Resources, Conservation & Recycling 155 (2020) 104552

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

CEIMA: A framework for identifying critical interfaces between the Circular Economy and stakeholders in the lifecycle of infrastructure assets

Tom B.J. Coenen[a], Willem Haanstra[b], A.J.J. Jan Braaksma[b,*], João Santos[a]

[a] Department of Construction Management and Engineering. University of Twente. Enschede, the Netherlands
[b] Department of Design, Production and Management. University of Twente. Enschede, the Netherlands

ARTICLE INFO

Keywords:
Sustainable infrastructure
Circular Economy
Design science
Stakeholder management
Bridges
Distribution transformers

ABSTRACT

As the infrastructure sector lays claim to large amounts of natural resources and is responsible for a considerable amount of waste, to reduce resource usage and waste, organisations in this sector are considering the implementation of circularity. Despite an abundance of circular methods, principles and strategies provided in literature, the implementation of these approaches into everyday practice is often considered challenging. One of the main problems with implementing circularity is that professionals are not always aware of the full spectrum of circular approaches. Likewise, many CE experts lack the intricate knowledge that is accumulated through managing assets throughout their lifecycle.

Following a Design Science Research-based approach, the Circular Economy Interface Matrix Analysis framework (CEIMA) is developed in which a bottom-up asset stakeholder perspective is linked to the existing top-down conceptualizations of circularity using an intermediate categorization. This framework connects infrastructure stakeholders to concrete applications of the Circular Economy by means of identification of possible interfaces. Based on the "9R" waste hierarchy, actions are formulated that provide a practical guide to more circular infrastructure.

In this paper, the CEIMA framework is applied to two case studies involving bridges and distribution transformers respectively. The case studies demonstrated that the framework helps to bridge the knowledge gap between the conceptualizations of circularity and their application in the infrastructure domain. The identified interfaces between stakeholders and circular actions reveal key opportunities for stakeholders within the infrastructure sector to start with the implementation of circular actions. Finally, the framework offers a starting point for a broad discussion on the implementation of circularity. Both the resulting insights and the discussions are valuable for focussing stakeholder efforts in the transition towards a circular economy.

1. Introduction

The Circular Economy (CE) is an approach that combines sustainable and environmental development with economic growth and has recently gained prominence on political agendas in Europe and East Asia. However, it is often difficult for organizations to evaluate how their assets can be made more circular. In the recent past, several extensive studies have been conducted on the definitions and conceptual implications of a CE, such as Kirchherr et al. (2017) and Korhonen et al. (2018). However, every domain or field has its own characteristics which offer particular opportunities for circularity, for example, regarding production processes, product lifecycles and markets. Furthermore, the lack of research regarding circularity in the field of infrastructure assets is remarkable, given the large waste flows in this sector. Therefore, infrastructure organizations require more practical guidance to effectively start the transition toward circular practices.

Scholars stress the need for a transition at a system level in order to arrive at the core of the CE concept, i.e. a wasteless economy (Geissdoerfer et al., 2017; Kalmykova et al., 2018). However, such a transition requires countless small steps, including many incremental innovations (Geels, 2002). Moreover, roughly half of the innovations originate bottom-up (Saari et al., 2015). As long as bottom-up innovations regarding circularity are not stimulated, much potential is lost in the transition to circular practices. Furthermore, a mere top-down approach is often criticised for its inability to encompass the perspectives and values of all stakeholders involved. This may result in a lack of support which in turn leads to inadequate implementation (Cairns, 2003).

* Corresponding author at: University of Twente, Faculty of Engineering Technology, Horst – Ring, P.O. Box 217, De Horst 2, 7422LW Enschede, the Netherlands.
E-mail address: a.j.j.braaksma@utwente.nl (A.J.J. Jan Braaksma).

https://doi.org/10.1016/j.resconrec.2019.104552
Received 15 November 2018; Received in revised form 18 October 2019; Accepted 19 October 2019
Available online 29 January 2020
0921-3449/

For the purpose of making the concept of CE more explicit and applicable, several efforts have been presented aimed at implementing more circular designs. These include design rules, processes, frameworks and roadmaps (Bovea and Pérez-Belis, 2018; Moreno et al., 2016). In general, each of these initiatives approaches the implementation of circularity from a top-down perspective (i.e. from the CE concept to a practical asset), while most infrastructure-asset related stakeholders have knowledge about their specific assets rather than CE.

The broad and extensive definitions generate difficulties regarding implementation of CE principles in practice, even when made more concrete by means of the abovementioned rules and guidelines. Professionals without a background in CE often struggle with the implementation of circularity due to the high level of abstraction and ambiguity of the concept (Kirchherr et al., 2018). Existing literature is focussed on operationalizing this concept instead of looking at where opportunities for circular actions exist in infrastructure practices. Despite the importance of this additional bottom-up approach to a successful transition, this perspective on circularity implementation is missing, both in scientific literature and in practice and guidance is required to get professionals started with circular practices. To fill this gap, we propose the design of a bottom-up framework for stimulating the first steps in the transition towards a CE within an infrastructure organization.

To consider circularity measure from a bottom-up perspective, a link between circular actions and practices within an organization needs to be established. For instance, Eisenbart, Gericke and Blessing (2011) developed a framework for comparing design modelling approaches across disciplines. They categorized aspects according to the principles used in the disciplines examined. Subsequently, generic design states were distinguished from the discipline-specific ones and examples from mechanical engineering, electrical engineering, software design and building construction design were used to illustrate the applicability of the framework.

Kalmykova et al. (2018) developed a list of strategies and categories, and divided these according to three perspectives: (1) scope of CE strategy; (2) value chain; and (3) implementation level. These categories were used to list circularity principles and strategies found in literature. However, this classification aims at covering all possible CE implementation strategies, including all domains and all levels of abstraction rather than coupling them to practice. Furthermore, Fregonara et al. (2017) proposed a methodology for selecting the preferable solutions among technological options in the buildings construction sector, considering both economic and environmental aspects, in terms of global performance of construction. Given the asset-oriented perspective of this study, these approaches are not suitable to our framework.

In addition, various methods have been presented in literature to conceive a group perspective from individual preferences. Among those methods, the widely established Analytic Hierarchy Process (AHP) has been object of particular attention to address, amongst other things, design decisions (e.g. Abdi and Labib, 2003) or prioritizations (e.g. Korkmaz et al., 2008). However, the use of this particular method within the proposed framework is not suitable due to three main reasons. (1) It requires users' prior CE expertise to express their preferences, which is assumed to be lacking in our case; (2) the number of pairwise comparisons becomes very extensive, which hampers framework usability; and (3) the AHP is intended to find preferences within hierarchies, whereas our framework aims to find similarities between domains.

We aim to bridge the gap within literature by proposing a systematic approach to identify CE actions for stakeholders involved with all types of infrastructure-related organizations by means of matching. Although we acknowledge the need for a system-wide transition rather than individual innovations to render the system fully circular, the necessity for quick and concrete operationalizations of the concept is evident to get professionals started. This is done by designing a framework to establish interfaces between CE and the selected domain through systematic classification.

In this paper, a structured bottom-up approach materialized through the Circular Economy Interface Matrix Analysis framework (CEIMA) is developed by considering a reverse perspective on circularity. The framework is developed by means of the Design Science Research (DSR) approach as will be discussed in section 3 of this paper. According to Van Aken et al. (2016, p.8), "DSR is a domain-independent research strategy focussed on developing knowledge on generic actions, processes and systems to address field problems or to exploit promising opportunities. It aims at improvements based on a thorough understanding of these problems or opportunities." Given the ambiguity that still exists in the CE concept and the framework development, DSR is considered the most promising methodology to address the research gap. This contributes both to conceptualization of the CE and by offering a hands-on framework to identify circular strategies for stakeholders.

The framework is initially intended to be applied in the infrastructure domain, and is demonstrated by means of two cases on bridges and distribution transformers respectively. This framework offers a helping hand to project managers, organizational decision makers and policymakers in selecting and prioritizing CE actions concerning relevant stakeholders within and outside their organizations. Furthermore, it may aid other researchers in operationalizing the concept of CE and in prioritizing circularity measures in relation to infrastructure practices.

The rest of paper has the following outline. A theoretical background on CE is provided in section 2. In section 3 the design science methodology is explained. Section 4 contains the design objectives, as well as the design principles of the framework. Following this, in section 5, the conceptual framework is presented. In section 6, an application of the conceptual framework to the cases of both bridge and distribution transformer stakeholders is presented. Finally, in sections 7 and 8, respectively, the results are discussed and conclusions, limitations and suggestions for future research are provided.

2. The Circular Economy

The concept of a CE as we know it today was firmly established in 2011 by the Ellen MacArthur Foundation (EMF). However, the general idea emerged from the seminal work of Boulding (1966) who stressed that the earth must be considered as a closed system. On this subject, Millar et al. (2019) stated that the earth has a "[…] limited assimilative capacity and as such the economy and environment must coexist in equilibrium". Since then, the underlying idea of a closed-loop economy has been shaped by different schools of thought and initiatives, such as cradle-to-cradle (C2C), regenerative design, sharing economy, green economy, performance economy, sustainable development, product-service systems and eco-efficiency (Braungart and McDonough, 2002; Haas et al., 2015; Jacobs, 1992; Tukker, 2015; World Commission on Environment and Development, 1987).

Despite being founded on the principles of these earlier initiatives, the CE has its own principles. However, given the myriad of agents – either professionals, politicians or academics – who attempt to conceptualize CE, a universal and cross-sector definition does not yet exist (Lahti et al., 2018). Nevertheless, to a certain extent, they all have several aspects in common, in the sense that they all consider the material output from products and processes to be input for new products and processes (Kirchherr et al., 2017). Another core principle found in nearly all conceptualizations is efficient use of resources in order to prevent waste (eco-efficiency). Nevertheless, the extent to which these aspects are emphasized varies significantly, ranging from mere recycling to an economic and ecological revolution.

The lack of consensus concerning the conceptualization of CE extends to the way it is measured. The relevance of this subject was recognized by the EU, which, in its action plan for CE, stated that "[to] assess progress towards a more circular economy and the effectiveness of action at EU and national level, it is important to have a set of

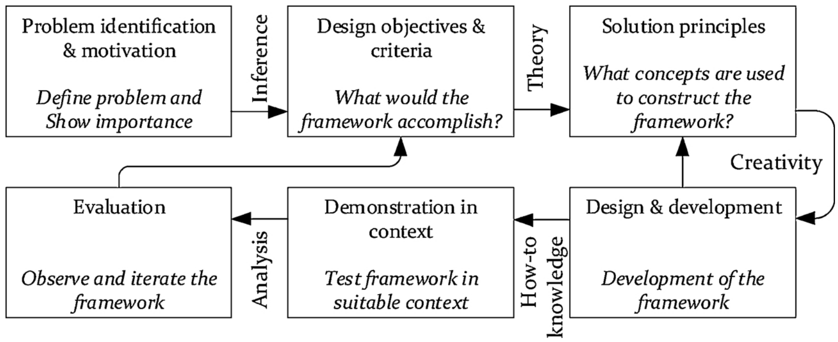

Fig. 1. Design science research methodology (adapted from Peffers et al., 2007).

reliable indicators" (European Commission, 2015). Responding to this call for action, various scientific attempts have been made at multiple levels and tailored to a variety of sectors. For instance, Saidani et al. (2019) conducted a systematic literature review of circularity-indicators developed by scholars, consulting companies and governmental agencies, which resulted in a taxonomy. To assess the degree of CE implementation in the construction sector, Nuñez-Cacho et al. (2018) proposed a set of indicators that have been validated by industrial and academic experts. Moreover, Niero and Kalbar (2019) aimed to link material circularity-based indicators to lifecycle-based indicators at the product level. Some of these indicators are more product-oriented and some are more lifecycle-oriented. Furthermore, some are better applied at the macro (e.g. region, nation, sector), while others aim at meso levels (e.g. industrial parks, multi-asset projects) or even at the product or asset level (Linder et al., 2017). The importance of measurements for circularity on all those scales and levels was, amongst others, acknowledged by Núñez-cacho et al. (2018) and Fregonara et al. (2017). However, a clear definition of the concept is necessary before assessment can be applied.

Considering the literature, and in particular the studies by Korhonen et al. (2018) and Kirchherr et al. (2017), for this paper the CE definition presented by Geissdoerfer et al. (2017, p.766) is adopted. For methodological reasons, the strategies are composed according to the waste hierarchy, which consists of a collection of "9Rs" that should lead to waste reduction. The approach to a CE that will be used in this study is hence formulated as follows: *The Circular Economy is a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design and management considering the "9Rs".*

The "9R" waste hierarchy mentioned above, captured by the "Rs" principle, is considered to be essential for a comprehensive definition (Korhonen et al., 2018). This concept is based on the 1979 *Lansink's Ladder*, the first version of a waste hierarchy, which makes a distinction between reuse, recycling and landfill, among other aspects (Lansink, 2017). This was extended and refined by the Netherlands Environmental Assessment Agency (PBL) into the "9R" waste hierarchy (Potting et al., 2017). The "9R" waste hierarchy primarily consist of three principles: (1) smarter use of materials; (2) lifespan extension; and (3) useful end-of-life (EoL). These principles and accompanying "Rs" are used to operationalize circularity at a later point in this study. These are presented, discussed and transformed into concrete circularity actions in section 4.2.

3. Methodology

Sections 1 and 2 provide a basis for developing the framework that fits the goal of this study. The methodology used to address this challenge is the Design Science Research (DSR). DSR "refers to an explicitly organized, rational, and wholly systematic approach to design; not just the utilization of scientific knowledge of artefacts, but design in some sense as a scientific activity itself" (Cross, 2001, p.3). Below, the DSR application is outlined in more detail, followed by an elaboration on the manner in which DSR is tailored for the purposes of this study.

3.1. Design Science Research

DSR follows an iterative process to develop a suitable artefact that can be used to solve a specific type of practical problem or challenge. The intended outcome of the DSR consists of both a practically applicable end-product and the creation of scientific knowledge. Hevner (2007) stressed the duality of DSR outcomes by emphasizing that the design cycle should seek not only relevance in the application domain but also rigor in the creation of theoretical knowledge. Thus, good design science involves more than the practical utility of the design. Wieringa (2014) acknowledged this duality by separating the interactions of a designed artefact into its social context on the one hand and its knowledge context on the other. Despite the apparent separation between practicality and knowledge creation, Wieringa (2014) explained that design science needs to be grounded in both general applicability and realism. As a result, both theoretical and empirical knowledge are developed concurrently during the design process.

3.2. Approach to framework development

The design cycle starts with the problem investigation and results in real-world implementation (Peffers et al., 2007; Wieringa, 2014). This design process involves multiple design iterations in order to reach the satisfactory design. However, DSR is not a specific method with fixed rules (van Aken et al., 2016). Peffers et al. (2007) proposed a model for producing and presenting DSR, which we have applied and tailored to our research. It consists of six iterative design stages, which are illustrated in Fig. 1.

The steps *solution principles* and *design & development* are often ill-defined, can, secondly, be difficult to coherently apply and, thirdly, depend on the creativity of the design researcher. "A design, therefore, cannot logically be deduced from the problem it is to solve, nor from extant theory or from problem solution specification" (Van Aken et al., 2016, p.2). Moreover, testing the application in the real-world is an essential step (Wieringa, 2014). We provided two case studies to test the framework, which resulted into two iterations of the design cycle. The development of actions using the "9Rs" in the *solutions principles* (section 4.2) and the eventual use of CE actions in the framework presented in the case study applications (section 6) can also be considered design iterations.

4. Design objectives and criteria, and solution principles

The particular goals and objectives of the comparative framework and the characteristics to which it should comply are discussed below. Furthermore, the performance criteria are outlined to allow the framework to be validated. Lastly, the solution principles to the framework design are discussed. This follows the design cycle presented in

Fig. 1 and provides a basis for the design and development of the framework.

4.1. Framework objectives and performance criteria

To arrive at a design that complies with the goals stated in the introduction, the comparative framework should encompass four main qualities. Firstly, it should offer clear-cut guidelines for activities which contribute to circularity. Secondly, it should refer to specific stakeholders in the field. Thirdly, it should illustrate clear links between circular activities and stakeholders. Lastly, the framework should be suitable for use as an independent tool that can be used by individuals who are not experts in the field of CE.

To verify the suitability of the framework, several performance criteria have been formulated. These criteria are: (1) representative stakeholders are included with respect to infrastructure asset; (2) the framework addresses both comprehensive and action-oriented circularity principles; (3) the identified interfaces are deemed to be worth considering according to the stakeholders; and (4) the framework can be used by a non-expert professional. These criteria have a qualitative nature and are validated by means of two case studies and accompanying expert interviews.

4.2. Solution principles

In this section, the CE principles according to which the framework will be designed are presented. Due to the comprehensiveness of the definitions presented in the section on CE (section 2), we consider them to be too abstract for the specific context of this study, since they include concepts that are difficult to operationalize from a bottom-up perspective. Because there are various principles underlying the definition of a CE, it can be considered as an *umbrella concept* (Blomsma and Brennan, 2017). In order to arrive at interfaces which are practically implementable, the overall concept needs to be parsed into specific chunks to allow for systematic analysis of the interfaces between CE and the infrastructure domain.

Although we acknowledge the need for a system-wide transition rather than individual innovations to render the system fully circular, we stress the need for a fast and concrete operationalization that enables professionals to get acquainted with the concept. In order to achieve this, practical approaches towards circularity are derived from the "9R" waste hierarchy by means of decomposition. The "9Rs" are still too abstract to offer a concrete plan of action for professionals. Below, these rather abstract "9R" strategies are translated into concrete actions towards circular practices. The aim of this list is not to be exhaustive, but to provide suggestions for the most important areas of action. Fig. 2 shows the linking of actions to the "9R" hierarchy and includes notes and references accompanying the particular actions.

In addition to the CE principles, the principles on the outline of the framework are defined. The frameworks and methods discussed in the introduction (section 1) display some essential differences in relation to the objectives of our study. For the development of the framework, we adopt the idea of Eisenbart et al. (2011) of using intermediate categorization to form a basis for comparison. In intermediate categorization, the various entities within different domains are characterized using a fixed set of categories. However, this study seeks to identify overlap between infrastructure stakeholders and CE, while reasoning from the perspective of the practical reality of the stakeholders. As such, our approach is different from the one taken by Eisenbart et al. (2011) in their study. A fixed categorization, largely based on Kalmykova et al. (2018), is used to identify overlap between two domains. Both domains are evaluated using similar assessment categories.

5. The conceptual framework - CEIMA

The framework principles discussed in section 4.3 consist of two matrices from which interfaces can be extracted into a third matrix based on intermediate categorization. The top-down matrix, which focusses on the existing waste hierarchy, is a model which was constructed and completed by CE experts. The bottom-up matrix was constructed and completed by professionals. The comparison between the matrices does not rely on users' CE expertise and may therefore be done by the users of the framework (i.e. non-expert professionals). Automation tools such as spreadsheets can aid in making these activities less laborious. Fig. 3 illustrates the processes by contrasting the academic CE knowledge with the knowledge input from infrastructure professionals. Here, we differentiate between the preparation phase and application phase of the framework. The framework as presented in Fig. 3, including the fixed categories and CE aspects are prepared before application. The case studies are executed within the application phase, which mainly includes development of the bottom-up matrix and generation of the results. This distinction allows professionals to focus exclusively on the application phase, which can be done in a relatively short period of time. As such, the design meets the first three performance criteria as defined in section 4.1.

The level of correspondence between the CE actions and stakeholders in the two tables can be established mathematically as shown in formula 1. As such, the interfaces can be found by the number category matches ($\sum_{a=1}^{M} X_{a,n}$) that are equal for a specific column i^{CE} and i^{St} of both graphs divided by the amount of columns M. In the example below, as illustrated in Fig. 4, the match between *St4* and *CE4* ($I_{4,4}$) would be the following: for category 1 and 3, both columns show an "x" and for category 4, both columns are empty. Regarding category 2 and 5, both columns differ and are, as such, zero. As a result, $I_{4,4} = \frac{(3 \times 1 + 2 \times 0)}{5} = 0.6$. Following the framework, the procedure described above is adopted during its application to the case studies presented in section 6.

$$I_{m,n} = \frac{\sum_{a=1}^{M} X_{a,n}}{M}, \ \forall\ n \in \{1, ..., N\} \quad where\ X_{a,n} = \begin{cases} 1 & if\ i_{a,n}^{L} = i_{a,m}^{R} \\ 0 & if\ i_{a,n}^{L} \neq i_{a,m}^{R} \end{cases} \tag{1}$$

6. Case studies

In this section, the framework discussed in section 5 is applied to two case studies: the first one involves bridges and the second one deals with distribution transformers. The applications are conducted for both demonstration and research validation purposes.

Although the approach to CE and application of the categories are similar in both case studies, they differ in the definition of stakeholders and the professionals' insights. These are used to complete the bottom-up matrix in linking the stakeholders with the categories. These case studies were conducted consecutively in order to incorporate the lessons learnt from the first case study into the second one.

Below, the use of the framework is briefly explained (section 6.1). Then, the CE expert matrix is explained including the definition of the individual categories (sections 6.2 and section 6.3). Finally, the framework is applied by filling in the bottom-up matrices and generating the results of the bridge case study (section 6.4) and the distribution transformer case study (section 6.5).

6.1. A brief guide to the framework application

Although the core of this paper consists of the framework presented in section 5, a specified categorization of the CE strategies according to the literature is proposed in this paper as well. Other users of the framework, however, might approach categorization and application differently. Below, the guideline for composing and applying the framework is presented. The steps to be taken in order to use the framework are shown in Fig. 5.

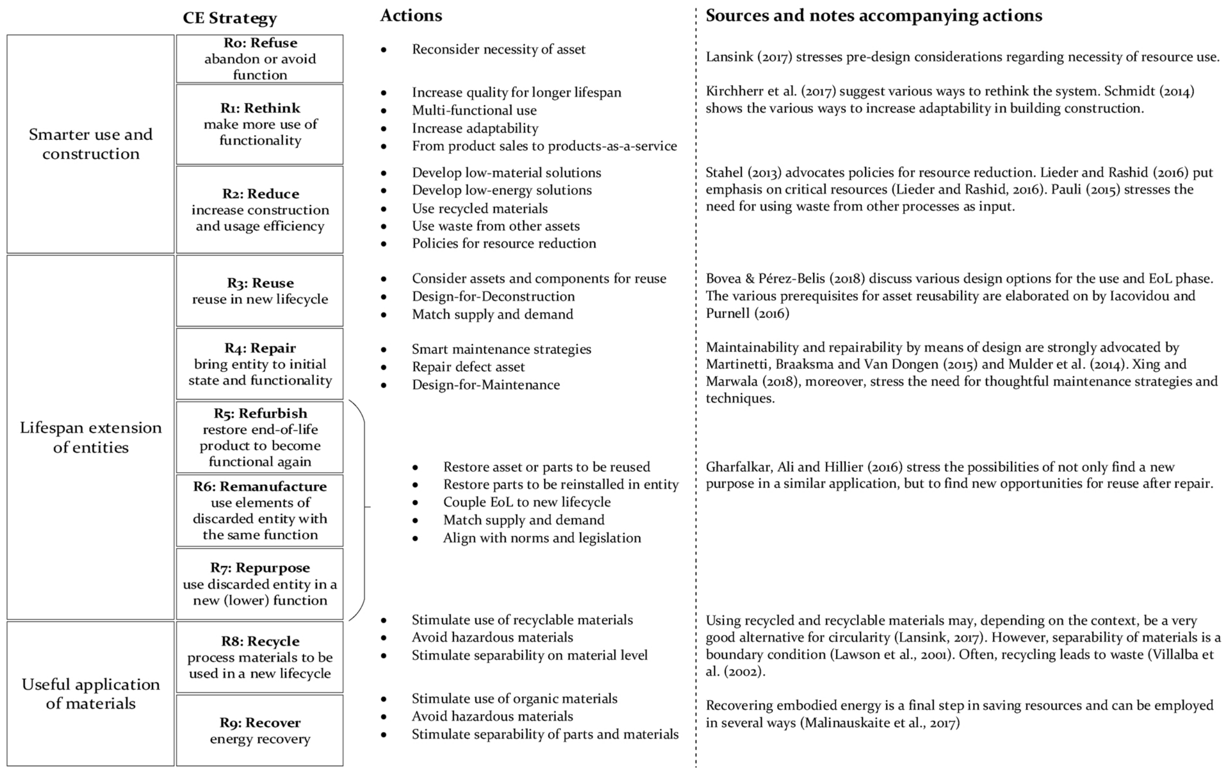

Fig. 2. Linking "9Rs" to circularity actions (amended from Potting et al., 2017).

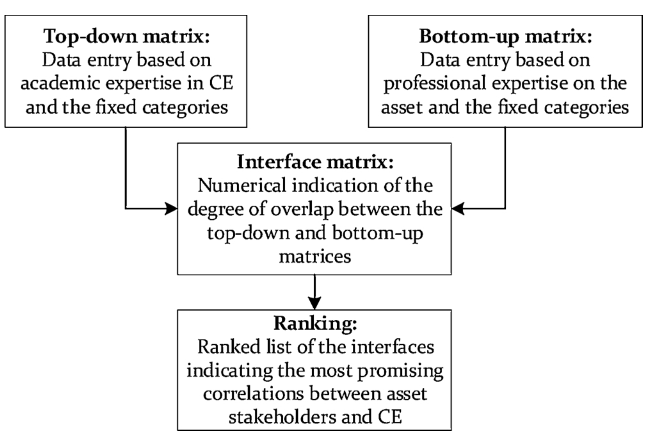

Fig. 3. Conceptual outline of the interface identification process.

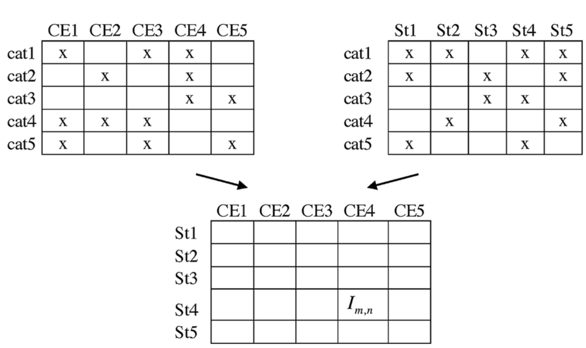

Fig. 4. Combining the top-down and bottom-up matrices into the interface matrix.

6.2. *Defining the categorization*

The first step in the application of the framework is to define the categorization, which serves the purpose of connecting both sides of the framework (Fig. 3). The resulting set of intermediate categories appears on the vertical axis of the upper and the lower matrices. The key requirement for each selected category is that it closely relates to both the CE actions and the selection of stakeholders. Within this requirement, a wide range of intermediate categories can be identified and selected by the user. A larger selection leads to a larger matrix which allows for a higher potential level of detail, but at the expense of making framework application more laborious. For demonstration purposes, we propose three dimensions, each with a set of categories that apply to both particular CE actions and infrastructure stakeholders. These dimensions are adopted from categories proposed by Kalmykova et al. (2018) and made applicable to the level of particular infrastructure assets, resulting in a total of twelve categories. In no particular order, these are *lifecycle phases, level of analysis* and *domain modalities.*

6.2.1. *Lifecycle phase*

During the lifecycle of an infrastructure asset, applicable processes vary strongly. As a result, possibilities for application of circularity actions differ for each lifecycle phase. CE embodies a multi-lifecycle approach: the end of one lifecycle is the beginning of a new one. Generally, five phases can be distinguished for infrastructure assets: pre-design phase, design phase, manufacturing/construction phase, operational/maintenance phase and EoL phase (Hernández-Moreno, 2011). Those five lifecycle phases are used as categories in the framework demonstration. This dimension provides the *time* component in the analysis.

6.2.2. *Level of analysis*

In much of the scientific literature, the CE is approached from three levels of analysis: macro level, meso level and micro level (Elia et al., 2017; Kalmykova et al., 2018; Kirchherr et al., 2017; Pomponi and

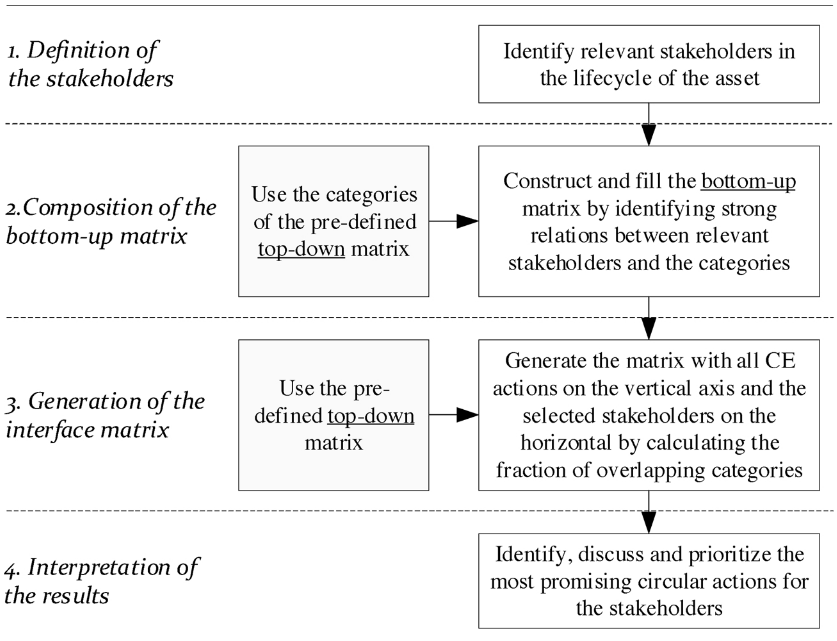

Fig. 5. Application process of the CEIMA framework.

Moncaster, 2017). The scope of CE actions can range from affecting large scale systems as a whole to only affecting specific system elements. In this study, the macro level is the infrastructure system, the meso level is a single asset including its major parts, and the micro level consists of the small elements and materials of the asset.

6.2.3. Domain modality

Process domain modalities are defined by El-Gohary and El-Diraby (2010) as part of the taxonomical structure of the construction and infrastructure sectors. These domain modalities are used to develop domain-oriented process types that strongly relate to the type of knowledge required. Process domain modalities proposed by Kalmykova et al. (2018) which fit in the "Scope of the CE" dimension are applied to this study. Firstly, engineering processes are selected based on the requirements of engineering knowledge and secondly, the environmental processes are chosen based on knowledge pertaining to the natural environment. Thirdly, the economic processes are selected based on knowledge relating to economic and financial methods of analysis and decision-making. Fourthly, social processes are chosen based on the principles of sociology, including, for example, stakeholder management. Finally, political processes are selected based on policymaking and higher-level decision making, utilizing the knowledge from political sciences.

6.3. The top-down matrix

Before its application to the case studies, the CE matrix should be developed. This table is represented by the left matrix in Fig. 3 (section 5). The top-down matrix of the framework consists of two axes: (1) the approach to circularity discussed in section 4.2 and (2) the fixed categorization discussed in section 6.2. Practical circularity actions have been derived from the existing "9R" waste hierarchy as discussed in section 4.2. This resulted in a list of 27 actions which were reviewed and reduced in number by removing overlapping actions – a design iteration. Consecutively, they were placed on the horizontal axis of the top-down matrix, resulting in a list of 23 actions towards circularity. The matrix resulting from the application of both axes is presented in Appendix A. Finally, by using scientific CE literature and thorough discussion among the authors, the matrix was filled in according to the method described in Fig. 5.

6.4. Case study 1: Bridges

The first case study is on bridges owned by the Dutch infrastructure agency. This infrastructure agency is responsible for the management of over 1000 nationally-owned bridges in the Netherlands, which are usually designed to last 100 years. We chose the domain of bridges, because these assets embody a high material usage infrastructure and show considerable opportunities regarding reuse and recycling. We present an example that is executed according to our insights on CE, while the outlines of the axes are adaptable to the user's specific goals. Below, the application of the framework axes is discussed, containing the three axes outlined in section 5. Finally, the comparative framework is applied to the case study of a group of bridge stakeholders to identify the interfaces between stakeholders and circular actions.

6.4.1. The bottom-up matrix

To demonstrate the operation of the framework, it is applied to stakeholders in the infrastructure sector to define their opportunities for implementing CE into their practices. In accordance with Nguyen et al. (2009), in this study a stakeholder is defined as an individual who has made an investment incurring risk in relationship with a particular industry. More specifically related to the scope of this study, infrastructure stakeholders are both individuals and groups who can affect or are affected by the performance of infrastructure assets (Hartmann and Hietbrink, 2013). In order to assign stakeholders from the list to the specific infrastructure-related domain, we addressed the following question: What groups or individuals can affect or are affected by the performance of bridges?

The list of stakeholders and the completion of the matrix comprise the case-specific side of the comparative framework. Using input from the Dutch infrastructure agency, two sets of bridge stakeholders are identified, in which a distinction is made between the client/owner (internal) and the others (external). This list, which is presented in Table 1, will form the vertical axis of the bottom-up matrix for dominant bridge stakeholder.

6.4.2. A bottom-up application to bridge stakeholders

Firstly, the matches between the stakeholders and categories are provided. It is followed by the identification of interfaces. Following the method presented in section 6.1, the stakeholders are matched with the

Table 1
Bridge stakeholders.

Internal	External
Project management	Engineering firm
Designer/engineer	Contractor
Asset manager	Suppliers
Experts	Inspectors
Programme manager/portfolio manager	Local/regional authorities
	Financer
	Maintenance contractor
	Road users
	Demolition contractor
	Local residents

Table 3
Distribution transformer stakeholders.

Internal	External
Asset Management – Specification & Standardization	Suppliers & producers
Logistics	Refurbishers
Purchasing	Demolition and recycling companies
Grid planners	Other DSO's
Asset management – Maintenance Engineering	DSO knowledge platform
Holding company	Regulatory body
Project engineers	
Maintenance operators	

categories, which is done with the help of bridge experts for the stakeholders in the table shown in Appendix B.

The bottom-up and top-down matrices of the conceptual framework shown in Fig. 2 are created using the tables in appendices A and B. The bridge experts establish for each stakeholder how many categories correspond with each of the CE actions and *vice versa*, using the method presented in section 5. This results in an extensive matrix providing CE actions on one axis and stakeholders on the other with a number between 0 and 1 for each cell, representing the level of overlap (Table 2). Although this comparison only reveals the similarity between categorizations, it indicates a likelihood of application of a specific CE action by the stakeholder. Other than resulting in a prescriptive guide to CE, it narrows down the possibilities of applicable CE actions for each stakeholder. The results of this case study are discussed in section 7.

Case study 2: Distribution transformers

To validate and test generalizability, the framework was applied to a second case study. We made minor changes to improve the framework application in this case study comparable to the first one. Those changes will be explained in section 6.5.2. The second case study was selected because, apart from belonging to the domain of infrastructure assets, the functionality and use profile are different from those of bridges. The subject of quasi-privately owned and managed distribution transformers is selected as a second case study. Distribution transformers are used in electrical grids to step down the voltages from a distribution network to a voltage suitable for consumers, such as households and industry. Both the technical composition and the life-cycle processes differ from bridges in many aspects. The stakeholders for these transformers were identified with the help of an Asset Manager of one of the largest Distribution System Operators (DSO) in the Netherlands, offering the basis for the bottom-up matrix. The DSO that was involved in this case study is responsible for the management of over 40.000 distribution transformers, which have a lifespan of approximately 60 years. Below, the stakeholders are linked to the categories and the framework is applied to the case study of distribution transformers.

6.4.3. *The bottom-up matrix*

Following the method applied to the bridge case study in section 6.4, the same top-down matrix is used for the distribution transformers. This includes a similar set of categories as used for the bridges. However, the stakeholders in this case study are DSO-specific and therefore differ from the stakeholders of the bridge case study. By using unstructured interviews with an asset manager of the distribution system operator, a list of dominant stakeholders was created (Table 3).

Table 2
Framework outcome: interfaces between bridge stakeholders and CE action.

Stakeholders / CE actions	Project management	Designer/ engineer	Asset manager	Experts	Programme/ portfolio manager	Engineering firm	Contractor	Suppliers	Inspectors	Local/ regional authorities	Financer	Maintenance contractor	Road users	Demolition contractor	Local residents
Reconsider necessity of asset	0,54	0,31	0,46	0,46	0,62	0,54	0,46	0,38	0,46	0,62	0,46	0,23	0,62	0,31	0,69
Increase quality for longer life span	0,46	0,69	0,38	0,38	0,08	0,46	0,85	0,77	0,38	0,23	0,69	0,62	0,54	0,54	0,62
Multi-functional use	0,38	0,46	0,62	0,62	0,62	0,69	0,46	0,23	0,62	0,62	0,62	0,38	0,62	0,46	0,38
Increase adaptability	0,54	0,77	0,46	0,62	0,15	0,54	0,77	0,69	0,46	0,31	0,62	0,54	0,46	0,77	0,38
Product-service system	0,54	0,46	0,46	0,62	0,62	0,69	0,46	0,23	0,46	0,62	0,62	0,38	0,46	0,31	0,54
Low-material solutions	0,54	0,92	0,46	0,46	0,31	0,69	0,62	0,69	0,46	0,15	0,46	0,85	0,15	0,77	0,23
Low-energy solutions	0,69	0,77	0,46	0,62	0,38	0,54	0,62	0,62	0,46	0,46	0,62	0,77	0,31	0,62	0,54
Use recycled materials	0,77	0,69	0,38	0,54	0,38	0,62	0,54	0,62	0,38	0,38	0,69	0,62	0,23	0,54	0,31
Use waste from other chains	0,69	0,62	0,62	0,62	0,62	0,69	0,31	0,38	0,62	0,46	0,46	0,54	0,31	0,62	0,23
Material-reducing policies	0,38	0,31	0,46	0,46	0,77	0,38	0,31	0,38	0,46	0,62	0,31	0,38	0,46	0,46	0,38
Consider entity for reuse	0,46	0,69	0,69	0,54	0,54	0,62	0,38	0,46	0,54	0,54	0,54	0,62	0,38	0,85	0,31
Design-for-Deconstruction	0,46	0,85	0,54	0,54	0,23	0,62	0,69	0,62	0,54	0,23	0,54	0,62	0,38	0,85	0,31
Match supply and demand	0,54	0,31	0,62	0,62	0,77	0,54	0,31	0,23	0,62	0,77	0,46	0,23	0,62	0,46	0,54
Smart maintenance strategies	0,23	0,62	0,62	0,31	0,46	0,54	0,62	0,62	0,62	0,54	0,62	0,69	0,62	0,62	0,54
Repair defective asset	0,38	0,77	0,77	0,46	0,46	0,54	0,46	0,54	0,77	0,46	0,46	0,85	0,46	0,92	0,38
Design-for-Maintenance	0,62	0,69	0,54	0,54	0,38	0,62	0,54	0,46	0,54	0,38	0,54	0,62	0,38	0,54	0,62
Restore for reinstallation	0,38	0,62	0,62	0,46	0,46	0,54	0,46	0,69	0,62	0,31	0,31	0,69	0,46	0,77	0,38
Link EoL to new lifecycle	0,54	0,31	0,54	0,62	0,85	0,54	0,15	0,23	0,62	0,77	0,23	0,38	0,46	0,46	0,31
Align norms and legislation	0,31	0,23	0,38	0,38	0,69	0,31	0,38	0,46	0,38	0,54	0,38	0,31	0,54	0,38	0,46
Stimulate use of recyclable materials	0,69	0,46	0,46	0,62	0,77	0,69	0,31	0,38	0,62	0,62	0,31	0,54	0,31	0,46	0,38
Avoid hazardous materials	0,62	0,69	0,23	0,54	0,23	0,46	0,69	0,77	0,23	0,23	0,38	0,62	0,23	0,54	0,46
Stimulate separability of materials	0,54	0,77	0,31	0,46	0,31	0,69	0,62	0,69	0,31	0,15	0,46	0,69	0,15	0,62	0,23
Use organic materials	0,69	0,62	0,31	0,62	0,31	0,54	0,62	0,69	0,31	0,31	0,31	0,54	0,31	0,46	0,54

Table 4
Framework outcome: interfaces between distribution transformer stakeholders and CE action.

CE actions \ Stakeholders	AM – Specif. & Stand.	Logistics	Purchasing	Grid planners	AM-ME	Holding company	Proj. Eng.	Maint. Oper.	Suppl./prod.	Refurbishers	Demol. & Recyc. Comp.	Other DSO's	DSO Knowledge platform	Regul. body
Reconsider necessity of asset	0,69	0,46	0,46	0,62	0,31	0,62	0,62	0,54	0,31	0,38	0,46	0,38	0,46	0,62
Increase quality for longer life span	0,15	0,38	0,54	0,38	0,69	0,23	0,69	0,62	0,69	0,62	0,54	0,62	0,69	0,23
Multi-functional use	0,54	0,31	0,31	0,62	0,62	0,31	0,46	0,69	0,46	0,23	0,31	0,54	0,62	0,31
Increase adaptability	0,38	0,62	0,62	0,62	0,77	0,31	0,62	0,54	0,77	0,69	0,62	0,54	0,62	0,31
Product-service system	0,54	0,31	0,15	0,46	0,46	0,46	0,46	0,54	0,31	0,08	0,15	0,54	0,46	0,46
Low-material solutions	0,23	0,46	0,62	0,46	0,46	0,62	0,62	0,38	0,62	0,54	0,62	0,38	0,46	0,62
Low-energy solutions	0,38	0,62	0,46	0,31	0,62	0,54	0,46	0,38	0,62	0,54	0,46	0,69	0,46	0,54
Use recycled materials	0,46	0,54	0,54	0,38	0,54	0,54	0,38	0,15	0,69	0,62	0,54	0,46	0,38	0,54
Use waste from other chains	0,54	0,62	0,62	0,46	0,62	0,46	0,31	0,38	0,62	0,54	0,62	0,38	0,46	0,46
Material-reducing policies	0,69	0,46	0,62	0,62	0,15	0,77	0,46	0,38	0,46	0,54	0,62	0,54	0,46	0,77
Consider entity for reuse	0,62	0,54	0,69	0,69	0,38	0,54	0,69	0,62	0,69	0,62	0,69	0,46	0,38	0,54
Design-for-Deconstruction	0,31	0,54	0,69	0,69	0,69	0,38	0,69	0,62	0,69	0,62	0,69	0,46	0,69	0,38
Match supply and demand	0,85	0,62	0,46	0,77	0,46	0,62	0,46	0,54	0,31	0,38	0,46	0,38	0,46	0,62
Smart maintenance strategies	0,38	0,31	0,46	0,77	0,46	0,62	0,77	0,69	0,31	0,46	0,46	0,38	0,62	0,62
Repair defective asset	0,38	0,62	0,77	0,62	0,62	0,46	0,62	0,69	0,62	0,69	0,77	0,54	0,62	0,46
Design-for-Maintenance	0,31	0,54	0,38	0,38	0,69	0,38	0,54	0,62	0,38	0,31	0,38	0,46	0,54	0,38
Restore for re-installation	0,38	0,62	0,62	0,62	0,62	0,46	0,62	0,69	0,46	0,54	0,62	0,23	0,46	0,46
Link EoL to new lifecycle	0,85	0,62	0,46	0,54	0,31	0,69	0,31	0,38	0,31	0,38	0,46	0,38	0,31	0,69
Align norms and legislation	0,62	0,38	0,54	0,69	0,23	0,69	0,54	0,46	0,38	0,46	0,54	0,46	0,54	0,69
Stimulate use of recyclable materials	0,69	0,62	0,46	0,46	0,31	0,77	0,31	0,23	0,31	0,38	0,46	0,38	0,31	0,77
Avoid hazardous materials	0,31	0,54	0,54	0,23	0,38	0,54	0,54	0,31	0,69	0,62	0,54	0,62	0,38	0,54
Stimulate separability of materials	0,23	0,31	0,62	0,31	0,31	0,46	0,62	0,38	0,77	0,54	0,62	0,54	0,46	0,46
Use organic materials	0,38	0,62	0,46	0,15	0,46	0,46	0,46	0,38	0,62	0,54	0,46	0,54	0,31	0,46

6.4.4. Changes in case study 2 compared to case study 1

While applying the framework, some changes have been made based on the lessons learnt from case study 1, which can be considered a design iteration. In case study 1, the framework input was mostly based on written input by bridge experts. On the contrary, in case study 2, we organized a session in which the bottom-up table was developed and filled in together with an expert. This has improved the involvement of the professionals in the process and created a lively discussion of the results. The discussion of the results and the differences in the application of the framework to the case studies are presented in section 7.

6.4.5. A bottom-up application on transformer stakeholders

Following a similar approach to that of the case study 1 – aside from the differences mentioned in section 6.5.2 – the interface table has been created. The distribution transformer stakeholder table can be found in Appendix C. Using the framework discussed in section 5, the interfaces between circularity actions and distribution transformer stakeholders have been determined. The results shown in Table 4 are discussed and compared to case study 1 in section 7.

7. Discussion and validation of the framework application

In this section, the results of the demonstration of the framework are discussed. Next, the outcomes of the two case studies are used to validate the design of the proposed framework.

7.1. Discussion of the results

The demonstration of the framework relied on both theoretical knowledge collected from scientific literature and the input from two case companies. The combination of this input has been used to construct both the bottom-up and top-down matrices. By using a spreadsheet, the overlap in categories was calculated resulting in a third matrix for each, which are shown in Tables 2 and 4 respectively (section 6). The output matrix of both case studies revealed a prioritized selection of concrete circular actions to promote discussion on the implementation of CE between asset-related stakeholders.

7.1.1. Results of the bridge stakeholder case study

The matrix presented in Table 2 indicates which links are not worth considering for the bridge case study. By eliminating all links with low similarity scores (less than 0.7), the possibilities for this particular case study are reduced by more than 92%. This process leaves only a selection of the most promising results, such as the interface of *designer/engineer* with *design-for-deconstruction* and *demolition contractor* with *consider entity for reuse* (Table 2). For demonstration purposes, the five stakeholders with the highest average similarity are listed vertically, while the five highest ranking matches are listed horizontally (Table 5). Although certain interfaces, such as *inspectors* with *use waste from other product chains* do not seem very applicable, a large majority of these top-5 actions offer concrete and applicable suggestions for the particular stakeholders.

For example, when we take a look at the “asset managers” column in Table 2, the two actions with the highest rating are *repair defective asset* and *consider entity for reuse*. Although asset managers will usually aim for maintenance and repair, the framework outcomes offer suggestions to consider what these actions mean for their daily activities and their relation to the asset with CE in mind. The stakeholders will be more easily able to consider what this particular action means as part of the “9Rs” and eventually for the CE as a whole. Consequently, the stakeholder’s potential role in the process of an organization-wide transition becomes more transparent.

7.1.2. Results of the distribution transformer stakeholder case study

Although the framework outline has remained the same as in the case study 1, there has been an iteration at the process level as discussed in section 6.5.2. This did not affect the framework outcomes, but it had a large impact on the interpretation of the results. The applicability of the framework has shown to be equally promising in both case studies. However, the larger involvement of professionals in the interfacing process resulted in a fruitful discussion. During this discussion, professionals with no background in CE, or sustainability in a broader sense for that matter, recognized and acknowledged the applicability of a large amount of actions for specific stakeholders. The distribution system operator’s asset manager remarked that “[…] the framework positively helps [professionals] to think about CE in a structured manner, and even this exercise itself, is beneficial for implementing circularity”.

A selection of the five most promising actions per stakeholder in the distribution transformer case study is shown in Table 6. Similar to the

Table 5
Highest ranking of the CE actions for bridge stakeholders.

CE action / Stakeholder	1st rank	2nd rank	3rd rank	4th rank	5th rank
Designer/ engineer	Low-material solutions (0,92)	Design-for-Deconstruction (0,85)	Increase adaptability (0,77)	Low-energy solutions (0,77)	Repair defective asset (0,77)
Demolition contractor	Repair defective asset (0,92)	Consider entity for reuse (0,85)	Design-for-Deconstruction (0,85)	Restore for re-installation (0,77)	Increase adaptability (0,77)
Maintenance contractor	Repair defective asset (0,85)	Low-material solutions (0,85)	Low-energy solutions (0,77)	Smart maintenance strategies (0,69)	Stimulate separability of materials (0,69)
Suppliers	Increase quality for longer life span (0,77)	Avoid hazardous materials (0,77)	Increase adaptability (0,77)	Restore for re-installation (0,69)	Use organic materials (0,69)
Engineering firm	Multi-functional use (0,69)	Product-service system (0,69)	Low-material solutions (0,69)	Use waste from other chains (0,69)	Stimulate separability of materials (0,69)

Table 6
Highest ranking of the CE actions for distribution transformer stakeholders.

CE action / Stakeholder	1st rank	2nd rank	3rd rank	4th rank	5th rank
Project engineers	Smart maintenance strategies (0,77)	Increase quality for longer life span (0,69)	Consider entity for reuse (0,69)	Design-for-Deconstruction (0,69)	Restore for re-installation (0,62)
Purchasing	Repair defective asset (0,77)	Consider entity for reuse (0,69)	Design-for-Deconstruction (0,69)	Low-material solutions (0,62)	Stimulate separability of materials (0,62)
Demolition and recycling companies	Repair defective asset (0,77)	Consider entity for reuse (0,69)	Design-for-Deconstruction (0,69)	Increase adaptability (0,62)	Low-material solutions (0,62)
Network planners	Match supply and demand (0,77)	Smart maintenance strategies (0,77)	Align norms and legislation (0,69)	Consider entity for reuse (0,69)	Design-for-Deconstruction (0,69)
Holding company	Material-reducing policies (0,77)	Stimulate use of recyclable materials (0,77)	Link EoL to new lifecycle (0,69)	Align norms and legislation (0,69)	Match supply and demand (0,62)

first case study, the outcomes include various predictable CE actions. Yet, this case study also revealed some new insights, such as the role of the holding company to indirectly stimulate the implementation of CE principles. This result indicates that the framework is not merely able to identify bottom-up actions, but also to indicate higher (meso) level circular actions. Furthermore, Tables 2 and 4 show that the design of more adaptable assets is likely to affect many stakeholders as indicated by the high frequency of strong matches. As a result, an action that suits many stakeholders carries the risk of being at the core of the business operation and therefore needs broad support to render its implementation successfully.

7.2. Framework validation and verification

To test the design of the framework, it was applied to a practical context involving two distinct infrastructure organizations. Although the results of these applications reveal concrete CE actions and stakeholders, the outcomes of the case studies are not at the heart of this paper. The main purpose of these applications is to study the validity of the main design principles that underpin the construction of the framework.

Both the principles of the bottom-up approach and the linking of stakeholders to practical circularity actions were immediately embraced by both organizations involved in the case studies. Although some of the identified matches may seem obvious in the eyes of a CE expert, professionals without CE expertise can use the framework to arrive at the same outcome without having to first understand the multitude of circular principles and approaches that exist in literature. Instead, the framework provides awareness and steers the discussion within the infrastructure organizations towards only the most promising and relevant aspects of circularity for the particular group of assets.

The design aspects were validated by making multiple design iterations until the outcome was satisfactory. The first iteration consisted of translating the “9Rs” into 27 concrete actions and refining this list into 23 actions. It resulted in more concrete and accessible actions and avoided overlap between actions. The second iteration involved the unstructured interview approach used in the second case study and resulted in an improvement of the overall process. The third iteration consisted of identifying the list of stakeholders and a discussion of the results with the professionals, which was successfully evaluated in the second case study. In addition to these design iterations and user testing, the framework was continuously checked against the four criteria discussed in section 4.1.

8. A brief reflection and future work

In this paper, a framework is proposed that helps non-experts in the area of CE to apply circular principles and to link these to the various actors in the infrastructure sector. The aim was to increase the awareness of CE principles in order to stimulate concrete actions. As a result, the framework enables infrastructure organizations to consider and implement circular principles that are more suitable to their specific assets. The framework helps to present, select and prioritize strategies, actions and directions for practical implementation of circular principles for infrastructure organizations. In the following sections, concluding remarks and future recommendations are provided.

8.1. Concluding remarks

In this study we have used the DSR approach to develop a generic comparative framework, called CEIMA, that can be used as a model to connect stakeholders in the practical work field to CE principles. This comparative framework has been developed based on a structured analysis of the CE domain and according to a rigorous methodological approach. The duality discussed in section 3 resulted in the framework design, as well as the generation of knowledge about application of circularity in the infrastructure domain. By using the CEIMA framework, an operationalization of the CE principles was proposed and linked to stakeholders within infrastructure organizations as demonstrated in the case studies. By differentiating between the preparatory stage done by CE experts, and the application stage in practice, the actual application of the framework within an infrastructure organization can be executed within a few hours.

Furthermore, the case studies illustrated that the bottom-up approach, which is strongly underrepresented in existing CE literature, is not likely to provide any fundamentally new insights for circularity experts. However, it aims to increase the awareness of CE opportunities at the organizational level, by linking stakeholders to concrete actions in a structured manner. The CEIMA framework accentuates the broad scope of actions that may contribute to circularize infrastructure practices as a result of the operationalization of the “9Rs”. This approach puts the stakeholder at the centre of the analysis. In case study 1, the results of the framework application have only been communicated to the professionals, rather than directly involving them in the application of the framework and resulting discussions. This has been changed in the second case study, in which the professionals were directly involved in the generation of the interface matrix in order to increase their impact. This resulted in a lively discussion which yielded useful insights and opportunities for circularizing practices regarding distribution transformers.

These outcomes resulted in several implications for practical application of the CEIMA framework. Initially, it can be used at the top-management level to promote the introduction of circularity within the organization. Moreover, it creates awareness of the wide range of possible measures that are part of the transition toward a CE and offers a basis for discussion on the applicability of CE. Furthermore, it enables professionals to systematically consider circularity measures in a broad sense. This illustrates opportunities to specific stakeholders who do not currently partake in the circularity discussion, to increase their awareness of CE and may foster support for the transition towards CE within the organization.

8.2. Future work

The CEIMA framework was developed for the purpose of identifying interfaces between CE and infrastructure stakeholders and was tested on two case studies within the infrastructure domain. Testing the CEIMA framework in more domains, industries and countries, and particularly in material and energy intensive areas where a large potential waste reduction exist, would increase the generalizability and external validity of the framework. To facilitate the involvement of multiple stakeholders in multiple domains, various expert-based techniques can be used to stimulate the implementation process that follows application of the CEIMA framework. Multiple applications of the framework within a particular sector or domain could eventually result in a general list of critical interfaces between CE actions and stakeholders. Moreover, the results are not statistically validated in this study due to a lack of case data. To investigate statistical relevance, application on multiple case studies would generate additional data, which could contribute to the mathematical robustness of the framework.

Acknowledgements

We thank Liander, especially for their support in conducting the case studies, and the Dutch regional wastewater agency of Limburg (WBL) for their assistance during the early development of the CEIMA framework.

Appendix A. Top-down matrix containing CE actions assessed on categories

		Lifecycle phases					*Level of detail*			*Process domain modality*				
no	Action	Pre-des.	Design	Manuf./ constr.	Operation/ maintenance	EoL	Macro	Meso	Micro	Engineering	Environmental	Economic	Social	Political
1	Reconsider necessity of asset	X					X	X					X	X
2	Increase quality for longer life span		X	X	X			X	X	X				
3	Multi-functional use	X	X		X	X	X	X		X		X	X	
4	Increase adaptability		X	X		X		X	X	X		X		
5	Product-service system	X	X		X		X	X		X		X	X	X
6	Low-material solutions		X						X	X	X	X		
7	Low-energy solutions		X	X	X			X	X	X	X	X		X
8	Use recycled materials	X	X	X					X		X	X		
9	Use waste from other chains	X	X			X			X		X	X	X	
10	Material-reducing policies	X				X	X				X			X
11	Consider entity for reuse	X				X		X		X	X	X		
12	Design-for-Deconstruction		X			X		X	X	X		X		
13	Match supply and demand	X				X	X	X				X	X	X
14	Smart maintenance strategies				X		X	X		X		X		
15	Repair defective asset				X	X		X	X	X	X	X		
16	Design-for-Maintenance		X		X			X	X	X		X	X	X
17	Restore for re-installation					X			X	X		X	X	
18	Link EoL to new life-cycle	X				X	X				X	X	X	X
19	Align norms and legislation	X				X	X							X

20	Stimulate use of recyclable materials	X					X		X		X	X	X	X
21	Avoid hazardous materials		X	X					X	X	X			X
22	Stimulate separability of materials	X	X						X	X	X			
23	Use organic materials		X	X					X	X	X		X	X

Appendix B. Bottom-up matrix containing bridge stakeholders assessed on categories

		Lifecycle phases					*Level of detail*			*Process domain modality*				
no	Stakeholder	Pre-des.	Design	Manuf./ constr.	Operation/ maintenance	EoL	Macro	Meso	Micro	Engineering	Environmental	Economic	Social	Political
1	Project management	X	X	X				X	X		X	X	X	X
2	Designer/engineer		X					X	X	X	X	X		
3	Asset manager				X	X		X			X	X	X	
4	Experts	X	X	X		X	X	X	X	X	X	X	X	X
5	Programme/portfolio manager	X			X	X	X				X	X	X	X
6	Engineering firm	X	X				X	X	X	X	X	X	X	
7	Contractor		X	X			X	X	X	X				
8	Suppliers			X					X	X				
9	Inspectors				X	X	X	X	X		X	X	X	
10	Local/regional authorities	X		X	X	X	X	X			X	X	X	X
11	Financer	X	X	X	X			X				X		
12	Maintenance contractor				X				X	X	X	X		
13	Road users			X	X	X	X	X					X	
14	Demolition contractor					X		X	X	X	X	X		
15	Local residents			X	X			X					X	X

Appendix C. Bottom-up matrix containing distribution transformer stakeholders assessed on categories

		Lifecycle phases					*Level of detail*			*Process domain modality*				
no	**Stakeholder**	Pre-des.	Design	Manuf./ constr.	Operation/ maintenance	EoL	Macro	Meso	Micro	Engineering	Environmental	Economic	Social	Political
1	Asset Management - Specification & Standardization	X		X		X	X	X			X	X	X	X
2	Logistics			X		X		X	X		X	X	X	X
3	Purchasing					X		X	X		X			
4	Network planners					X	X	X				X		
5	Asset Management – Maintenance Engineering		X	X	X	X		X	X			X	X	
6	Alliander (holding company)						X				X	X		X
7	Project Engineers							X		X				
8	Maintenance operators				X	X		X		X			X	
9	Suppliers/producers	X	X	X		X		X	X	X	X			
10	Refurbishers			X		X		X	X		X			
11	Demolition & Recycling companies					X		X	X		X			
12	Other DSO's (like Liander)	X	X	X	X	X	X	X	X	X	X			X
13	Knowledge platform Ksandr		X		X	X	X	X	X					
14	Regulatory body ACM						X				X	X		X

References

Abdi, M.R., Labib, A.W., 2003. A design strategy for reconfigurable manufacturing systems (RMSs) using analytical hierarchical process (AHP): a case study. Int. J. Prod. Res. 41, 2273–2299. https://doi.org/10.1080/0020754031000077266.

Blomsma, F., Brennan, G., 2017. The emergence of circular economy: a new framing around prolonging resource productivity. J. Ind. Ecol. 21, 603–614. https://doi.org/10.1111/jiec.12603.

Boulding, K.E., 1966. Environmental quality in a growing economy BT - (null). Environ. Qual. Issues a Grow. Econ. 3–15. https://doi.org/10.4324/9781315064147.

Bovea, M.D., Pérez-Belis, V., 2018. Identifying design guidelines to meet the circular economy principles: a case study on electric and electronic equipment. J. Environ. Manage. https://doi.org/10.1016/j.jenvman.2018.08.014.

Braungart, M., McDonough, W., 2002. Remaking the Things We Make. North Point Press.

Cairns, J., 2003. Integrating top-down/bottom-up sustainability strategies. An ethical challenge. Ethics Sci. Environ. Polit. 3, 6. https://doi.org/10.3354/esep003001.

Cross, N., 2001. Designerly ways of knowing: design discipline versus design science. Des. Issues 17, 49–55. https://doi.org/10.1162/074793601750357196.

Eisenbart, B., Gericke, K., Blessing, L., 2011. A framework for comparing design modelling approaches across disciplines. In: 18th International Conference On Engineering Design. The Design Society, Copenhagen. pp. 344–355.

El-Gohary, N.M., El-Diraby, T.E., 2010. Domain ontology for processes in infrastructure and construction. J. Constr. Eng. Manag. 136, 730–744. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000178.

Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: A critical analysis. J. Clean. Prod. 142, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196.

European Commission, 2015. Closing the loop - An EU action plan for the Circular Economy 614 final. pp. 1–21. https://doi.org/10.1017/CBO9781107415324.004.

Fregonara, E., Giordano, R., Ferrando, D.G., Pattono, S., 2017. Economic-environmental indicators to support investment decisions: a focus on the buildings. MDPI Build. 7. https://doi.org/10.3390/buildings7030065.

Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res. Policy 31, 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8.

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.

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How circular is the global economy?: an assessment of material flows, waste production, and recycling in the European union and the world in 2005. J. Ind. Ecol. 19, 765–777. https://doi.org/10.1111/jiec.12244.

Hartmann, A., Hietbrink, M., 2013. An exploratory study on the relationship between stakeholder expectations, experiences and satisfaction in road maintenance. Constr. Manag. Econ. 31, 345–358. https://doi.org/10.1080/01446193.2013.768772.

Hernández-Moreno, S., 2011. Importance of Service Life Planning in. Manag. Res. Pract. 3, 21–31.

Hevner, A.R., 2007. A three cycle view of design science research. Scand. J. Inf. Syst. 19, 87–92. https://doi.org/http://aisel.aisnet.org/sjis/vol19/iss2/4.

Jacobs, M., 1992. The Green Economy: Environment, Sustainable Development and the Politics of the Future. Pluto Press.

Kalmykova, Y., Sadagopan, M., Rosado, L., 2018. Circular economy – from review of theories and practices to development of implementation tools. Resour. Conserv. Recycl. 135, 190–201. https://doi.org/10.1016/j.resconrec.2017.10.034.

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.

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.

Korhonen, J., Honkasalo, A., Seppälä, J., 2018. Circular economy: the concept and its limitations. Ecol. Econ. 143, 37–46. https://doi.org/10.1016/j.ecolecon.2017.06.041.

Korkmaz, I., Gökçen, H., Çetinyokuş, T., 2008. An analytic hierarchy process and two-sided matching based decision support system for military personnel assignment. Inf. Sci. (Ny). 178, 2915–2927. https://doi.org/10.1016/j.ins.2008.03.005.

Lahti, T., Wincent, J., Parida, V., 2018. A definition and theoretical review of the circular economy, value creation, and sustainable business models: where are we now and where should research move in the future? Sustainability 10, 1–19. https://doi.org/10.3390/su10082799.

Lansink, A., 2017. Challenging Changes - Connection Waste Hierarchy and Circular Economy. LEA.

Linder, M., Sarasini, S., van Loon, P., 2017. A metric for quantifying product-level circularity. J. Ind. Ecol. 21, 545–558. https://doi.org/10.1111/jiec.12552.

Millar, N., Mclaughlin, E., Börger, T., Millar, N., Mclaughlin, E., Börger, T., 2019. The circular economy: swings and roundabouts? Environ. Econ. 1–26.

Moreno, M., De los Rios, C., Rowe, Z., Charnley, F., 2016. A conceptual framework for circular design. Sustainability 8. https://doi.org/10.3390/su8090937.

Nguyen, N.H., Skitmore, M., Wong, J.K.W., 2009. Stakeholder impact analysis of infrastructure project management in developing countries: a study of perception of project managers in state-owned engineering firms in Vietnam. Constr. Manag. Econ. 27, 1129–1140. https://doi.org/10.1080/01446190903280468.

Niero, M., Kalbar, P.P., 2019. Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. Resour. Conserv. Recycl. 140, 305–312. https://doi.org/10.1016/j.resconrec.2018.10.002.

Nuñez-Cacho, P., Górecki, J., Molina-Moreno, V., Corpas-Iglesias, F.A., 2018. What gets measured, gets done: development of a circular economy measurement scale for building industry. Sustainability 10. https://doi.org/10.3390/su10072340.

Núñez-cacho, P., Górecki, J., Molina, V., Antonio, F., 2018. New Measures of Circular Economy Thinking In Construction Companies. https://doi.org/10.5171/2018.909360.

Peffers, K., Tuunanen, T., Rothenberger, M.A., Chatterjee, S., 2007. A design science research methodology for information systems research. J. Manag. Inf. Syst. 24, 45–77. https://doi.org/10.2753/MIS0742-1222240302.

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.

Saari, E., Lehtonen, M., Toivonen, M., 2015. Making bottom-up and top-down processes meet in public innovation. Serv. Ind. J. 35, 325–344. https://doi.org/10.1080/02642069.2015.1003369.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. J. Clean. Prod. 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014.

Tukker, A., 2015. Product services for a resource-efficient and circular economy - a review. J. Clean. Prod. 97, 76–91. https://doi.org/10.1016/j.jclepro.2013.11.049.

van Aken, J., Chandrasekaran, A., Halman, J., 2016. Conducting and publishing design science research: Inaugural essay of the design science department of the Journal of Operations Management. J. Oper. Manag. 47–48, 1–8. https://doi.org/10.1016/j.jom.2016.06.004.

Wieringa, R., 2014. Design science methodology. In: Proceedings of the 32nd ACM/IEEE International Conference on Software Engineering - ICSE' 10. Springer. https://doi.org/10.1145/1810295.1810446.

World Commission on Environment and Development, 1987. Our Common Future.