Contribution

In terms of scientific contribution, this research integrates micro-, meso-, and macro-scales with respect to CE for transport infrastructures, clarifiing the ambiguity of the three scales brought by different articles (e.g., (Pomponi and Moncaster, 2017), (Kirchherr et al., 2017), (Heshmati, 2015), (Su et al., 2013)).

This research first examines the interface between assets (meso-scale) and construction/building materials (micro-scale) for sustainability via CE. The lists of construction materials and assets can be used by other scholars. During the process of analysis and review, we have shown that although systematic bibliometric literature analyses stick to the literature data set objectively in most cases in earlier studies, the method can to some extent generate misleading results. With terms such as "Recover" and "Reduce", we proposed that a careful review considering the meaning of key terms is needed to grasp relevant literature, in addition to the larger-scale bibliometric analysis. Secondly, ways forward for better CE implementation have been proposed both at the sector level (macro-scale) and the project level (meso-scale). Chapter 4 innovatively adopted SIS to compare CE in the infrastructure construction sector of China and the Netherlands. Chapter 5 proposed the 4Wh-iRESOLVE framework after reviewing the relevant well-established CE frameworks from literature and comparing the two most important, BECE and CEIMA. The proposed framework also considers the environmental, economic and social impacts, which reflects the TBL.

6.2.2 Practical Contribution

As for practical relevance, this study provides knowledge for different stakeholders of the infrastructure construction sector to further CE's successful implementation by studying both the Netherlands and China. Different from earlier research, a list of primary and secondary stakeholder roles of the sector is also proposed for future use. Primary stakeholder roles include clients, designers, material suppliers, engineering/technical consultants, government officials, investors, and contractors; secondary stakeholder roles include financing parties, finance consultants, law consultants, the general public and community residents, academic researchers, and the media. In our case, with the stakeholder roles list, different sets of questions were assigned to the two general groups to help acquire data of good quality.

In Chapter 4, this dissertation presents further directions for both China and the Netherlands to implement CE in the infrastructure construction sector better, which can also act as a reference for other countries. In Chapter 5, the CE application framework can be used by different stakeholders of transport infrastructure projects to analyze and implement CE, as verified by several experts of the studied case projects. Compared with the ReSOLVE framework (shown for example in (Diacono and Baldacchino, 2023) and (Sadeghi et al., 2023)), the 4Wh-iReSOLVE framework is more suitable for implementation; while in contrast with the CEIMA framework (Coenen et al., 2020), our modified framework offers practitioners heuristics for implementation directions as well.

6.3 Limitations and Recommendations for Further Research

This dissertation provides several insights regarding the implementation of CE in transport infrastructure projects, but there are also some limitations. This section reflects on those limitations and offers recommendations for future research.

In Chapter 3, only one case in China was conducted due to the time limitation. Since Chapter 4 is about the comparison of China and the Netherlands, a counterpart case study in the Netherlands can be a better add-on.

In Chapter 4, only Jiangsu Province was chosen as the representative area of China, partly because China is much larger than the Netherlands. In the future, a broader coverage of China is suggested to gain a better understanding of the CE situation in the infrastructure construction sector in China. Besides, a larger coverage of different stakeholders in both countries with a large number of easier simple-click questions in the online survey would reflect China and the Netherlands better. We bring this argument forward because although it seems data from "only" 50 respondents were obtained in Chapter 4, actually since some open questions were asked, the amount of data used in the final analysis was still largely sufficient.

In Chapter 5, the framework was only applied to existing project documents and the project type is just viaduct. In the future, it can be applied to different (types of) projects during the planning phase, and the situation of such projects can be studied later to have better ideas about the application of the 4Wh-iRESOLVE framework.

Although the relationship between CE and SD has been discussed in Chapter 1, it is proposed recently that despite the recognized benefits of CE (e.g., enhanced environmental performance), the lack of consideration of potential rebound effects triggered by CE is delaying the achievement of CE's full potential; thus integrating the rebound effect concepts into the CE practice is suggested (Castro et al., 2022). Overall, in response to the sector CE challenges mentioned in Section 1.3, supply chain (Nasir et al., 2017; Chen et al., 2022; Wu et al., 2019) is the only one that has not been covered much by this thesis. Supply chain stays between the focal organization (company) and the sector, related to projects as well. Supply chain and the higher supply chain ecosystem (Massari et al., 2024; Jagani et al., 2024) provide another perspective compared with the project-sector one adopted in this thesis. Therefore, it is beneficial to include supply chain management and supply chain ecosystem in future research.

References for Chapter 6

Castro, C.G., Trevisan, A.F., Pigosso, D.C.A., Mascarenhas, J., 2022. The rebound effect of circular economy: Definitions, mechanisms and a research agenda. J. Clean. Prod. 345, 131136.

Chen, Q., Feng, H., de Soto, B.G., 2022. Revamping construction supply chain processes with circular economy strategies: A systematic literature review. J. Clean. Prod. 335, 130240.

Coenen, T.B.J., Haanstra, W., Jan Braaksma, A.J.J., Santos, J., 2020. CEIMA: A framework for identifying critical interfaces between the Circular Economy and stakeholders in the lifecycle of infrastructure assets. Resour. Conserv. Recycl. 155, 104552. https://doi.org/10.1016/j.resconrec.2019.104552

Diacono, S., Baldacchino, L., 2023. Identifying entrepreneurial opportunities in the circular economy. J. Manag. Organ. 30 (1),165-187. https://doi.org/10.1017/jmo.2023.47

Heshmati, A., 2015. A Review of the Circular Economy and its Implementation. IZA Discuss. Pap. No. 9611, 63. https://doi.org/10.1504/IJGE.2017.089856

Jagani, S., Marsillac, E., Hong, P., 2024. The Electric Vehicle Supply Chain Ecosystem: Changing Roles of Automotive Suppliers. Sustainability 16 (4), 1570.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resour Conserv Recycl 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Massari, G.F., Nacchiero, R., Giannoccaro, I., 2024. Circular supply chains as complex adaptive ecosystems: A simulation-based approach. J. Clean. Prod. 475, 143517.

Nasir, M.H.A., Genovese, A., Acquaye, A.A., Koh, S.C.L., Yamoah, F., 2017. Comparing linear and circular supply chains: A case study from the construction industry. Int. J. Production Economics. 183, 443-457.

Pomponi, F., Moncaster, A., 2017. Circular economy for the built environment: A research framework. J. Clean. Prod. 143, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Sadeghi, M., Mahmoudi, A., Deng, X., Luo, X., 2023. Prioritizing requirements for implementing blockchain technology in construction supply chain based on circular economy: Fuzzy Ordinal Priority Approach. Int. J. Environ. Sci. Technol. 20, 4991–5012https://doi.org/10.1007/s13762-022-04298-2

Su, B., Heshmati, A., Geng, Y., Yu, X., 2013. A review of the circular economy in China: Moving from rhetoric to implementation. J. Clean. Prod. 42, 215–227. https://doi.org/10.1016/j.jclepro.2012.11.020

Wu, H., Qian, Q.K., Straub, A., Visscher, H., 2019. Exploring transaction costs in the prefabricated housing supply chain in China. J. Clean. Prod. 226, 550-563.

Appendix

A. The 1st search query:

((TITLE-ABS ("construction material" OR "building material" OR "construction materials" OR "building materials") OR AUTHKEY ("construction material" OR "building material" OR "construction materials" OR "building materials")) AND (TITLE-ABS ("infrastructure" OR "building" OR "infrastructures" OR "buildings") OR AUTHKEY ("infrastructure" OR "building" OR "infrastructures" OR "buildings")) AND (TITLE-ABS ("circular economy" OR "circular construction" OR "refus*" OR "rethink" OR "redesign" OR "reduc*" OR "reus*" OR "repair" OR "refurbish" OR "remanufactur*" OR "repurpos*" OR "recycl*" OR "recover") OR AUTHKEY ("circular economy" OR "circular construction" OR "refus*" OR "rethink" OR "redesign" OR "reduc*" OR "reus*" OR "repair" OR "refurbish" OR "remanufactur*" OR "repurpos*" OR "recycl*" OR "recover")) AND (TITLE-ABS ("sustainability" OR "sustainable development" OR "environmental" OR " economic" OR "social") OR AUTHKEY ("sustainability" OR "sustainable development" OR "environmental" OR " economic" OR "social"))) AND DOCTYPE (ar OR re) AND PUBYEAR > 1987 AND PUBYEAR < 2025 AND LANGUAGE (English)

B. The four queries used for the review:

- Group 1: ((TITLE-ABS ("construction material" OR "building material" OR "construction materials" OR "building materials") OR AUTHKEY ("construction material" OR "building material" OR "construction materials" OR "building materials")) AND (TITLE-ABS ("infrastructure" OR "building" OR "infrastructures" OR "buildings")) AND (TITLE-ABS ("circular economy" OR "circular construction") OR AUTHKEY ("circular economy" OR "circular construction")) AND (TITLE-ABS ("sustainability" OR "sustainable development")) AND (TITLE-ABS ("flax" OR "aggregate" OR "aluminium" OR "asphalt" OR "bamboo" OR "basalt" OR "bitumen" OR "cardboard" OR "carpet" OR "cement" OR "ceramic" OR "clay" OR "coal" OR "concrete" OR "copper" OR "graphene" OR "glass" OR "granite" OR "gravel" OR "gypsum" OR "lumber" OR "metal" OR "mortar" OR "mud" OR "papercrete" OR "plaster" OR "plastic" OR "plywood" OR "polyethylene" OR "polystyrene" OR "polyvinyl chloride" OR "rock" OR "rubber" OR "sand" OR "sludge" OR "soil" OR "steel" OR "stone" OR "graphite" OR "timber" OR " polyurethane" OR "wood" OR "wool" OR "zinc")) AND (TITLE-ABS ("asset" OR "aqueduct " OR "bridge" OR "building" OR "dam" OR "embankment" OR "harbour" OR "harbor" OR "highway" OR "hospital" OR "house" OR "infrastructure" OR "motorway" OR "pavement" OR "port" OR "rail" OR "railway" OR "reservoir" OR "road" OR "tunnel"))) AND DOCTYPE (ar OR re) AND PUBYEAR > 1987 AND PUBYEAR < 2025 AND LANGUAGE (English)
- Group 2: ((TITLE-ABS ("construction material" OR "building material" OR "construction materials" OR "building materials") OR AUTHKEY ("construction material" OR "building material" OR "construction materials" OR "building materials")) AND (TITLE-ABS ("infrastructure" OR "building" OR "infrastructures" OR "buildings")) AND (TITLE-ABS ("circular economy" OR "circular construction")) AND

(TITLE-ABS ("environmental" OR "economic" OR "social") OR AUTHKEY ("environmental" OR " economic" OR "social")) AND (TITLE-ABS ("flax" OR "aggregate" OR "aluminium" OR "asphalt" OR "bamboo" OR "basalt" OR "bitumen" OR "cardboard" OR "carpet" OR "cement" OR "ceramic" OR "clay" OR "coal" OR "concrete" OR "copper" OR "graphene" OR "glass" OR "granite" OR "gravel" OR "gypsum" OR "lumber" OR "metal" OR "mortar" OR "mud" OR "papercrete" OR "plaster" OR "plastic" OR "plywood" OR "polyethylene" OR "polystyrene" OR "polyvinyl chloride" OR "rock" OR "rubber" OR "sand" OR "sludge" OR "soil" OR "steel" OR "stone" OR "graphite" OR "timber" OR "polyurethane" OR "wood" OR "wool" OR "zinc")) AND (TITLE-ABS ("asset" OR "aqueduct " OR "bridge" OR "building" OR "dam" OR "embankment" OR "harbour" OR "harbor" OR "highway" OR "hospital" OR "house" OR "infrastructure" OR "motorway" OR "pavement" OR "port" OR "rail" OR "railway" OR "reservoir" OR "road" OR "tunnel"))) AND DOCTYPE (ar OR re) AND PUBYEAR > 1987 AND PUBYEAR < 2025 AND LANGUAGE (English)

- Group 3: ((TITLE-ABS ("construction material" OR "building material" OR "construction materials" OR "building materials") OR AUTHKEY ("construction material" OR "building material" OR "construction materials" OR "building materials")) AND (TITLE-ABS ("infrastructure" OR "building" OR "infrastructures" OR "buildings")) AND (TITLE-ABS ("refus*" OR "rethink" OR "redesign" OR "reduc*" OR "reus*" OR "repair" OR "refurbish" OR "remanufactur*" OR "repurpos*" OR "recycl*" OR "recover")) AND (TITLE-ABS ("sustainability" OR "sustainable development") OR AUTHKEY ("sustainability" OR "sustainable development")) AND (TITLE-ABS ("flax" OR "aggregate" OR "aluminium" OR "asphalt" OR "bamboo" OR "basalt" OR "bitumen" OR "cardboard" OR "carpet" OR "cement" OR "ceramic" OR "clay" OR "coal" OR "concrete" OR "copper" OR "graphene" OR "glass" OR "granite" OR "gravel" OR "gypsum" OR "lumber" OR "metal" OR "mortar" OR "mud" OR "papercrete" OR "plaster" OR "plastic" OR "plywood" OR "polyethylene" OR "polystyrene" OR "polyvinyl chloride" OR "rock" OR "rubber" OR "sand" OR "sludge" OR "soil" OR "steel" OR "stone" OR "graphite" OR "timber" OR "polyurethane" OR "wood" OR "wool" OR "zinc")) AND (TITLE-ABS ("asset" OR "aqueduct " OR "bridge" OR "building" OR "dam" OR "embankment" OR "harbour" OR "harbor" OR "highway" OR "hospital" OR "house" OR "infrastructure" OR "motorway" OR "pavement" OR "port" OR "rail" OR "railway" OR "reservoir " OR "road" OR "tunnel"))) AND DOCTYPE (ar OR re) AND PUBYEAR > 1987 AND PUBYEAR < 2025 AND LANGUAGE (English)
- Group 4: ((TITLE-ABS ("construction material" OR "building material" OR "construction materials" OR "building materials") OR AUTHKEY ("construction material" OR "building material" OR "construction materials" OR "building materials")) AND (TITLE-ABS ("infrastructure" OR "building" OR "infrastructures" OR "buildings")) AND (TITLE-ABS ("refus*" OR "rethink" OR "redesign" OR "reduc*" OR "reus*" OR "repair" OR "refurbish" OR "remanufactur*" OR "repurpos*" OR "recycl*" OR "recover") OR) AND (TITLE-ABS ("environmental" OR "economic" OR "social") OR AUTHKEY ("environmental" OR "economic" OR "social")) AND (TITLE-ABS ("flax" OR "aggregate" OR "aluminium" OR "asphalt" OR "bamboo" OR "basalt" OR

"bitumen" OR "cardboard" OR "carpet" OR "cement" OR "ceramic" OR "clay" OR "coal" OR "concrete" OR "copper" OR "graphene" OR "glass" OR "granite" OR "gravel" OR "gypsum" OR "lumber" OR "metal" OR "mortar" OR "mud" OR "papercrete" OR "plaster" OR "plastic" OR "plywood" OR "polyethylene" OR "polystyrene" OR "polyvinyl chloride" OR "rock" OR "rubber" OR "sand" OR "sludge" OR "soil" OR "steel" OR "stone" OR "graphite" OR "timber" OR "polyurethane" OR "wood" OR "wool" OR "zinc")) AND (TITLE-ABS ("asset" OR "aqueduct" OR "bridge" OR "building" OR "dam" OR "embankment" OR "harbour" OR "harbor" OR "highway" OR "hospital" OR "house" OR "infrastructure" OR "motorway" OR "pavement" OR "port" OR "rail" OR "railway" OR "reservoir " OR "road" OR "tunnel"))) AND DOCTYPE (ar OR re) AND PUBYEAR > 1987 AND PUBYEAR < 2025 AND LANGUAGE (English)

C. The Survey Questions (enlightened by (Siva et al., 2017))*

SIS components	Question number
	Q1: Please type in your name and email.*
	Q2: Please select your role to the Dutch (Chinese) infrastructure construction sector.*
	Q3: If other stakeholder roles are missing in Q2, please indicate below.
Technological Regime	<u>Technology</u> **Q4:** According to you, what technologies are dominantly used to implement CE in the infrastructure construction sector (if you don't find applicable categories, you can mention examples of technologies in "Other")?* **Q5:** What is the economic feasibility of implementing each of these technology categories (as mentioned in Q4)?* **Q6**: What is the economic feasibility of implementing the technology or technologies you mentioned as examples in Q4? Please provide a score per example technology. **Q7:** Have these technology categories (in Q4) been implemented successfully? (please explain why or why not)*
	<u>Complementarities and interdependencies</u> **Q8:** Does the CE align with existing technologies in the Dutch (Chinese) infrastructure construction sector or is it overthrowing existing technologies? Please provide arguments.*

	Knowledge base **Q9:** What is your assessment of the existing pool of knowledge on CE in the Dutch (Chinese) infrastructure construction sector? Please provide arguments.*
	Learning **Q10:** How are relevant learning outcomes of CE implementation from Dutch (Chinese) infrastructure construction projects shared? Please give examples.
Market Demand	**Q11:** According to you, what criteria (expectations) do clients have for infrastructures? Please consider the performance and design of infrastructures in your answer (this question is not related to CE).* **Q12:** Do these criteria (expectations) match with implementing CE in the Dutch infrastructure constructions? Please explain why or why not.*
Agents, interaction and networks	Actors **Q13:** According to you, which of the following actors are involved in developing CE in the Dutch infrastructure construction sector?* **Q14:** Which actors are more influential than others? Please provide arguments.*
	Interactions and Networks **Q15:** Are there platforms where knowledge is shared and actors are interacting regarding CE in the Dutch (Chinese) infrastructure construction sector? (If the answer is "Yes", then Q16-Q19 will be asked) **(Q16:** Please specify the platform(s). (please use numbers per platform, and not more than 5)* **Q17**: Please rate how well each of these platforms (by the order of your numbers) support innovations and diffusion of CE in the Dutch infrastructure construction sector.* **Q18:** Please rate the level of your participation in these platforms (by the order of your numbers). **Q19**: How well are these platforms supported or facilitated by government or other actors? Please provide arguments. **Q20:** Do you facilitate or attend any networking sessions regarding CE in the Dutch (Chinese) infrastructure construction sector?* (If the answer is "Yes", then Q21 will be asked) **Q21**: Please specify which network session you attended or how you facilitated it.
Institutional Framework	Policy **Q22:** How effective are the following policy instruments to promote the transition to CE in the Dutch (Chinese) infrastructure construction sector?* **Q23**: Please provide your arguments for the scoring in the aforementioned question.*

	Q24: Which other policy instruments to promote CE in the infrastructure construction sector do you know? You may elaborate on your opinion of their effectiveness. **Q25:** Is there sufficient support from central and local government for CE implementation in the Dutch (Chinese) infrastructure construction sector?* **Q26**: Please explain your answer to the aforementioned question (on government support).* **Q27**: How effective are the following policy instruments to promote the transition to CE in the Dutch (Chinese) infrastructure construction sector? **Q28**: Please provide your arguments for the scoring in the aforementioned question. **Q29**: Which other policy instruments to promote CE in the Dutch infrastructure construction sector do you know? You may elaborate on your opinion of their effectiveness.
	Non-policy **Q30:** How do informal institutions* (of general public) influence the development of CE in the infrastructure construction sector? Please rate below.* **Q31:** Please explain your answer to the aforementioned question (on informal institutions). **Q32:** Please elaborate on how non-policy ways* are being used for promoting CE in the Dutch infrastructure construction sector.*
	Q33: Do you know other persons who might be relevant or interesting to invite for this survey? Contact information is appreciated.
	Q34: Are you willing to be interviewed on some follow-up questions later?*

* for brevity, some supporting information for some questions is excluded from this table; the numbers in Table A2 and Table A3 are used for indication of the content of questions, therefore they may be different from what is shown in the survey due to logical settings

D. Survey links

Survey link (in Chinese): https://forms.office.com/Pages/ResponsePage.aspx?id=DQSIkWdsW0yxEjajBLZtrQAAAAAAAAAAAANAAQEkeshUMkxTSTdQTjRZSVBVMzFNM1IzWEw1M003RC4u

Survey link (in English): https://forms.office.com/Pages/ResponsePage.aspx?id=TVJuCSlpMECM04q0LeClez366SX1-4VIgpzGBNxZ0jFUOFgwMzZIVzMyN0FTS1BMSFhHNDJKOUxRVC4u

Survey link (in Dutch): https://forms.office.com/Pages/ResponsePage.aspx?id=TVJuCSlpMECM04q0LeClez366SX1-4VIgpzGBNxZ0jFUQzFJMUFZMlY4UjlSREtaRDBaMkc1UjNBMC4u

E. Questions set to different stakeholder roles

Stakeholder roles*										**All respondents need to answer**	**General question**
	Q4-7, Q8	Q22-24	Q9	Q10	Q11-12	Q15 (including Q16-19; If the answer is "No" for Q15, then jump to Q20)	Q25-26	Q20 (including Q21; If the answer is "No" for Q20, then jump to Q22)	Q27-29, Q30-31, Q32	Q2-3; Q13-14,	Q1, Q33-34
Client		■	■	■	■	■	■	■		■	■
Investor		■					■		■	■	■
Designer	■	■	■	■	■	■	■	■		■	■
Contractor	■	■	■	■	■	■	■	■		■	■
Material supplier	■	■	■	■	■	■	■	■		■	■
Representative from financing party									■	■	■
General public and community resident									■	■	■
Government official		■			■	■	■	■		■	■
engineering/technical consultant	■	■	■	■	■	■	■	■		■	■
finance consultant									■	■	■
law consultant									■	■	■
Consultant on other fields									■	■	■
Academic researcher	■	■	■	■	■	■	■	■		■	■

Representative from media											
Project developer**											
Other											

* the stakeholder roles in bold are primary stakeholders; **Project developer is not included in the Chinese version

F. The List of Survey Respondents (CN: China; NL: the Netherlands)

No.	Role with code	No.	Role with code
CN1	Investor CN1	NL1	Infrastructure user NL1
CN2	Client CN1	NL2	Finance consultant NL1
CN3	Academic researcher CN1	NL3	Infrastructure user NL2
CN4	General public and community resident CN1	NL4	Government official NL1
CN5	Engineering/Technical consultant CN1	NL5	Representative from media NL1
CN6	Law consultant CN1	NL6	Client NL1
CN7	Academic researcher CN2	NL7	Client NL2
CN8	Material supplier CN1	NL8	Academic researcher NL1
CN9	Designer CN1	NL9	Law consultant NL1
CN10	Finance consultant CN1	NL10	Academic researcher NL2
CN11	Contractor CN1	NL11	Government official NL2
CN12	Contractor CN2	NL12	Engineering/Technical consultant NL1
CN13	Infrastructure user CN1	NL13	General public and community resident NL1
CN14	Government official CN1	NL14	Representative from financing party NL1
CN15	Representative from media CN1	NL15	Engineering/Technical consultant NL2
CN16	General public and community resident CN2	NL16	General public and community resident NL2
CN17	Representative from financing party CN1	NL17	Other: CE and sustainable investments consultant NL1
CN18	Designer CN2	NL18	Designer NL1
CN19	Other: green building consultant CN1	NL19	Investor NL1
CN20	Investor CN2	NL20	Project developer* NL1
CN21	Material supplier CN2	NL21	Other: Ambassador of an association of a Circular region NL2
CN22	Client CN2	NL22	Contractor NL1
CN23	Government official CN2	NL23	Contractor NL2
		NL24	Material supplier NL1
		NL25	Material supplier NL2
		NL26	Designer NL2
		NL27	Contractor NL3

G. Pro(s)/Con(s)[59] and criteria that the 17 CE "frameworks" met

Reference	Framework name	Pro(s)	Con(s)	Criteria met
Iacovidou et al. (2017)	CVORR framework	Multi-actor	Confined to the assessment of resources recovered from waste	②③④
Witjes and Lozano (2016)	ProBiz4CE framework	A collaborative framework between SPP (sustainable public procurement) and SBM (sustainable business model)	The framework is based on CE only by closing loops through recovery	②③④
Mendoza et al. (2017)	BECE framework	Generic and applicable across different products and business sectors; flexible; integrating top-down (business model) and bottom-up (product-service design) considerations; helping companies to develop sustainable business models that translate CE principles into industrial practice; bridging the gap between the strategic and operational levels	Complex	①②③④
(Ang et al., 2021)	PM9R framework	A systematic framework to guide the implementation of the CE concept	Confined to the pharmaceutical manufacturing (PM) industry	①②
(Çetin et al., 2021)	CDB framework	Provides a fruitful starting point for the novel research avenue at the intersection of CE, digital technology and the built environment, and gives practitioners inspiration for	Confined to digital technologies	②④

[59] In respect to the focus of this chapter

		sustainable innovation in the sector		
(Coenen et al., 2020)	CEIMA framework	Connects infrastructure stakeholders to concrete applications of CE through identification of possible interfaces; based on the "9R" waste hierarchy, actions are formulated that provide a practical guide to more circular infrastructure	CE actions are limited	①②③④
Winning et al. (2017)	global ENGAGE-materials model	Can address both upstream and downstream impacts of resource efficiency and the CE policy implications	At a macro-economic and sectoral level	③
(Muranko et al., 2018)	P-CCM framework	Supporting Pro-Circular behaviors	Confined to technical goods	①
(van Stijn et al., 2021)	CE-LCA model	Supports an ex-ante assessment of circular building components in a theoretical context	Time-consuming to use	②③④
(Sinclair et al., 2018)	Consumer Intervention Mapping tool	Can create scenarios that describe existing product service systems and new product concepts adapted to a CE paradigm	Confined to Product Service Systems	①③④
(Álvarez and Ruiz-Puente, 2017)	SymbioSyS tool	Helps promote the efficient use of resources and new business models through the detection of the main synergies among companies based on the substitution of raw materials from waste, sub-products, or recycled materials, and the possibility of new opportunities for collaboration in the sharing of infrastructure and services	Mainly lies in industrial ecology (IE)	①③④
(Lauten-Weiss	CBF tool	An extensive guide for structuring business	Confined to business case	②③④

and Ramesohl, 2021)		models (BMs)		
(Ferronato, 2021)	NAVA-CE approach	Supporting solid waste management development projects	Confined to low to middle-income countries	③
(van Bueren et al., 2023)	“eco Quintuple Helix Model” (eco-5HM)	can better inform decision-makers for CE operations and tactics to achieve the strategic goal of sustainability	Would not guide to a more limited scope of tactics and operations	②③
(D’Urzo and Campagnaro, 2023)	Design-led Repair & Reuse (DLRR) framework	generates a higher quality of processes and products from circular, low entropy and low capital-intensity production activities	Confines in the reuse market	①②③
(Wiprächtiger et al., 2023)	IE4CE approach	combines Industrial ecology (IE) methodologies to determine the environmental impact mitigation potential of CE strategies for a defined geographic region	the design of the scenarios is associated with many uncertainties	③
(Diacono and Baldacchino, 2023); (Sadeghi et al., 2023)[60]	ReSOLVE framework	e.g., a useful framework to advance knowledge on circular entrepreneurship	e.g., Opportunities evaluation and exploitation were not explored	①②③④

[60] These two papers both just used the established ReSOLVE framework so the pro(s) and con(s) here are examples.

H. The “4Wh-iReSOLVE” analytical framework for urban transport infrastructure projects*

4wh	**Specification:**		**Environmental impact (total)**	**Economic impact (total)**	**Social impact (total)**
Who: Stakeholders	1 Public agency 2 Contractor 3 … … N …		…	…	…
When: Life cycle stages	☐ (D/P) Design/preparation ☐ (C) Construction ☐ (O/M) Use and Maintenance ☐ (D/D) Decommissioning and demolition		…	…	…
Where: Summary of specific locations and attributes	i. Roof ii. Off-site factory iii. … … N …		…	…	…
What: **iReSOLVE Actions**	**iReSOLVE requirement activities**	*Example specification (who, when, where) **	**Environmental impact (per action)**	**Economic impact (per action)**	**Social impact (per action)**
Regenerate	Shift to renewable energy and materials	*use of bioplastics (2, C, ii)*	Long or Short term	N/A	N/A
	Reclaim, retain, restore health of ecosystems	*promote restoration of grasslands (2,D/D,…)*	N/A	Long or Short term	N/A
	Return recovered biological resources to biosphere	*N/A*	…	…	…
Share	Share assets	*share appliances (2,C,…)*	…	…	…
	Reuse, second-hand use	*biofuels derived from used cooking oil (2,C,…)*	…	…	…
	Prolong product life (durable, design, maintenance, repair)	*easy to clean filters (…,…,…)*	…	…	…

Optimise	Increase product performance and efficiency	*use engines with improved fuel efficiency (2,C,…)*	…	…	…
	Remove waste in production and supply chain		…	…	…
	Leverage big data, automation, remote sensing, steering		…	…	…
Loop	Remanufacture products or components	*label repairable/recyclable/elements (…,…,…)*	…	…	…
	Recycle materials	*increase recycled content and recyclability (…,…,…)*	…	…	…
	Digest anaerobically	*N/A*	…	…	…
	Extract biochemical from organic waste	*N/A*	…	…	…
Virtualize	Dematerialize directly	*remove the wiring system cordless (…,…,…)*	…	…	…
	Dematerialize indirectly	*online shopping (…,…,…)*	…	…	…
Exchange	Replace old with advanced non-renewable materials**		…	…	…
	Apply new technologies	*3D printing (2,C,…)*	…	…	…
	Choose new products/services	*use graphene (…,…,…)*	…	…	…
Implement	An ambitious vision/target	*consumption of energy, water and materials minimized (2,C,…)*	…	…	…
	A scaled-up business plan with a roadmap		…	…	…
	Stakeholder engagement	*government authorities (…,…,…)*	…	…	…
	Systems thinking	*value chain, cross-cycle, cross-sector*	…	…	…

		(…;…;…)			
	Specific step-by-step guidelines and supporting tools				

*according to Mendoza et al. (2017); the phrases in parentheses and italics are examples of the corresponding "iReSOLVE requirements"

** We doubt that the "non-renewable" here in the original table should be "renewable"

I. The overall list of CE activities of Projects 1 to 10

No.	(D/P) (C)
1.1	harvest all materials from the viaducts to be demolished in the A76 (p4)
1.2	The baffle plates and girders, including railings from the Holeweg viaduct, are also reused (p21)
1.4	the foundation consists of recycled steel tubular piles (p4)
	(D/P)
1.6	Strategic sessions with administrators for further scaling up and further development of the CTL concept (p11)
1.8	The connections are designed in such a way that any future disassembly is possible (p26)
1.12	Interviewing managers within and outside Rijkswaterstaat to gain insight into demolition plans of existing structures (p11)
1.13	Develop and determine the content of the "reusability scan" together with (knowledge) partners and stakeholders (p11)
1.14	Testing and further development of the design concepts with knowledge partners and knowledge institutions (TNO and TU Delft) (p12)
1.15	Testing the feasibility of the parts to be harvested together with Lek Sloopwerken (p12)
1.16	Prior to the application of the 'reusability scan', the content of the tool was determined together with the (knowledge) partners (p14)
	(O/M)
1.7	regular maintenance of the parts to be reused is substantiated (p26)
	(D/P) (O/M)
1.9	production of circular concrete and asphalt (p28)
	(D/D)
1.3	72.5% of the existing viaduct components can be reused in a high-quality manner (p5)
1.5	removal of the asphalt for high-quality recycling (p24)
	(D/P) (C) (O/M) (D/D)
1.10	Knowledge sharing within and outside our consortium (p6)
1.11	knowledge sessions and dialogues with administrators and market parties (p9)
1.17	bring supply and demand together and guarantee that the concept is suitable for every organization and customer (p29)
No.	(D/P) (C)
2.1	use the beams released at the Kromwijkdreef (p10)
	(C)
2.2	Reuse of physically unaltered inverted T-beams (p17)

	(D/P)
2.5	We are introducing our platform www.liggerbank.nl to better match market-wide supply and demand (p2)
2.6	to better coordinate market-wide questions and answers and are continuing with the database to detect reusable beams from the area of viaducts to be demolished (p16)
	(D/P) (D/D)
2.7	We are leading the way in establishing a non-exclusive, public marketplace to connect supply & demand (p3)
	(D/P) (C) (O/M) (D/D)
2.3	make our acquired knowledge, insights and experiences available to the market free of charge (p3)
2.4	A large storage capacity is also secured via Dura Vermeer Urban Miner. The consortium works in the same project environment, so that all information is available to everyone. (p5)
No.	(D/P) (C)
3.1	The concrete arch construction ensures efficient power transfer and makes impact plates unnecessary (p3)
3.2	no joint transitions and bearing blocks are required (p3)
3.3	maintenance-sensitive parts such as joint transitions, bearing blocks and kick plates are not required (p20)
3.5	a green connection makes a positive contribution to defragmentation of natural areas and increasing biodiversity (p15)
3.6	All elements can be disassembled and have standardized dimensions and connections. This makes the system reusable and interchangeable on element level (p3)
3.7	a fully recoverable, modular arch construction and substructure (p2)
3.8	detachable connections of the arch construction and the recoverable, demountable substructure (p3)
3.9	The soil backfill to the superstructure results in completely releasable connections to the road surfacing, rainwater drainage and sheathing pipes for cables and pipes. This provides a high degree of flexibility and adaptability, but also offers advantages in terms of management and maintenance (p25)
	(D/P) (C) (O/M) (D/D)
3.4	The parties involved complement each other to form a complete and integral team with all the necessary expertise in the field of technology, sustainability and entrepreneurship. We work shoulder to shoulder from one consortium to one common goal: a maximum reduction in the use of primary raw materials for viaducts (p3)
3.10	we use the knowledge and skills of all team members and the underlying organizations (p7)
3.11	we evaluated our cooperation every month and adjusted it where necessary (p7)
3.12	We make the right to use our innovation available to everyone (p31)
3.13	all parties have access to the circular construction system and the entire sector can contribute to scaling up (p31)
No.	(D/P) (C)
4.1	Substantial material reduction by applying UHSVB in the ultimate bend-free shape (p5)
4.2	the arch shape from UHSVB saves volume and the geopolymer concrete saves cement and new aggregates (p18)

4.3	the design with UHSVB has been optimized so that less material is needed during construction (p19)
4.5	pressure lines are pushed closer together, the bending is reduced and therefore also the use of materials (p21)
4.6	The Circular Arch Viaduct is an integral bridge in which the construction is mechanical as much as possible coupled with foundation piles. This is material efficient and allows easy disassembly (p23)
	(D/P)
4.4	integral bridges have no supporting devices, expansion joints that require a lot of maintenance and where problems often arise that have a negative impact on the overall lifespan of the construction (p5)
4.7	the Circular Arch Viaduct lends itself perfectly as an ecoduct to allow fauna to pass through (highway) roads (p17)
4.13	a concrete mixture based on a 100% secondary granular skeleton in combination with a binder free of Portland cement (= 100% circular geopolymer concrete) (p24)
4.14	a geopolymer concrete with 100% secondary skeleton (recycled sand and granulate) (p24)
4.15	A processable geopolymer concrete with 100% recycled material for application in the abutment (p25)
4.21	With an international contractor, international engineering firm, prefab concrete producer and specialist knowledge of UHSVB and geopolymer concrete in our consortium, we are able to scale up innovation in the Netherlands and beyond (p6)
4.22	The length of the arch beams can be varied to make the dimensions suitable for each project. The arch beams will be in a number of standard sizes come onto the market, so that they are also interchangeable between different projects (p29)
	(D/P) (D/D)
4.8	reusable foundation piles (p5)
	(D/D)
4.9	Abutments of circular and cementless geopolymer concrete where granulate from old viaducts as 100% recycled building materials are reused (p5)
4.10	The UHSVB (Ultra High Strength Fiber Reinforced Concrete) elements can be reused during their longer lifespan (p19)
4.11	The UHSVB elements and steel tubular piles are reused during a life cycle (p19)
4.12	A modular, demountable and reusable viaduct of UHSVB elements (p5)
4.16	regularly screw out the tubular piles for reuse (p26)
	(D/P) (C) (D/D)
4.17	a connection has been developed that makes the pile foundation detachable from the abutments, in order to recover the tubular piles after the lifespan of the Circular Arc Viaduct (p11)
	(D/P) (C) (O/M) (D/D)
4.18	The results are published online under the public open-source license CC-BY-SA of Creative Commons (p27)
4.19	To ensure fitability for future projects, we hold an (online) seminar for project teams of clients to take into account the adaptability of the Circular Arch Viaduct (p27)
4.20	For the further dissemination of the ideas in the Rijkswaterstaat organization, we use the network of the SBIR Call for Circular Viaducts Project Team to organize lectures and inform project teams (p27)

No.	(D/P) (C)
5.1	Application of wood (p2)
5.2	All secondary elements such as the edge elements, guide rails and parts of the substructure are made of circular building materials such as European wood (p8)
5.3	Slim steel deck sections; with which we achieve a large weight reduction (p2)
5.4	The deck sections have a closed cell structure, creating a relatively lightweight solution (p8)
5.5	using a steel bridge deck and hollow foundation elements (p12)
5.9	The Variaduct consists of light, remountable building elements that are easily reusable (p8)
	(D/P)
5.6	Foundation without piles; the light construction makes it possible to omit pile foundations in 9 out of 10 cases (p2)
5.7	Due to a large reduction in its own weight (73%) (compared to the reference viaduct), a pile foundation is not necessary (p3)
5.8	Reduction of the construction height; thus limiting material (p2)
5.12	a circular, modular and remountable design for the substructure (p4)
5.13	We can extend the Variaduct or replace parts while preserving the existing construction and foundation. As a result, the Variaduct will not have to be demolished in the future before the end of the technical life, which is often the case now (p8)
5.14	all interfaces and connections have been designed according to IFD (Industrial, Flexible and Demountable Building) (p16)
5.15	The elements are mutually connectable with a bolt connection. This connection is durable and easy to disassemble (p18)
5.16	An angled abutment with joint construction is, of course, removable and applicable everywhere (p19)
	(D/P) (D/D)
5.11	the Variaduct can be disassembled and then reassembled
	(D/P) (C) (O/M) (D/D)
5.10	In addition to settlement behaviour, we monitor the traffic intensity with a traffic counter. We process this information in the materials passport and use it, among other things, to increase the reusability of the building elements (p15)
5.18	The open source approach of the Variaduct ensures that many parties can use it (p4)
	(C) (O/M) (D/D)
5.17	the use of electrical equipment, clean fuel and the use of NOX filters (p3)
No.	(C)
6.1	a pressure-optimized construction that makes very efficient use of the material (p17)
	(D/P) (C)
6.2	Additive manufacturing (AM): material is only placed where it is needed and cutting losses and auxiliary structures such as formwork are prevented (p3)
6.3	AM does not require mold material (p24)
6.11	Applying improved and new low-CO_2 (concrete) mixtures (p3)
6.12	efficient light spatial structure of 3D-printed concrete (p2)
6.17	Digital supply chain: design, production and realization take place in a digital supply chain (p3)
	(D/P)

6.4	Parametric and Optimized Designs: This leads to scalable designs and a strong reduction of material use (up to 60%) (p3)
6.5	The arch construction is composed of blocks with a light hollow structure (p4)
6.22	The concept is ideal for combining with other circular partial solutions (p7)
	(O/M)
6.16	Broken or damaged parts can be replaced quickly and cheaply (p12)
	(D/P) (D/D)
6.6	the raw materials used are 100% reusable in a second phase of life and beyond (p12)
6.10	Waste-free production process (no moulds) (p12)
6.14	Modular and detachable design: the printed blocks are joined together using prestressing techniques (p3)
6.15	composing the viaduct from modular elements (approx. 80%) (p7)
6.7	The 'manual for reuse' contains everything for the next generations: the specifications, the different ways in which the object can be dismantled and how the building blocks can be reused according to the current insights and standards (p24)
	(D/P) (C) (O/M) (D/D)
6.8	The knowledge that is shared through user groups concerns the specifications, requirements and design aspects that the building blocks must meet in order to guarantee a safe construction and to encourage reuse (p29)
6.9	The Format 'Manual for reuse' is freely available (p29)
6.13	A service market instead of a producing market (p24)
6.18	constant focus on our shared ambition and attention to each other's interests (p11)
6.19	The fascination for the opportunities of 'digital concrete' for circular construction is an important shared motivation (p11)
6.20	Through dedication to the subject and the partners' complementary business models, the collaboration runs very smoothly. This underlines the intrinsic motivation of the parties. They are all authorities on their own expertise and knowledge is shared as much as possible (p26)
6.21	Knowledge is shared reciprocally in user groups (p28)
No.	(D/P) (C)
7.1	a completely wooden superstructure on a conventional substructure (p15)
7.7	all non-replaceable load-bearing parts are protected, standing water on the bridge is prevented, the side is protected against rain impact, the elements are ventilated and inspectable (p17)
7.8	The deck and a waterproof membrane protect the main beams and prevent rain from falling onto the beams from above (p18)
7.9	ventilation around the main girders and the ventilation between deck and main girder formed by the transverse beams. If water does come through the deck, there is no direct surface contact with the main beams (p18)
	(D/P) (C) (O/M)
7.10	The detachability of the cover elements serves to change the elements in unexpected situations and to protect the main carrying system (p17)
	(D/P) (C) (D/D)
7.11	The simplicity of the construction and the releasable connections make the assembly and disassembly method easy (p21)

	(D/P) (D/D)
7.2	replaceable decking elements for reuse (p16)
7.3	The first priority in reuse is to use the beams as beams in a subsequent viaduct (p24)
7.4	Another use is as a beam with lesser load, such as a bicycle/pedestrian bridge (p24)
7.5	Re-use outside the original use is sawing the girders into trusses or purlins in roof constructions for large spans (p24)
7.6	the wood can be used as sawn planks and beams or as input for derived wood products (p24)
	(D/P) (C) (O/M) (D/D)
7.12	Mutual reviews resulted in an exchange of knowledge and information (p4)
No.	(D/P) (C)
8.4	The cover plates are made of UBB. By the application of this high-strength concrete and the industrially standardized fabrication, a concrete surface is created of very high quality that is extremely durable. The concrete is resistant to freezing and de-icing salts and no sealing (such as hydrophobizing agent and/or asphalt) needs to be applied (p14)
	(D/P)
8.1	we generate our own renewable energy (wind and solar energy), with which we operate our prefab factories supplied with green energy (p10)
8.2	We have developed the environmentally friendly high-strength geopolymer concrete Umweltbeton Bögl (UBB) (named GPB 2.0 in the project proposal) for our cover plates (p6)
8.3	Mageba has developed modular bearing blocks made of corrosion-free steel (p8)
8.5	The steel beams are manufactured in standard sizes of 39.90 m, 31.92 m, 26.60 m and 21.28 m. All these dimensions are a multiple of 2.66 m which is the standard width of our cover plate. As a result, there are no fitting plates required and each cover plate is interchangeable (p13)
8.15	abutments of building blocks made of UBB, or recycled concrete (p8)
8.17	We have further elaborated our vision on the application of the All-in consortium (p9)
8.18	All parts of the MVB are modular and circular (p3)
8.19	By means of a steel sleeper between the longitudinal beams we have a detachable connection with the abutment created (p8)
8.20	We have developed a modular joint transition in collaboration with Mageba. This joint transition is bolted to the abutment side and to the cover plate side and can be dismantled without cutting and breaking (p8)
	(D/P) (D/D)
8.16	After the service life of 200 years, the beams can be melted down into new steel products (p13)
	(D/P) (C) (D/D)
8.7	The pillar and base are linked together, creating a single element that can be disassembled and reused (p8)
8.8	At the bottom, the pillars are attached to the base, whereby the base and the pillars form one modular element. This element can be disassembled and reused as a whole. This makes the pillars removable and reusable (p13)
8.10	The building blocks can be easily disassembled and subsequently reused (p12)
8.11	The concrete L-walls and building blocks are produced in standard sizes, are demountable and reusable (p13)
8.12	The cover plates are fitted perpendicular to the direction of travel on the support strips of the steel

	girders and post-tensioned to form a compact deck. As a result, the deck and the seams between the deck plates are watertight and no sealing and asphalt need to be applied. This makes the cover plates removable and reusable (p14)
8.14	The distribution of the load on the bearing blocks on one support point can be checked and adjusted so that tolerances are eliminated. The modular bearing blocks are removable and reusable (p15)
	(D/P) (C) (O/M)
8.13	The joint transition only uses removable, reusable components and materials, is maintenance-free (p14)
	(D/P) (C) (O/M) (D/D)
8.6	all MVB components are modular and circular with a reduced CO_2 emissions and minimal material consumption (p3)
8.21	The data collected by us is made available as open source (p9)
8.22	we grant the right to use our innovation free in the Netherlands (p9)
8.9	All MVB components are removable and reusable; The building blocks can be easily disassembled and subsequently reused (p10)
No.	(D/P) (C)
9.1	The prefab beam has a width of 1.6 meters and consists of ¼ part of recycled concrete and ¾ part of European spruce. The wood is protected against weather influences by the concrete (p3)
9.5	Instead of cement, we (re)use industrial by-products as a binding agent (p6)
9.6	Our beam design is suitable for reusing existing abutments and foundations, provided the function of the viaduct to be replaced remains the same. Due to the weight reduction of the deck construction, it is plausible that existing abutments and foundations are sufficient (p7)
9.12	With a thoughtful design of the concrete cover layer and edge element, the wood is protected from moisture and other weather influences (p7)
9.13	We protect the ends of the wood at the abutments with a solid concrete headboard (p11)
9.14	To protect the wooden beam on the outside of the viaduct against weather influences, it has been chamfered in the shape of a staircase and placed under the edge element. This means that no direct rainwater can reach the edge girders (p11)
9.15	the wooden beams are completely shielded on the top, longitudinal and end sides due to the concrete deck design (p13)
9.18	We finish the concrete surface with a waterproof layer, for example a (prefab) bituminous membrane (p11)
	(D/P)
9.2	a new tree is planted for every tree felled for forest conservation (p7)
9.9	Recycled concrete made with secondary raw materials such as recycled sand, gravel and/or concrete granulate (p7)
9.10	The concrete is made of recycled concrete or geopolymer concrete (p10)
9.16	Our design has a detachable center support (p7)
9.17	We provide the beams with a waterproof coating and hardening (p10)
	(D/P) (D/D)
9.3	The circular value of the products and materials used at the end of their technical life offers opportunities for high-quality reuse, also outside civil engineering (p6)

9.4	After the viaduct's functional lifespan (average 43.6 years), the girders can be reused in a new viaduct to be built (p6)
9.7	Our wood-concrete design has a modular structure on 4 levels. With this we achieve high-quality reuse after the first use phase (p9)
9.8	Steel tubular piles can be recovered for reuse (p11)
	(O/M)
9.11	Using new techniques, the sensors generate data and send it via the Internet of Things to intelligent systems (p13)
	(C) (O/M)
9.19	By spacing the wooden beams there is enough space to inspect the individual beams (p13)
No.	(D/P)
10.1	Replacing the glass fibers with flax fibers (p7)
	(D/P) (D/D)
10.2	The advantage of a geotextile is that it can be completely removed and reused at another location. Most textiles are already made from (partly) recycled material (p5)
	(D/P) (C) (O/M) (D/D)
10.3	By sharing our acquired knowledge open source (via a website), we share our acquired knowledge free of charge for other parties to include this innovation in their products catalogue. This increases awareness among clients and administrators (p4)
10.4	constructive interaction between RWS, knowledge institutions and the experts (p5)
	(D/P) (C)
10.5	light weight biobased composite (p1)

iReSOLVE requirement activities based on different lifecycle phases of Project 1-10 (with page number information according to the original reports of Project 1-10) [note: Design/preparation: (D/P), construction: (C), use and maintenance: (O/M), decommissioning and demolition: (D/D)]

J. CE activities of Project 1-10 based on iReSOLVE action categories (the numbers are in correspondence with those in Appendix I; the numbers in italics mean the corresponding CE statements belong to more than one sub-category)

R: Regenerate	R1 Shift to renewable energy and materials (e.g. Use of bioplastics)	5.1, 5.2, 7.1, 8.1, 9.1,
	R2 Reclaim, retain, restore health of ecosystems (e.g. Promote restoration of grasslands))	3.5, 4.7, 9.2,
	R3 Return recovered biological resources to biosphere	
S: Share	S1 Share assets (e.g. Share appliances))	
	S2 Reuse, second-hand use (e..g. Biofuels derived from used cooking oil))	1.2, *1.3*, 2.1, 2.2, 3.6, 4.22, 4.8, 4.9, 4.10, 4.11, 4.12, 4.16, 5.9, 5.10, 6.6, 6.7, 6.8, 6.9, 7.2, 7.3, 7.4, 7.5, 7.6, 8.7, 8.8, 8.9, 8.10, 8.11, *8.12*, 8.13, 8.14, 9.5, 9.6, 9.3, 9.4, 9.7, 9.8, 10.2,
	S3 Prolong product life (durable design, maintenance, repair) (e.g. Easy-to-clean filters)	*1.3*, 1.7, 1.8, 3.7, 3.8, 3.9, 4.17, 5.12, 5.13, 5.14, 5.15, 5.16, 5.11, 6.16, 6.14, 6.15, 7.7, 7.8, 7.9, 7.10, 7.11, *8.4*, *8.12*, 8.18, 8.19, 8.20, 9.12, 9.13, 9.14, 9.15, 9.18, 9.16, 9.17, 9.19,
O: Optimize	O1 Increase product performance and efficiency (e.g. Use engines with improved thermal, fuel efficiency)	6.1, 8.2, 8.3,
	O2 Remove waste in production and supply chain	6.10,
	O3 Leverage big data, automation, remote sensing, steering	6.17,

L: Loop	L1 Remanufacture products or components (e.g. Label reparable/upgradable elements)	
	L2 Recycle materials	1.1, 1.4, 1.5, 4.13, 4.14, 4.15, 8.15, 8.16, 9.9, 9.10, 10.2,
	L3 Digest anaerobically	
	L4 Extract biochemical from organic waste	
V: Virtualize	V1 Dematerialize directly (e.g. Remove the wiring system (cordless))	3.1, 3.2, 3.3, 4.1, 4.2, 4.3, 4.5, 4.6, 4.4, 5.3, 5.4, 5.5, 5.6, 5.7, 5.8, 6.2, 6.3, 6.12, 6.4, 6.5, *8.4*, 8.5
	V2 Dematerialize indirectly (e.g. online shopping)	
E: Exchange	E1 Replace old with advanced renewable materials	10.1,
	E2 Apply new technologies (e.g. 3D printing)	6.11, 9.11,
	E3 Choose new products/services (e.g. multimodal transport)	1.9,
I: Implement	I1 An ambitious vision/target (e.g. The consumption of energy, water and raw materials minimized as much as possible)	3.4, 8.6,
	I2 A scaled-up business plan with a roadmap	1.6, *4.21*, 6.13, 8.17,
	I3 Stakeholder engagement	*1.10, 1.11, 1.12*, 1.13, 1.14, *1.15*, 1.16, *1.17*, 2.3, 2.4, 3.10, 3.11, 3.12, 3.13, *4.21*, 4.18, 4.19, 4.20, 5.18, 5.17, 6.18, 6.19, 6.20, 6.21, 7.12, 8.21, 8.22, (*10.3*), (10.4), 10.5
	I4 Systems thinking (value chain, cross-cycle, cross-sector)	*1.10, 1.11, 1.12, 1.15, 1.17*, *2.5*, 2.6, 2.7, 6.22,

		(*10.3*)
	I5 Specific step-by-step guidelines and supporting tools	*2.5*,

About the Author

I was born in Dalian, a coastal city in northern China, a city I am proud of being born and raised in. The Russo-Japanese War (1904-1905) happened here. My grandfather (爷爷, resting in peace) was brought from Tianjin via the sea route many years ago. My grandfather (姥爷， resting in peace), or his family, as I was told, came from Shandong Province. "People should not forget their origins ("本" in Chinese, which can also cover meanings like "history", "base")", that is cultivated in me.

I enjoyed learning English during my teenager period and chose "Environmental Science" as the future major in high school, although at university I studied Ecology at School of Environment, Liaoning University. During Master, Environmental Science became my major at Beijing Normal University and my Master thesis was about (urban) sustainability.

For PhD, it took quite some time to find the research direction, as I did not work on a particular project, which gave sort of freedom but a little confusion about where to go back then as well. Marcel offered me some Master graduation theses to read, Daan and I discussed about like environmental impact assessment…but finally and sort of suddenly, we decided to choose Circular Economy (CE) in transport infrastructures. It is a good fit, I would say, considering research interests we have and what CME people do. Then my real PhD journey got started, which is not typical. I first wrote a paper about CE frameworks (it is the base for Chapter 5), then thanks to Martin, I was involved in the Jingmen project, to have the chance to get the data I need to publish the 1st article during PhD (Chapter 3). Next the idea about Chapter 2 was forged, but as the process is complex, the work about it lasted alongside the work of Chapter 4, which is also attributed mainly to Daan, about introducing me the SIS concept and the viaduct cases.

From Sept. 2020 to Dec. 2022, I served as a researcher for IDM. It is a precious period, thanks mainly go to Prof. Bakker.

In Oct. 2022, I luckily received the Research Associate position offer from Loughborough University and joined Loughborough Business School in Apr. 2023 ("from" Faculty of Civil Engineering and Geosciences of TUD) to work on Circular Supply Chain. For this transition, I am grateful to Prof. Godsell. The school/faculty I work in keep jumping, but sustainability (and CE) is always my academic interest.

List of Publications

1. **Liu, X.Y.**, Schraven, D., Ma, W.T., de Jong, M. and Hertogh, M. (2024) "Achieving a framework of the circular economy in urban transport infrastructure projects: a meso-scale perspective" ***Frontiers in Sustainability*** 5, https://doi.org/10.3389/frsus.2024.1475155
2. **Liu, X.Y.**, Schraven, D., de Bruijne, M., de Jong, M. and Hertogh, M. (2019) "Navigating Transitions for Sustainable Infrastructures – The Case of a New High-Speed Railway Station in Jingmen, China" ***Sustainability*** 11 (15), 4197. https://doi.org/10.3390/su11154197
3. **Liu, X.Y.**, Liu, G.Y., Yang, Z.F., Chen, B. and Ulgiati, S. (2016) "Comparing National Environmental and Economic Performances through Emergy Sustainability Indicators: Moving Environmental Ethics beyond Anthropocentrism toward Ecocentrism" ***Renewable & Sustainable Energy Reviews*** 58, 1532-1542. https://doi.org/10.1016/j.rser.2015.12.188
4. Liu, G.Y., Yang, Z.F., Chen, B., Zhang, J.R., **Liu, X.Y.**, Zhang, Y., Su, M.R. and Ulgiati, S. (2014) "Scenarios for Sewage Sludge Reduction and Reuse in Clinker Production towards Regional Eco-industrial Development: A Comparative Emergy-based Assessment" ***Journal of Cleaner Production*** 103, 371-383. https://doi.org/10.1016/j.jclepro.2014.09.003
5. **Liu, X.Y.**, Schraven, D., Hoppe, T., Wu, J., Hertogh, M. and de Jong, M. (2024) "Introducing Circular Economy in the infrastructure construction sector: Comparing sectoral innovation systems in China and the Netherlands" ***Sustainable Futures*** (under the 2^{nd} round review)
6. **Liu, X.Y.**, Schraven, D., Di Maio, F., de Jong, M. and Hertogh, M. (2025) "Tracing circular strategies in the construction literature: an analysis of their use for sustainability goals and on different materials and assets" ***Clearner Environmental Systems*** (under the 2^{nd} round review)
7. Wang C., Liu, G.Y., Ren S.H., **Liu, X.Y.** and Hao, Y. (2016) "Provincial Sustainability Evaluation Based on the Standardized National Emergy Database" ***Energy Procedia*** 88, 153-159. https://doi.org/10.1016/j.egypro.2016.06.040
8. Liu, G.Y., **Liu, X.Y.**, Yang, Z.F., Chen, B., Su, M.R. and Zhang, Y. (2014) "A Predictive Analysis of China's Energy Security Based on Supply Chain Theory" ***Energy Procedia*** 61, 184-189. https://doi.org/10.1016/j.egypro.2014.11.1054
9. Zhang, J.R., Liu, G.Y., Chen, B., Song, D., Qi, J. and **Liu, X.Y.** (2014) "Analysis of CO_2 Emission for the Cement Manufacturing with Alternative Raw Materials: A LCA-based Framework" ***Energy Procedia*** 61, 2541-2545. https://doi.org/10.1016/j.egypro.2014.12.041

Acknowledgement

Finally, it is the time for me to write this part of my thesis after the PhD "torture" (a joke word once said by Daan) during these years.

First and foremost, I thank my supervision team, Prof. Hertogh, Prof. de Jong and A.Prof. Schraven. Marcel, I still keep the bread box of the first Christmas, on which you wrote "Thanks for joining our group!"; actually, thank you for letting me join IDM. If I knew IDM and you earlier, I would definitely apply to join IDM. You truly are a gentleman, a nice person. Martin, I remember you replied me in the evening email saying "See you tomorrow."; thanks for introducing Marcel and Daan to me. As mentioned, thanks for involving me in the Jingmen project. Besides, thanks for all the humor, the revisions for the papers during weekend/evening, the shared articles you wrote. Daan, you are like an academic role model and a friend to me, always energetic and responsive. I even feel you take too much work. I can't forget the first time we met, the happiness you had when you spoke "twins" to me. It is quite strange that I missed reading your first email. Thanks for not "kicking me out" because of the silly mistake I made. I appreciate all the communications and discussions, without you my thesis cannot be finished.

Secondly, I'd like to express my gratitude to Prof. Hans Bakker again, it is a pleasure to work for you. Besides, I also thank IDM, CEG, TUD (and beyond) colleagues: A.Prof. Marian Bosch-Rekveldt, Sandra, Ingrid, Yue, Maryam, Martine, Jaap, Maria, Johan, Leon, Sander, Erik-Jan, Maedeh, Erfan, Prof. Henk Jonkers, Prof. Arjan van Timmeren, Prof. Paul Chan, Dr. YANG Wei, Meiling, Wenting, etc. I either luckily worked with you or received your help. Special thanks to A.Prof. Qian for being a committee member for me.

I am grateful to the co-authors: Dr. Mark de Bruijne, Dr. Francesco Di Maio and Prof. Thomas Hoppe. Mark, it is enjoyable working with you, fluid and swift; Francesco, thank you for the support you offered for Chapter 2; Thomas, I really appreciate your professional comments for Chapter 4, your expertise is very helpful.

I thank China Scholarship Council (CSC) for supporting me in doing PhD at TUD. I am also grateful for the inputs provided from the interviewees for Chapter 2; to Wietse de Jong and Yuri Wolf (RWS), Richard Busse (Antea Group), Arno Van Wittmarschen and Huibert De Brabander (Max Bögl Nederland B.V.), Gert-Jan van Eck and Rob Vergoossen (HaskoningDHV Nederland B.V.), as well as Stephanie Lamerichs (Witteveen+Bos) for their kind help for Chapter 5; to Dr. Yang Yang (Oxford Brookes University) as an editor, to Prof. Giacomo Di Foggia (University of Milano-Bicocca) and Dr. BAO Zhikang (Heriot-Watt University) (disclosed after publication) as well for the comments; to Mr. LIU Yonggang and Ms. LI Yueshu, etc. for offering help or doing the survey for Chapter 4.

Specially, I am willing to thank the colleagues in the UK. I am fortunate to be able to work on the CicularMetal project as a Research Associate. The work I am doing at Loughborough not only broadens my eyeview, but also provides me the timely essential salary for living. Special gratefulness to Prof. Jan Godsell. It is great pleasure to work with you, Jan. I also thank Dr. Kamran Chatha and Dr. Alessio Franconi (Royal College of Art) for bringing me onboard and the help from the start of the journey. Other colleagues at Loughborough (and beyond) I'd thank include Dr. Usman Ghani, Yufei, Dr. Grammatoula Papaioannou, Prof. Nick Hajli, Prof. Crispin Coombs, Dr. Lennie Foster, Emma, Shelly, A.Prof. Fabrizio Ceschin (Brunel University

London), Prof. David Harrison (Brunel University London), Chris (Brunel University London), Tamba (Brunel University London), Dr. Ahmet Onur Agca (Aston University), Dr. Andrew Law (Newcastle University), Amy Beierholm (University of Birmingham) and so on. I enjoy working at Loughborough and the academic communication opportunities (perhaps because I am at a different stage compared with in the Netherlands). The UK Metals Expo (2023) in Birmingham, International Workshop on Circular Economy and Sustainability in Prato (2023, 2024, joined together with Daan), the NICER Early Career Researcher Summer School (2023) in Exeter, the InterAct Conference (2023) in London, the CENTS Research Showcase and Celebration Event (2023) in London, the Ideas to Innovation course (2024) in Cranfield, the ECR Net Zero Conference (2024) in Birmingham, the 11th EurOMA Sustainable Operations and Supply Chains Forum (2024) in Hamburg, the NICER Programme Circular Economy Showcase (2024) in London and the InterAct Global research mission (2024) to Kuala Lumpa are all wonderful memories for me. I also want to thank C-DICE, for the precious diverse opportunities, such as the Research Proposal Development Grant (GBP 3000), which is of great help.

Many thanks to my friends, A.Prof. PANG Mingyue, as well as WANG Pengye, etc.

A big THANK YOU to my respected senior relatives: Prof. Yin, Prof. Wang, Mrs. YIN Hua, Mrs. YIN Min; also to my brothers and sisters: Mr. YIN Xinjie, Mrs. YU Hongli, Mrs. JIAO Tiantian, and TaoTao.

I am proud to be the grandson of my grandfather, respected Mr. YIN (resting in peace; a former Platoon Leader of the 120th Division of the 40th Army, PLA). You are a hero to me, fighting against the so-called “UN Forces” in Korea. I learnt endurance and perseverance from you. Apology to my grandma, Mrs. LV (resting in peace) that 2017 was the last year I had the chance meeting you. I was raised and cared for by you both for a long period during my childhood. In Chinese culture, we have a saying “knowing what happened on earth at heaven”, I believe you are seeing me. Sorry to my grandmother, Mrs. ZHAO, I have been absent for quite long. Hope you have health, happiness, and longevity.

Many many thanks to my partner, WU, Jiarong, for being the companion and the best friend in life. My gratitude also goes to my parents-in-law for their understanding.

Finally, but definitely not the least, 谢谢、感谢 (THANKS) to my father Mr. Liu and mother Mrs. Yin. I owe you too much since I came to the world. It is impossible to express even the 1% of the unconditional love, support, faith, trust, care…you had, you are, and you will continuously exert to me. If I have made a little bit sort of achievement, it is all because of you. This thesis, basically, is for you, my beloved parents.

刘心宇 Xinyu,

At Room 170, Loughborough Business School, Loughborough University, UK

2025.02.07 (18:33) (edited on 2025.04.22)

FROM CIRCULAR TO SUSTAINABLE

The Implementation of Circular Economy in Transport Infrastructure Projects in China and the Netherlands

LIU Xinyu

Implementing Circular Economy (CE) principles is often considered as a key contributor to greater sustainability in the construction sector. As a major kind of infrastructure, there is an urgent need for transport infrastructures to be circular and sustainable. This dissertation answers how to implement CE in transport infrastructure projects, with the aim to achieve sustainability by 1) exploring the material-asset relationship connecting the ability of circular strategies to realize sustainability through a bibliometric analysis and literature review; 2) investigating the real case in a CE-representative city, Jingmen in China; 3) using the Sectoral Innovation Systems (SIS) approach to assess CE in the infrastructure construction sector in both China and the Netherlands to discern how key functions of SIS are related to challenges to CE introduction on the one hand, and solution directions on the other; and 4) proposing an analytical/implementation framework containing specific-related aspects of CE in urban transport infrastructure projects based on current literature.

Faculty of Civil Engineering and Geosciences
Department of Materials, Mechanics, Management & Design (3MD)

TU Delft