Universiteit
Antwerpen

This item is the archived peer-reviewed author-version of:

Translating the circular economy to bridge construction : lessons learnt from a critical literature review

Reference:
Anastasiades Kostas, Blom Johan, Buyle Matthias, Audenaert Amaryllis.- Translating the circular economy to bridge construction : lessons learnt from a critical literature review
Renew able and sustainable energy review s - ISSN 1364-0321 - Oxford, Pergamon-elsevier science ltd, 117(2020), 109522
Full text (Publisher's DOI): https://doi.org/10.1016/J.RSER.2019.109522
To cite this reference: https://hdl.handle.net/10067/1638370151162165141

uantwerpen.be
Institutional repository IRUA

Title

Translating the Circular Economy to Bridge Construction: Lessons Learnt from a Critical Literature Review

Authors

ANASTASIADES, K.[1,*]; BLOM, J.[1]; BUYLE, M.[1,2]; AUDENAERT, A.[1]
1 = Energy and Materials in Infrastructure and Buildings (EMIB), University of Antwerp, Campus Groenenborger, Groenenborgerlaan 171 – 2020 Antwerp, Belgium

2 = Sustainable Materials Management, Flemish Institute for Technical Research (VITO), Mol, Belgium

* = corresponding author, kostas.anastasiades@uantwerpen.be, +3232659246

Abstract

'Sustainability', 'circular economy', 'circular construction' have received increasing attention in the last decade. However, their interpretation is often unclear, as is the way a certain study fits into these research fields. In this paper, therefore, first a definition of both 'sustainability' and 'circular economy' is proposed. It is concluded that sustainability is the goal, while the circular economy is a means to achieve a more sustainable economy.
Subsequently, the application of the circular economy in the construction industry is investigated, with a special focus on bridge construction. Reason is that, for instance, many concrete pedestrian bridges currently find themselves in the end-of-life phase, are demolished and often merely rebuilt, with a lot of material and energy loss as a consequence. An investigation of the available circular construction principles is therefore performed in order to determine certain limitations and gaps for future research and to stipulate the path to be followed towards circular bridge construction. This is necessary in order to prevent the same cycle of demolition and replacement from being run through again in a few decades.
It is concluded that the meso-scale, the construction in general, is rarely discussed. Yet, an in-depth investigation is necessary in order to develop specific design strategies for circular bridges. A certain standardisation scheme to facilitate circularity, needs to be developed. This scheme should, however, still allow enough architectural freedom. Additionally, this scheme needs to be accompanied by, to be developed, meso-scale circularity indicators to effectively assess the eventual circularity of a bridge.

Keywords

circular economy; circular construction; sustainability; circular bridge construction; design principles; circularity assessment

List of abbreviations

BREEAM: Building Research Establishment Environmental Assessment Method
CDW: Construction and Demolition Waste
CE: Circular Economy
CLT: Cross-Laminated Timber
CO_2: Carbon Dioxide
DfA: Design for Adaptability
DfAD: Design for Adaptability and Deconstruction

DfD: Design for Disassembly, Design for Deconstruction
EMF: Ellen MacArthur Foundation
EU: European Union
GPP: Green Public Procurement
LCA: Life Cycle Assessment
LCCA: Life Cycle Costing Analysis
LEED: Leadership in Energy and Environmental Design
LVL: Laminated Veneered Lumber

1. Introduction

The idea of 'sustainability' has been a matter for extensive research and discussion ever since the 1987 Brundtland Report [1]. The importance of the idea is widely recognised, as for example resources are not unlimited and as pollution is triggering both a climate change and a harmful environment for humans and any other species and organism on earth.

Along with the sustainability discourse, also circularity, closing loops, has been discussed in literature. Mostly during the last decade the 'circular economy' has gained increasing attention, certainly since the launch of the Ellen MacArthur Foundation (EMF) in 2010 whom have made it their primary focus [2]. Similar to sustainability, the idea of the Circular Economy (CE) originates from an environmental awareness and consequent call to preserve our planet.

Yet it seems that both for sustainability and circularity, there is no clear definition. Different studies often adopt different approaches to both paradigms. Sometimes the way sustainability and circularity are perceived is not discussed at all or the terms are used seemingly randomly. This illustrates the importance of adopting a clear definition for sustainability and CE and defining how they relate to each other. The first section in this paper will therefore deal with this matter.

Subsequently, the idea of circular construction will be discussed, making use of the adopted definitions for sustainability and CE. The special focus in this literature review will be on bridge construction. Many concrete pedestrian bridges ranging from 30 to 50 years in age, presently need to be replaced as they reached their end-of-life phase and appear to be in a severe condition of disrepair [3–5]. This also corresponds to the typical design working life that is mentioned in e.g. the Eurocodes [6,7].Typically these bridges are not just being demolished, they are replaced by new ones. If the designs of these bridges, as well as their material use is not thought through more carefully, the exact same scenario of demolition and replacement of the bridges will need to be run through again in 30 to 50 years. Hence, the aim is to find research opportunities and to stipulate the path to be followed towards circular bridge construction.

2. A vocabulary and reflections

2.1. Sustainability

The omnipresent and most referenced definition of sustainability remains the general description in the 1987 Brundtland report: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. [It] is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations." [1] Most commonly, three pillars of sustainability are defined, also known as Triple P: People (culture/society), Profit (economy), Planet (environment/ecology). Yet, some authors add Politics (policy making/financial incentives) to the list

[8,9], which was, in fact, already embedded in the Brundtland report's general definition: "direction of investments […] and institutional change" [1]. Even though one can argue that politics is not a necessary factor for sustainable development, it is a driving motor to reach this envisioned goal.
The general character of this definition has given rise to two separate interpretations of the matter: weaker sustainability and stronger sustainability [10,11]. In weaker sustainability an "anthropocentric" worldview is adopted for the relationship between nature and mankind [10]. The underlying principle is that science and technology will be able to solve any kind of environmental problem. In weaker sustainable development, there is no need for mankind to reduce its consumption behaviour in order to reduce its demands from nature, as technological advances will solve any problem concerning resource depletion. [10–14] The focus of weaker sustainability thinkers is thus much more oriented towards the pillars of Profit and Planet in order to improve mankind's wellbeing, the People. The idea of stronger sustainability is that the future of mankind is greatly dependent on mankind's attitude towards nature and thus the state of the natural capital, and more importantly the critical natural capital [10,14]. A critical natural capital is non-substitutable, or at least very limitedly, by man-made capital when it comes to its contribution to human well-being [12,13]. For stronger sustainability followers, the demand-side of the consumer society needs to be altered and in fact they see 'sustainable development' as a contradictio in terminis [10]. They believe development will increase the consumption rate, which is not sustainable. Stronger sustainability is primarily focussed on the People pillar of sustainability and emphasises the necessity of a complete change in our consumer behaviour, advocating a return to a small-scale economy in order to reduce our environmental footprint.
Weaker and stronger sustainability can be seen as opposites, two extremes. Each side is right and wrong at the same time and thus there is also moderate sustainability combining elements of both weaker and stronger approaches [10,14]. Moderate sustainability focusses on technological advances to solve environmental problems (weaker sustainability) whilst at the same time focussing on the reduction of the demand from nature through cultural change as well (stronger sustainability).

2.2. Circular economy

2.2.1. Definition

The circular economy shifts away from the currently predominant linear economy (shown in Figure 1), in which there is a high demand from nature for resources, whilst the end-products are merely disposed in the end-of-life stage.

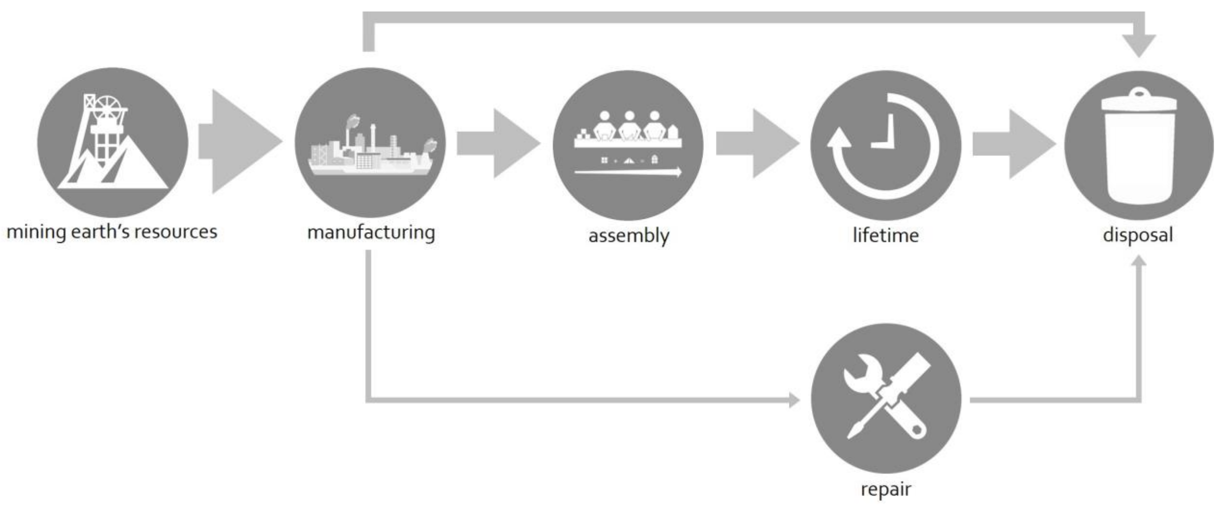

Figure 1: Representation of the material-flow in the linear economy. The arrow sizes represent a weighting for the amount of material in the concerning flow.

Primarily, the circular economy was brought up as a solution for the depletion of resources [15]. In general, "the 3R framework[, Reduce, Reuse, Recycle,] is at the core of the 2008 Circular Economy Promotion Law of the People's Republic of China [whereas] the core of the 2008 European Union Waste Framework Directive [is a 4R framework] introducing 'Recover' as the fourth R." [16] Building further on the 4R and 3R framework, Reike et al. searched for all the R's that are used in literature to define the CE. They found a total of 38 different R's. [17] However, when looking more closely, one can conclude that they are all embedded in the 4 R's defined by the European Union (EU): Reuse, Reduce, Recycle and Recover. For example, repair and refurbish can be categorised under Reuse.

According to the EMF, ideally only bio-based, renewable materials are used and the use of hazardous materials and products is avoided. If a material is not renewable, the end-product's life-cycle should be closed through a longer use-period of the end-product and through maximising the recycling rate of every material, either in the same production cycle or an external one. All these should result in a reduction, and ideally an annihilation, of the resource demand from nature. [18]

The European Commission states that "in a circular economy, the value of products and materials is maintained for as long as possible. Waste and resource use are minimised, and when a product reaches the end of its life, it is used again to create further value." [19] This definition is less elaborate than the EMF's and is in fact embedded in the EMF's definition.

Circle Economy on its turn has mapped 7 key elements which define the circular economy: "prioritise regenerative resources, preserve and extend what is already made, use waste as a resource, rethink the business model, design for the future, incorporate digital technology, collaborate to create joint value". [20] These 7 key elements elaborate on the EMF's definition, adding technology and new business models. However, in all these common definitions the 3R or 4R framework is never referred to. Kirchherr et al. made a more elaborate investigation of 114 different definitions of CE and found that different authors often focus on different combinations of the R's and that many authors entirely neglect the social aspects of sustainability within the CE paradigm. From this investigation, they formed a new, more complete definition of CE which the authors of this study retain entirely [with some minor additions]: "A circular economy describes an economic system that is based on [technological advances and new] business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials [and energy] in production/distribution and consumption processes [in order to keep products at their highest possible value], thus operating at the micro-level (products, companies, consumers), meso-level (eco-industrial parks) and macro-level (city, region, nation and beyond), 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." [16] Apart from materials, also energy should be recovered whenever possible, and the choice between Reuse, Recycle and Recover should always be based on the value retention of the product.

2.2.2.General material flows

The general material flows in a circular economy are represented in Figure 2 and Figure 3. It was chosen to differentiate two systems: one general system (Figure 2), applicable to most products, and one system for bio-based products (Figure 3). The idea of these two diagrams is that any material in a circular economy can be traced in one of these diagrams. It is important to note that these material flows do not consider any waste disposal, which is the ideal situation that the circular economy strives towards.

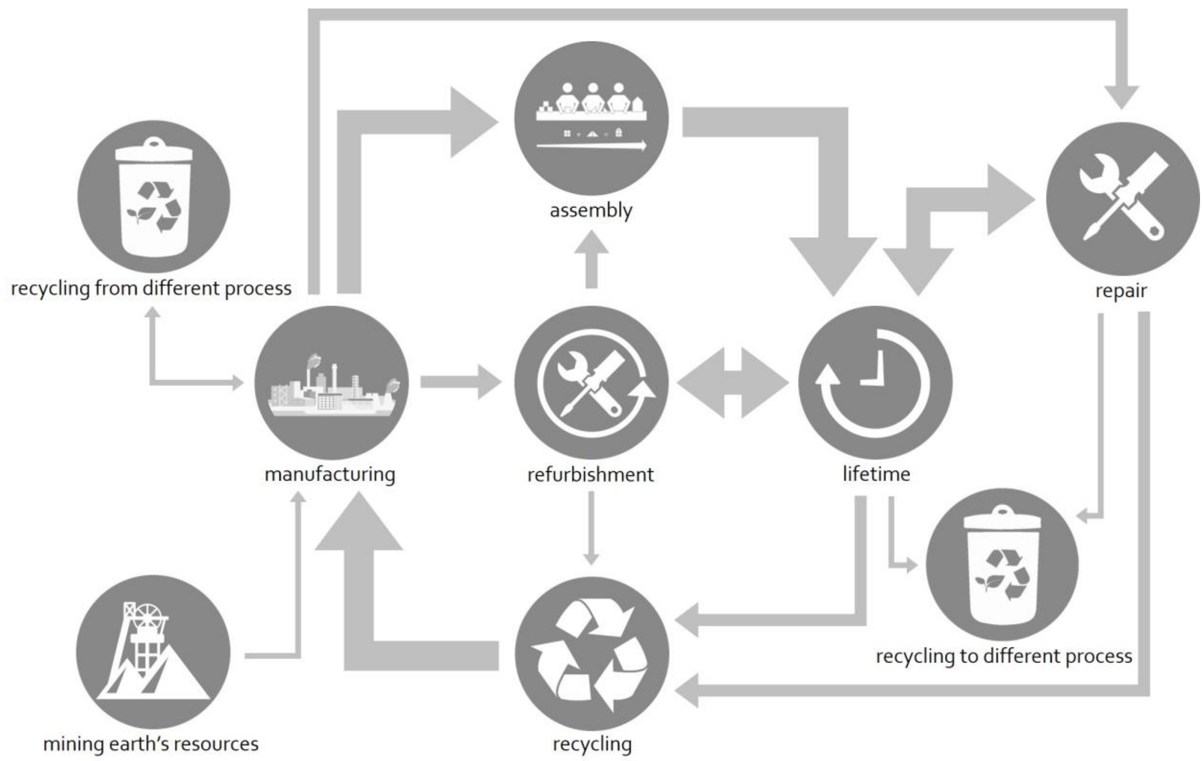

Figure 2: Representation of the material flow in the circular economy. The arrow sizes represent a weighting for the amount of material in the concerning flow as well as for the preferred direction of the material flow.

The general system represents the typical idea behind the circular economy. The initial phase is resource mining, which can be recycled material from the same or another process, or there may be a demand from nature which should always be minimised and ideally non-existent. Subsequently, there is a manufacturing and assembly phase, followed by the service life of the finished product. This product may be repaired and refurbished to prolong its usability and to keep it at its highest value as long as possible. Alternatively, it can be reused in a lower value application. Eventually, in the actual end-of-life phase, when the product cannot be reused anymore, it is disassembled and its base-components are recycled either in the same or in another process. This last step brings us right back to the initial phase, which closes the cycle. Important to note here is that major technological advances will be necessary in order to make this feasible.

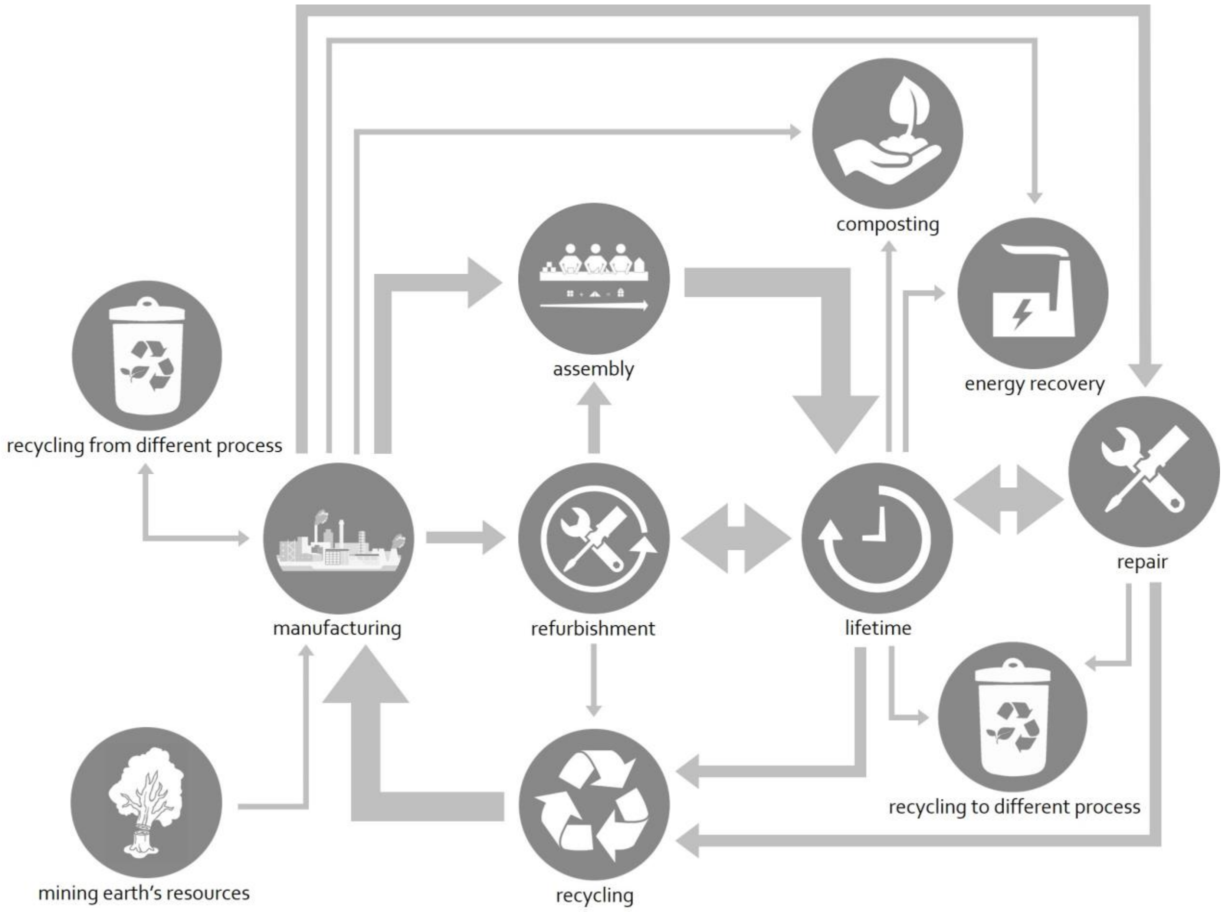

Figure 3: Representation of the material-flow in the bio-based circular economy. The arrow sizes represent a weighting for the amount of material in the concerning flow as well as for the preferred direction of the material flow.

The cycle of bio-based products is similar, but there are some important differences, because the resources for bio-based products are renewable. The initial phase consists again of resource mining, either from recycled material from the same or another process, or from a natural, renewable resource. Subsequently, there is the manufacturing process which is followed by the service life of the product. If possible, the product should again be repaired and refurbished to extend its lifetime, or recycled in a lower value application (cascade system). When it comes to the end-of-life treatment, there are different possibilities. Sometimes, the generated waste material can be recycled in the same or another process. Other materials allow for them to be composted and turned into e.g. fertiliser for agricultural use. Alternatively, the embedded energy can be recovered through incineration or in a biomass power plant. The latter may seem more linear than circular, but here the circularity lies in the renewable character of the material source and recovering the embedded energy in the end-of-life stage. However, energy recovery through incineration or in biomass power plants is a very low efficient process.

2.2.3.Technical solutions

In order to successfully close material loops, as discussed above, the way that a product is designed becomes an important factor in making this effectively possible. Hence the design approaches Design for Adaptability (DfA) [21–23] and Design for Disassembly (DfD) [24–26] have gained increasing importance. The general definition of DfA, also retained here, is that an adaptable product can be modified by the users to fit their ever-changing needs, demands and conditions [21–23]. This can be approached mechanically [22], but also, in part through DfD [21], with the latter illustrating a clear overlap between both DfA and DfD approaches. The DfD approach is oriented towards lifetime extension, through easy repair/replacement of components due to the disassemblability of the product, and towards easy recycling of the different product components [24–26]. DfA and DfD are thus enablers for the 3 R's Reuse, Reduce and Recycle (to a lesser extent for DfA). Reuse because DfA and DfD make it easier for products to be repaired, refurbished and modified in order to keep them in use for as long as possible. Reduce because a longer lifetime means less consumption. Additionally, the complete product does not need to be discarded when dysfunctional, only the broken parts need to be replaced, especially for DfD. When the product is entirely in the end-of-life phase, DfD makes that the different materials can be easily separated for Recycling.

2.2.4. User behaviour and ownership

Apart from the, relatively easily controllable, product design, it is important to acknowledge that the circular economy's success is also greatly dependent on the, less easily controllable, user's behaviour. The circular economy's success requires a shift in mind-set of both consumers and producers and how they interact with each other [27,28]. However, the users are mostly unaware of the environmental burden of their consumption behaviour and do not take responsibility when it comes to changing it [27,29,30]. This uncertainty of user behaviour emphasises the need to reconsider the concept of ownership in the circular economy [27,31]. Should the user be the owner of the end-product or should the manufacturer or a service provider be the owner? The latter means that the product is provided to the end user as a service. It also means that the product's life-cycle, and most importantly the end-of-life phase, can be controlled much better [27]. Additionally, this makes for an incentive for the manufacturer for more intelligent product-design, i.e. DfA and DfD, and to deliver higher quality products. [29,30,32]

All the above requires a complete change of mind-set, both on the side of the consumer and on the side of the manufacturer. Social behaviour and culture are the determining factors here, but equally politics, as legislation can be a driving motor for cultural change.

2.3. Sustainability vs. circular economy

One can conclude that the CE focusses on technological advances in order to solve the economic and environmental problem of finite resources by closing the product and production cycle [15]. Therefore, the CE is often associated and assimilated to the weaker sustainability approach [33,34]. However, the CE also acknowledges the fact that user behaviour, culture, will need to change as well in order to truly be able to close the cycle, reduce consumption and thus reduce and even eliminate non-renewable resource mining. The new business models of product service systems will help in that. This need for a cultural change is typical for the stronger sustainability approach.

As both aspects, technological advances and behaviour change, are combined, not in a fundamental but in a pragmatic way, it becomes clear that the CE paradigm should in fact be classified under 'moderate sustainability'.

For the circular economy, the four pillars of sustainability are important as well. Profit is obvious as it is an economic system and Planet exists in countering resource depletion. People becomes apparent in the user behaviour that needs to be altered in order to effectively reach a CE and Politics is the driving motor for change. Schroeder et al. made an in depth investigation to what extent the CE paradigm helps in achieving the 17 Sustainable Development Goals (SDGs), which are dealing with 169 targets, defined by the United Nations. They found that CE practices directly and indirectly help in achieving 49 targets and that there is no link with 35 targets. For the remaining targets there is a potential to create synergies. [35]

Where sustainability is the goal, the CE is a means to this end. It is a road map that should lead us to a more sustainable economy. Yet, the CE will not be sufficient in itself.

3. Translating the Circular Economy to bridge construction

The special focus in this literature review is bridge construction. As discussed in the introduction, now is the time to undertake action to establish and implement circular bridge construction principles. However, to the authors' knowledge, no studies on this more specialised consideration of the circular construction principles for bridge building were published yet. Therefore, the application of the circular economy in the building construction sector is investigated in order to identify research opportunities for circular bridge construction.

Pomponi and Moncaster consider the three levels of the circular economy within the built environment. They explain that Cradle-to-Cradle represents the micro-scale, the scale of the material/building component itself. [36] The Cradle-to-Cradle philosophy reflects the idea of endless recyclability of resources [37]. The meso-scale is represented by the entire building or construction in general, an assembly of components. The highest level, the macro-scale, considers eco-cities -fully self-sustaining, carbon neutral cities. [36] Note that the macro-scale is in fact again the general circular economy, rather than its application to the building sector.

The following sections maintain a similar structure to the previous part of this paper. First the technical solutions are discussed in terms of circular construction, followed by user behaviour and ownership. Also some insights on biobased construction are shared. Additionally, the question how to actually measure circularity rose. Therefore, eventually circularity assessment tools are discussed and compared to their sustainability counterparts.

In each section, the relevance for bridge construction of all the acquired insights is assessed and future research opportunities to pave the road towards circular bridge construction are identified.

3.1. Technical solutions

Until now, a lot of the research done in the field of circular construction is focussed on recycling [34,38–43]. Hence, the primary focus seems to be on Pomponi and Moncaster's micro-scale, the scale of the material and thus the cradle-to-cradle principle [36]. This may be a consequence of the fact that the European Commission found that as much as 25-30% of all waste generated in the EU is construction and demolition waste (CDW). They found that it comprises numerous materials of which many are reusable and recyclable. This high potential for reusing and recycling, as well as the high resource value of some of the components in CDW have led to the identification of CDW as a priority waste stream by the European Union. [44] However, until today this high potential for recycling and reuse has still not been addressed. Only in the Dutch construction sector over 95% of the CDW is being recycled [45]. When looking more closely, however, the majority of the Dutch CDW is recycled as foundation in road construction and thus downcycled [17]. This is not the value retention as propagated in the CE paradigm. Certainly not if one considers that with the current mining practices and consumption rate, earth's resources of e.g. zinc and lead will have depleted by 2025 and will be entirely unavailable by 2030 [46].

When considering concrete on the micro-scale, as concrete is also very often used in bridge construction, one will find that concrete recycling is currently being investigated, but also that this is in general not a problem with a straight-forward solution and it may not even lead to an improved sustainability at all [47]. Reuse of concrete construction elements could be considered as well. However, nowadays concrete elements are often connected through plastic joints, making disassembly for reuse elsewhere practically impossible. Right from the conceptual design stage this should be taken into account through the design of mechanical joints, also for concrete construction elements [48]. This is where the approaches of DfD and DfA come into play, acting as an important symbiosis between the micro- and meso-scale. When applied to construction, the DfD approach is also referred to as Design for Deconstruction (also DfD) [49–52]. In DfD, none of the building components are permanently fixed. Instead, the use of reversible connections is advocated. When done correctly, this eases the disassembly and replacement of a particular element in the end-of-life stage. Additionally, it facilitates the dismantlement of the complete building in the end-of-life phase so the recovered building components can be directly reused in new buildings elsewhere, in order to increase their lifetime at their highest value. If this is deemed impossible, because of e.g. damage, they can be reused in a lower value application or recycled as raw material. [49–53] Often, screws are brought forward as the preferred mechanical connection, but they are far from ideal as they might get concealed when painted over [50]. As such, this should be thought through more carefully. When considering concrete structural elements, screws are in any case not applicable. Additionally, concrete structural elements are usually designed for a specific application and it is impossible to see from the outside how they are reinforced, which makes reuse of these components not that straight-forward [49]. In general, a complete knowledge on the building over its complete life span, including all the changes that it has undergone, which may have affected the building components, is necessary to facilitate this intelligent resource reuse [53]. A promising tool for effectuating the knowledge transfer of building components and materials in general is the materials passport. Of primary importance here is that the materials passport contains all relevant information that defines the value for recovery, and that these data are shared in a centralised platform, accessible by all stakeholders [54]. In an interesting addition, certain studies focus on documenting current building material stocks and predicting material flows [55–57], both on city-scale, the macro-scale. It is argued that the potential of directly reusing building components always needs to be considered prior to recycling [56]. Note that DfD, DfA and materials passports will play a facilitating and effectuating role in this.

The social benefits of DfD are high, as the increased labour-intensity of deconstruction brings opportunities for creating jobs for unskilled workers [52]. On the other hand, the culturally embedded negative perception of reused materials being of inferior quality poses a major challenge [52], not only for DfD, but for the CE in general. The latter problem will not be as apparent in DfA. In the DfA approach, a building is designed to be adaptable in order to prolong the building's lifetime. The idea is that a building, serving its present purpose, can easily be adapted to the changing requirements, conditions and demands of future generations, whereas otherwise it would be completely or partially demolished. [58–62] In this way, a lot of energy and materials can be saved [58]. In DfA, it is thus important that architects learn and understand how buildings tend to change and evolve over time in order to improve their designs to meet the DfA principles [60]. The Reuse aspect in DfA is practically entirely focussed on the building in its entirety, on prolonging its lifetime through making it adaptable and consequently increasing its multifunctionality. The end-of-life phase of the building, or the building components that allow it to be adaptable, is not exactly considered. Often in this context, the shearing layers defined by Stewart Brand, are referred to. Brand defined the shearing layers so as to establish a reference base for distinguishing building components that age at different rates and which are replaced more or less frequently due to changing boundary conditions [63]. The adaptation of the building over time and replacement of certain components is embedded in this system, it discusses a certain volatility that is inherent to the building. However, this system does not propose any post-use treatment for elements that need to be removed due to this volatility, it does not discuss the end-of-life-phase.

Any partial combination of DfD and DfA is possible, coupling disassemblability to partial adaptability [50,51] and vice versa [61]. In these, one can point out the special variety which fully combines both DfD and DfA. In this variety, the building components can easily be disassembled to be replaced whenever necessary, and the layout of such a building can easily be adjusted/adapted whenever new requirements rise. Also extensions to the concerning building will be possible through (partial) deconstruction and adaptations without any material loss. Thus, this combined design approach synthesises all advantages of both DfD and DfA. The current scientific discourse on design methodologies does not deal with this variety very extensively, nor has a specific name been given to it yet. Until now in literature this design methodology is referred to simply as Design for Adaptability and Deconstruction (DfAD) [64,65].

When projecting these circular design principles back onto bridges, it is clear that implementing the pure DfA principle will not be that straight-forward. The primary use of a bridge is to be a connection between two points, creating a crossing that would otherwise be difficult or even impossible. This use will only very rarely change over time. In this sense, DfD is more relevant as a design approach and is in fact already partially implemented. As an example, one can think of steel truss bridges. The implementation of DfAD in bridge construction will be challenging, but definitely relevant, considering the every-increasing traffic intensity. One can in any case agree that these design approaches will be of interest for bridge construction in order to facilitate and improve their circularity. Firstly, it will be important to consider and redefine Brand's shearing layers in order to apply them on bridges. Subsequently, specific circular design strategies for bridges should be developed, which can be based on DfD, DfA and DfAD but adjusted in order to meet the specific needs and requirements of bridges. Additionally, a certain degree of standardisation will be necessary to truly effectuate these design strategies. Further research will need to focus on a standardisation scheme on the meso-scale that sets certain boundaries, but which still allows enough architectural freedom. The latter is important, because the impact of bridges on the environment is very high. Bridges can both cause the revival as well as the destruction of a neighbourhood. Through their architecture, the specific environment in which the bridge is to be placed, needs to be taken into account and, while standardisation is highly needed to effectuate the circular construction of bridges, it should not be an architectural obstruction. It has also been pointed out that when it comes to CE in construction, there is no industrywide CE awareness [66,67]. Interestingly, it seems that designers are, along with clients and subcontractors, the most important parties lacking this CE awareness, while main contractors and manufacturers are aware of the CE principles [66]. It will be important to mobilise designers, whom lie at the basis of projects being unfolded, to take on their important role and responsibility as drivers for change. Up until today, only very few buildings have been designed taking into account the end-of-life treatment of the building, e.g. through DfD and DfA [52]. In fact, there seems to be little interest in general to adopt the CE across the construction industry and adapt the construction supply chain accordingly [66,67]. This indicates that the construction sector somehow seems to be opposed to the changes that need to be made to become really sustainable. This is where the fourth pillar of sustainability, Politics, should take the lead through legislation and well-oriented incentives.

3.2. User behaviour and ownership

As discussed, CDW has been identified by the European Union as a top priority. Following this, CDW best management practices are being investigated. Jiménez-Rivero and García-Navarro argue that for end-of-life gypsum there are three fundamental best practices: on-site segregation, clear waste acceptance criteria and clear recycled gypsum quality criteria [40]. These best practices are rather situated on the meso-scale as they become important when a building is partly or entirely in the end-of-life phase. Additionally, the same best practices are important and necessary for any recyclable material. Unfortunately, these CDW best management practices have still not been implemented in construction companies and the construction industry in general, mainly due to legislative and economic barriers [34,38]. Of great importance here as well is the role of the users, e.g. the house-owners, who may start removing gypsum -or any other recyclable material- carelessly from their houses. Sonego et al. explain that the adequate end-of life treatment of a product depends greatly on the consumer giving the correct destination to the discarded product. If the consumer fails to return the discarded product to the right place, some initial manufacturing strategies may also fail. [68] Again here, a cultural change, a complete change of mind-set towards full segregation of CDW will be necessary. The question is whether the user should carry this responsibility. This problem does not pose itself in the case where the building is offered to the client/user as a service of e.g. habitation space or work space. An interesting example of this is the Brummen townhall, which was built in 2013 in this philosophy by the CE100 member BAM Utiliteitsbouw. The Brummen municipality had ordered a building with office space for a duration of 20 years, so as to take into account their changing needs and requirements. The agreed upon contract keeps BAM Utiliteitsbouw as the owner of the building, thus also in charge of the maintenance, and the Brummen municipality rents the building from them. As the new building has a historical building as foundation, it needs to be disassembled after this 20 year timelapse. Hence, it was designed in the DfD principle with high quality materials to make direct reuse possible in the end-of-life phase. The complete building is documented with material passports in order to effectuate this. [69]

In an interesting addition, especially applicable to buildings, Heeren and Hellweg found that closing loops alone will not lead to meaningful reductions of environmental impacts, at least not compared to the reductions that can be achieved by reducing a building's energy consumption during its use phase [55]. Certainly, as the circular economy also strives towards service life extension of a building, the latter remains very important. Additionally, they state that end-of-life material recycling, e.g. urban mining, and wood construction are promising, but it will take a considerable amount of time before the effects will finally show [55].

Considering this discourse for bridges, it is important to note that usually the government is the owner of the bridge and thus it is in fact always offered to the public as a service. The bridge fulfills the public service of connecting places to each other and the user pays for this service through taxes. Hence, the role of the government to set the example becomes very clear. A government ordering a new bridge, will thus need to take on its responsibility in taking into account the DfD/DfAD principle as well as CDW best management practices right from the start. In this, it is worthwhile mentioning the concept of Green Public Procurement (GPP) which was first introduced by the EU already in 2005 [70], but only recently has gained increasing attention and importance. The idea of GPP is that Europe's public authorities as major consumers are encouraged to "procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured" [71]. Hence, GPP is the EU's encouragement for governments to indeed take on their responsibility in society to set the example.

Additionally, it might be interesting to elaborate the service that a bridge fulfills more, i.e. add services, as the bridge has got space on top and underneath. One can in this sense think of medieval bridges which were e.g. designed to be a complete shopping street. Thus, reconsidering the bridge as a service may create an additional value for society and the environment, as space will be used more efficiently. Note that the latter is a responsibility of both the government as owner and the architect as designer.

3.3. Bio-based construction

Since the development of wood construction types like Cross-Laminated Timber (CLT) and Laminated Veneered Lumber (LVL), the interest in multi-storey wood-frame construction has increased [72]. The more general wood industry with its cascading system, and the broader bio-based economy, are often

cited as an example for the circular economy. Firstly, however, it is important to note that the bio-economy can only be environmentally beneficial if their bio-based resources are managed sustainably [15]. Additionally, the wood products should have “a design life span that at least matches timber rotation periods”, i.e. over 30 years or even over 100 years [73]. Otherwise, a sustainable wood industry is impossible due to a mismatch between demand (too high) and supply (too low). Hence, the cascading system was established to prolong the life span of wood products through reusing or recycling them at their highest possible value [73,74]. Energy recovery through incineration is only preferential in the cascade if recycling is not possible. After all, the efficiency of the energy recovery in a combined heat and power biomass plant is typically only 29% -22% power and 7% heat [73,75,76].
Often wood is treated to alter its properties, mainly to improve moisture and fire resistance in order to prolong its life span, or to improve its mechanical performance, e.g. CLT and LVL. It is not that straight-forward for these treated wood types to follow the cascade system. Companies are often reluctant to use these wood types, or even waste wood in general, due to the possible presence of chemical components, which could damage their reputation [77]. Additionally, incineration of this “contaminated” wood for energy recovery can only take place in “special stations with appropriate combustion facilities” [73]. On a critical note, energy recovery from wood waste only requires the wood waste to be collected and transported to the biomass heat and power plant, which is much easier than reusing and recycling it, as this requires additional sorting, cleaning, chemical and mechanical treatments in order to stay in the consumption cycle [77]. This again points out the necessity of a major change in socio-cultural mind-set and behaviour of both the industry and the consumer.

Considering the above, it becomes clear that this will require special attention in the case of bridges. A bridge is an outdoor structure with very specific mechanical requirements. If wood is used without any treatment to improve its performance, it will either deteriorate very quickly or it will require continuous maintenance, mainly painting it for protection against the elements. On the other hand, if the wood is treated, the critical notes mentioned above, apply.

3.4. Sustainability and circularity assessment

The sustainability of bridges is extensively researched from different angles. Some authors claim that arch bridges are the preferred most sustainable bridge typology both for their historical and aesthetical value [78], and for their historically proven durability [79]. In general, it was found that the durability of bridges, and thus the extension of their useful lifetime, is brought up as an important aspect for relatively reducing CO_2 emissions -considering their complete life time- and thus increasing the bridges' sustainability [79–84].
The most common tools applied to evaluate the sustainability of a product, also in the construction industry, are Life Cycle Assessment (LCA) [76,85,94,86–93] and Life cycle Costing Analysis (LCCA) [84,95,96]. A LCA evaluates the environmental hazard that a certain product causes, while a LCCA will evaluate the economic/financial burden that it generates, often focussing on the durability of the product. Both consider the complete life cycle of the concerning product. Sometimes both are applied within the same study [83,97,98], so as to perform a more holistic investigation. Note that the People pillar, the social aspects of sustainability, are not investigated with LCA and LCCA.
There is a plethora on studies applying LCA for environmental evaluation. However, even though LCA is widely recognised as a comprehensive method for measuring a subject's environmental profile, it must be acknowledged that the methodology needs to be simplified in order for it to be truly practically applicable during the design/development stage [99–102]. This could be done e.g. through embedding it in BIM-software [103]. Some studies also incorporate LCA and LCCA principles for the development of new optimisation and decision-making methodologies for the design of different

structural members [80,104–109]. These optimisation and decision-making tools will then find the most optimal parameters -resulting in the lowest CO_2 emissions and economic costs- for a certain type of structural member (e.g. for the concrete I-beam in [104]), but it does not mean this type of structural member will thus be a sustainable solution. Indeed, a LCA or an optimisation tool with embedded LCA principles only indicates whether one subject is more sustainable relative to another subject fulfilling the exact same goal and scope [91]. This does not directly prove the subject's sustainability. Therefore, it is necessary that for a given subject, e.g. housing, certain benchmarks, reference values, are defined, indicating from which point onwards the subject is sustainable [110].
Additionally, even though in a LCA and LCCA the complete life cycle of a product is considered in principle, it was found that in many studies the end-of-life phase is not or inconsistently taken into account [111,112]. Often a certain recycling rate for steel is considered without taking into account the consequent loss of the embedded energy[1] in the steel structural member when it is merely used as raw material for new steel structural members, nor taking into account the energy requirements to melt and remanufacture them (e.g. [113]). Note that the energy loss in this case is double, but it is still a better option than increasing the demand from nature to manufacture new steel structural members. Also, the environmental impact of concrete rubble being used as landfill is not considered (e.g. [88,89]), nor is the high loss of embedded energy when concrete rubble is 'reused' as road foundation (e.g. [90,94]). Especially in the latter case this gives a false impression of concrete being sustainable, while the concrete industry is in fact responsible for between 5 and 8% of all man-made CO_2 emissions globally (depending on the source [114–118]). It must also be noted that the application of end-of-life concrete as landfill will have an environmental impact on the longer term as well. Concrete does not contain any nutrients, so the fertility of the soil will be affected by it [119].

When considering the CE, it must be acknowledged that a circular product or building is not necessarily a sustainable product or building [55,120]. Circularity in the construction industry may solve the material side of the sustainability problem, but it does not in itself solve the environmental impact of a building's lifetime. Certainly, as the CE also strives towards lifetime extension of a building, the latter remains very important. To investigate the sustainability of materials and building elements which are designed for circularity, a LCA can be performed [47,120]. In this way, Buyle et al. conclude for a set of inner wall partitioning systems that, when a refurbishment cycle is considered every 15 years over a certain, assumed life time of the materials/components, the circular building elements do outperform the current, conventional alternatives in terms of environmental footprint [120]. This is an interesting conclusion, but it is not a measurement of the inner wall partitioning systems' circularity.
Van der Voet et al. investigated the environmental impact of the future demand for several metals and found that closing cycles seems to be effective for reducing greenhouse gas emissions, but reducing the demand will be necessary as well [121]. The latter can for example be achieved through direct reuse instead of recycling, keeping the product at its highest possible value. Thus, when one actually wants to measure a product's circularity, LCA and LCCA are not the best evaluation tools, as they do not assess the product's reuse performance in the same or a lower value application, neither do they evaluate the product's recycling performance. Instead of a Life Cycle Assessment and a Life Cycle Costing Analysis, it might be better to perform a "Multi-Cycle Assessment" and a "Multi-Cycle Costing Analysis" [45]. Some studies focus on the application of the CE principles by certain construction material manufacturers. Typically, these studies discuss the recycling practices for resource waste reduction during the manufacturing process [41]. Yet, they do not really measure circularity. Some actual circularity indicators have already been developed, but none of them are without controversies,

[1] Embedded energy: in this context, this refers to the energy that was needed to manufacture the product, which is also an important part of the value of the product.

as some of them are applicable to the micro-scale but not to the macro-scale and vice versa [122]. The Material Circularity Indicator of the EMF can be applied both on product level and on company level [123]. Both applications are situated in the micro-scale. In China, several indicators for urban circularity evaluation have been developed, but none of them seems to be comprehensive enough to be used universally throughout China [124]. These are all situated in the macro-scale of the eco-city. Often the three 3's Reduce, Reuse and Recycle are evaluated [122]. The fourth R of Recover, defined by the EU, is not considered. Also, the material value is rarely considered and the main focus is on quantity, rather than on efficient (re)use [122]. Looking at the construction sector, we find that certification schemes for the environmental performance of buildings, such as BREEAM and LEED, apply some LCA principles and can thus lead to more sustainable solutions, but also they do not rate the circularity of buildings yet [49,125]. They do appoint extra credits for "material salvation and waste diversion" [52], but this does not cover the full scope of the CE. It is possible to find circularity indicators for construction companies (e.g. [126]), but these are very similar to the Material Circularity Indicator of the EMF and focus thus on the micro-scale. The authors did not find any circularity indicators that evaluate the meso-scale, the construction, the building. Yet, there seems to be a demand for assessment tools, as Akanbi et al. have made a first attempt to integrate CE principles for primary building structures in BIM through their Whole Life Performance Estimator. Interestingly, they also take into account a time-function for the deterioration of materials, even though only steel, wood and concrete were modelled. Additionally, they only focus on Reuse and Recycle. [42]

Alas, the construction industry is critical for the CE and thus circular construction indicators on the meso-scale are not just desirable, they are necessary. Possibly, meso-scale circularity indicators have not been developed yet, because they require to be as detailed as micro-scale indicators, yet need to take into account the previously discussed design principles and associated standardisation schemes as well. The general philosophy of a meso-scale circularity indicator for buildings will be equal, or at least very similar, to the one for bridges. Yet, bridges are very different kinds of constructions as opposed to buildings, and thus they will probably require their own dedicated set of parameters and benchmarks. In any case, the 4 R's of the CE -Reduce, Reuse, Recycle, Recover- will be a good starting point to evaluate these meso-scale circularity indicators when they are being developed.

4. Conclusion

In this paper, we presented a study that is bifold. It was found that sustainability and CE somehow remain vague and undetermined concepts, seemingly free to use randomly. Also, how they relate to each other remained unclear or not addressed at all. Therefore, in a first section, the general philosophies of the sustainability and CE paradigms were discussed and defined. The general and bio-based material cycles were discussed and additionally, the CE was elaborated further in terms of technical solutions and user behaviour. It was concluded that sustainability is the goal and that the CE is a means to an end, in this case a sustainable economy. Yet, stand-alone CE will not be sufficient in achieving this.

In the second section, an in-depth literature review was performed to find out to what extent the CE principles have already been investigated for the specific case of the construction industry, and more specific in bridge construction. Circularity in the construction sector is being discussed extensively in the current scientific discourse, though nothing relating to bridge construction was found. Therefore, this review discusses what has been and is being done in terms of circular construction, and the relevance for bridge construction of all the acquired insights is assessed in order to identify future research opportunities to reach circular bridge construction. The findings are summarised in Table 1 as a set of action points necessary to truly reach a circular bridge construction sector.

Table 1: Summary of the action plan to achieve circular bridge construction

Aspect	Circular bridge construction – action point	Responsible
Technical solutions	Redefine Brand's shearing layers of longevity for bridges	Designers
	Adjust the DfA, DfD and DfAD principles to the specific needs and requirements of bridges	Designers
		Manufacturers
	Develop a complimentary standardisation scheme without compromising on architectural freedom	Designers
		Manufacturers
		Governments
User behaviour and ownership	Local governments as bridge owners need to be incentivised to implement DfA, DfD and DfAD strategies as well as CDW best management practices	Governments
	Elaborate the service that a bridge fulfils, i.e. add services on top and underneath	Designers
		Governments
Bio-based construction	Treated wood is necessary but is more difficult to fit into the cascade system	Manufacturers
		Governments
Circularity assessment	Bridges are situated on the meso-scale, so meso-scale circularity indicators need to be developed	Designers
		Governments
	Dedicated sets of parameters and benchmarks for bridges are required	Designers
		Governments

Firstly, the technical solutions, i.e. design principles, are considered. DfD, DfA and DfAD are already being researched in the building sector. These design approaches are of interest to bridge construction as well and can be used as a basis for the development of specific, circular design strategies for bridges. Additionally, a certain degree of standardisation will be necessary to effectuate these circular design strategies. Further research will need to focus on a standardisation scheme on the meso-scale of the building, or the construction in general, that sets certain boundaries, but which still allows enough architectural freedom.

Secondly, user behaviour and ownership are discussed. CDW best management practices require the user to correctly segregate CDW and to give it the correct destination. The responsibility to do this does not necessarily have to lie with the user. A building can also be offered to the client as a service. This creates the incentive for the service-provider to use high quality materials and to implement more intelligent design strategies, such as DfD. When considering bridges, one can argue that they are in fact already offered to the public as a service. The bridge owner is usually the government whom thus carries the responsibility to implement circular design principles and CDW best management practices. It was found that the EU's concept of GPP forms a good basis for governments to set the example. Additionally, elaborating more on the service that bridges fulfill by letting bridges fulfill additional services may create an additional value for society and the environment. It is important to note that here the responsibility lies both with the government as owner and the architect as designer.

Also the bio-economy is explored in construction, mostly in terms of wood construction. However, wood is often chemically treated to improve its durability and mechanical properties, and exactly this seems to be a draw-back when it comes to its reusability and recyclability. As bridges are, usually, outdoor structures, this problem also here requires special attention.
In general, the micro-scale and macro-scale have gained a lot of attention within the CE discourse. Recycling possibilities for materials, the micro-scale, have been thoroughly researched and predictions for material flows on city scale, the macro-scale, have been mapped. Yet, the meso-scale, the scale of the construction in general, seems to be discussed and investigated very limitedly.
To quantify circularity, several circularity indicators have already been developed. Most of these are focussed on product and company level, and thus again the micro-scale. Other indicators, mostly developed in China, aim to measure circularity on the city-scale, the macro-scale. It is important to realise that the micro-scale circularity indicators cannot be applied to measure macro-scale circularity, and vice versa. Additionally, again, the meso-scale seems to be neglected, even though the meso-scale is exactly what defines the construction industry, the scale of the building or the construction in general. Alas, the construction industry is critical for the CE and thus Circular Construction Indicators on the meso-scale are not just desirable, they are necessary. Possibly, meso-scale circularity indicators have not been developed yet, because they require to be as detailed as micro-scale indicators, yet need to take into account the previously discussed design principles and associated standardisation schemes as well. Additionally, as bridges are very different kinds of constructions as opposed to buildings, they will probably require their own dedicated set of parameters and benchmarks. In any case, the 4 R's of the CE -Reduce, Reuse, Recycle, Recover- will be a good starting point to evaluate these meso-scale circularity indicators when they are being developed.

In this paper the application of the CE in the construction sector is investigated and the relevant aspects for bridge construction are identified. Following this investigation, the authors will continue researching the identified research gaps. The solutions that will be found, will contribute to changing the construction sector's mind-set, which is an essential part in order to truly move towards circular bridge constructions.

Bibliography

[1] Commission on Environment and Development. Report of the World Commission on Environment and Development: Our Common Future. 1987.

[2] Ellen MacArthur Foundation. Milestones 2017. https://www.ellenmacarthurfoundation.org/our-story/milestones (accessed February 5, 2019).

[3] Shuck-Britson, Snyder & Associates. Structural evaluation report. 2015.

[4] City of Ottawa. Harmer Avenue Pedestrian Bridge Replacement 2019. https://ottawa.ca/en/city-hall/public-engagement/projects/harmer-avenue-pedestrian-bridge-replacement#public-information-boards-march-27-2018 (accessed March 15, 2019).

[5] CTV News Calgary. City Inspections Determine Two Pedestrian Bridges Need to Be Replaced 2018.

[6] CEN. Eurocode: Basis of Structural Design. 2002.

[7] CEN. Eurocode 2: Design of Concrete Structures - Part 1-1: General Rules and Rules for Buildings. 2004.

[8] James P. Urban Sustainability in Theory and Practice: Circles of Sustainability. Routledge; 2015.

[9] Owen A, Kruijsen J. The Transition to Future Energy. In: Letcher TM, editor. Futur. Energy - Improv. Sustain. Clean Options our Planet. 2nd ed., 2014, p. 667–77.

[10] Williams CC, Millington AC. The diverse and contested meanings of sustainable development. Geogr J 2004;170:99–104.

[11] Adams WM. The Future of Sustainability: Re-Thinking Environment and Development in the Twenty-First Century. 2006.

[12] Gutes MC. The Concept of Weak Sustainability. Ecol Econ 1996;17:147–56.

[13] Pelenc J, Ballet J. Strong Sustainability, Critical Natural Capital and the Capability Approach. Ecol Econ 2015;112:36–44.

[14] Oliveira Neto GC de, Pinto LFR, Amorim MPC, Giannetti BF, Almeida CMVB de. A Framework of Actions for Strong Sustainability. J Clean Prod 2018;196:1629–43.

[15] D'Amato D, Veijonaho S, Toppinen A. Towards sustainability? Forest-Based Circular Bioeconomy Business Models in Finnish SMEs. For Policy Econ 2018:1–11.

[16] Kirchherr J, Reike D, Hekkert M. Conceptualizing the Circular Economy: An Analysis of 114 Definitions. Resour Conserv Recycl 2017;127:221–32.

[17] Reike D, Vermeulen WJV, Witjes S. The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. Resour Conserv Recycl 2018;135:246–64.

[18] Ellen MacArthur Foundation. Concept 2017. https://www.ellenmacarthurfoundation.org/circular-economy/concept (accessed February 8, 2019).

[19] European Commission. Circular Economy 2019. https://ec.europa.eu/info/legal-notice (accessed March 21, 2019).

[20] Ramkumar S. Making Sense of the Circular Economy - The 7 Key Elements 2019. https://www.circle-economy.com/the-7-key-elements-of-the-circular-economy (accessed March 21, 2019).

[21] Kissel M, Schrieverhoff P, Lindemann U. Design for Adaptability – Identifying Potential for Improvement on an Architecture Basis. Proc. Nord. Conf. 2012, Aalborg, 2012.

[22] Kasarda ME, Terpenny JP, Inman D, Precoda KR, Jelesko J, Sahin A, et al. Design for adaptability (DFAD)—a new concept for achieving sustainable design. Robot Comput Integr Manuf 2007;23:727–34.

[23] Schrieverhoff P, De Neufville R, Lindemann U. Valuation of product adaptability in architecture design. Proc. Int. Des. Conf. Des., 2014, p. 373–84.

[24] Soh SL, Ong SK, Nee AYC. Design for disassembly for remanufacturing: Methodology and technology. Procedia CIRP, vol. 15, Elsevier B.V.; 2014, p. 407–12.

[25] Takeuchi S, Saitou K. Design for Optimal End-of-Life Scenario Via Product-Embedded Disassembly. Proc. LCE2006, 2006, p. 423–8.

[26] Yoga Mule J. Design for Disassembly Approaches on Product Development Jaykumar Yoga Mule. Int J Sci Eng Res 2012;3:1–5.

[27] Claessen F, Schreurs J. Consumer Behaviour as a Critical Factor. In: Hinssen J, editor. 4'33" Time a Circ. Econ., 2017, p. 91–3.

[28] Piscicelli L, Ludden GDS. The potential of Design for Behaviour Change to foster the transition to a circular economy. DRS 2016 - Des. Res. Soc. 50th Anniv. Conf., 2016, p. 1–16.

[29] Mugge R. Product Design and Consumer Behaviour in a Circular Economy. Sustainability 2018;10.

[30] Wastling T, Charnley F, Moreno M. Design for Circular Behaviour: Considering Users in a Circular Economy. Sustainability 2018;10.

[31] Lofthouse V, Prendeville S. Human-Centred Design of Products And Services for the Circular Economy – A Review Human-Centred Design of Products And Services for the Circular Economy – A Review. Des J 2018;6925.

[32] Antikainen M, Uusitalo T, Kivikytö-Reponen P. Digitalisation as an Enabler of Circular Economy. Procedia CIRP, vol. 73, Elsevier B.V.; 2018, p. 45–9.

[33] Sauvé S, Bernard S, Sloan P. Environmental Sciences , Sustainable Development and Circular Economy: Alternative Concepts for Trans-Disciplinary Research. Environ Dev 2016;17:48–56.

[34] Ghisellini P, Ji X, Liu G, Ulgiati S. Evaluating the Transition towards Cleaner Production in the Construction and Demolition Sector of China: A Review 2018;195:418–34.

[35] Schroeder P, Anggraeni K, Weber U. The Relevance of Circular Economy Practices to the Sustainable Development Goals. J Ind Ecol 2019;23:77–95.

[36] Pomponi F, Moncaster A. Circular economy for the built environment : A research framework. J Clean Prod 2017;143:710–8.

[37] McDonough W, Braungart M. Cradle to Cradle: Remaking the Way We Make Things. New York: North Point Press; 2002.

[38] Huang B, Wang X, Kua H, Geng Y, Bleischwitz R, Ren J. Construction and Demolition Waste Management in China through the 3R Principle. Resour Conserv Recycl 2018;129:36–44.

[39] Gálvez-Martos JL, Styles D, Schoenberger H, Zeschmar-Lahl B. Construction and Demolition Waste Best Management Practice in Europe. Resour Conserv Recycl 2018;136:166–78.

[40] Jiménez-Rivero A, García-Navarro J. Best Practices for the Management of End-of-Life Gypsum in a Circular Economy. J Clean Prod 2018;167:1335–44.

[41] Nußholz J, Milios L. Applying Circular Economy Principles to Building Materials: Front-Running Companies ' Business Model Innovation in the Value Chain for Buildings. SustEcon Conf., 2017.

[42] Akanbi LA, Oyedele LO, Akinade OO, Ajayi AO, Delgado MD, Bilal M, et al. Salvaging Building Materials in a Circular Economy: A BIM-Based Whole-Life Performance Estimator. Resour Conserv Recycl 2018;129:175–86.

[43] Ghisellini P, Ripa M, Ulgiati S. Exploring Environmental and Economic Costs and Benefits of a Circular Economy Approach to the Construction and Demolition Sector. A Literature Review. J Clean Prod 2018;178:618–43.

[44] European Commission. Construction and Demolition Waste (CDW) 2018. http://ec.europa.eu/environment/waste/construction_demolition.htm (accessed March 25, 2019).

[45] Rijkswaterstaat. Circular Economy in the Dutch Construction Sector. 2015.

[46] Circular Flanders. Born in 2010: How much is left for me? 2019.

[47] Zanni S, Simion IM, Gavrilescu M, Bonoli A. Life Cycle Assessment Applied to Circular Designed Construction Materials. 25th CIRP Life Cycle Eng. Conf. Procedia CIRP, vol. 69, Elsevier B.V.; 2018, p. 154–9.

[48] Jensen KG, Sommer J. Building A Circular Future. 3rd ed. 2018.

[49] Webster MD, Costello DT. Designing Structural Systems for Deconstruction: How to extend a new building's useful life and prevent it from going to waste when the end finally comes. Greenbuild Conf., Atlanta: 2005, p. 1–14.

[50] Hood T, Priselac A, Van Gendt S, Atkins D, Melton M, Shell S, et al. Design for Deconstruction. 2005.

[51] Metin B, Aydın İpekçi C. An Approach for Sustainable Buildings: Architectural Deconstruction Design. ARCHDESIGN '15, 2015, p. 519–27.

[52] Cruz Rios F, Chong WK, Grau D. Design for Disassembly and Deconstruction - Challenges and Opportunities. Procedia Eng., Elsevier B.V.; 2015, p. 1296–304.

[53] Guy B, Ciarimboli N, Hendrickson K. Design for Disassembly in the Built Environment: A Guide to Closed-Loop Design and Building. 2005.

[54] Heinrich M, Lang W. Materials Passports - Best Practice. 2019.

[55] Heeren N, Hellweg S. Tracking Construction Material over Space and Time - Prospective and Geo-Referenced Modeling of Building Stocks and Construction Material Flows. J Ind Ecol 2018;23.

[56] Arora M, Raspall F, Cheah L, Silva A. Residential Building Material Stocks and Component-Level Circularity: The Case of Singapore. J Clean Prod 2019;216:239–48.

[57] Stephan A, Athanassiadis A. Towards a More Circular Construction Sector: Estimating and Spatialising Current and Future Non-Structural Material Replacement Flows to Maintain Urban Building Stocks. Resour Conserv Recycl 2018;129:248–62.

[58] Estaji H. A Review of Flexibility and Adaptability in Housing Design. Int J Contemp Archit "The New Arch" 2017;4:37–49.

[59] Geldermans RJ. Design for Change and Circularity - Accommodating Circular Material & Product Flows in Construction. Energy Procedia Build Green Renov. Deep, Tallinn and Helsinki: The Author(s); 2016, p. 301–11.

[60] Kelly G, Schmidt III R, Dainty A, Story V. Improving the Design Process for Adaptability: Linking Feedback and Architectural Values. Proc. 2011 27th Annu. Conf. Assoc. Res. Constr. Manag., Bristol: 2011, p. 43–52.

[61] Schmidt III R, Toru E, Alistair S, Alistair G. "What Is the Meaning of Adaptability in the Building Industry?" Open Sustain. Build., 2010, p. 360–76.

[62] Jakšić Ž, Trivunić M, Adamtsevich A. Flexibility and Adaptability - Key Elements of End-User Participation in Living Space Designing. MATEC Web Conf., vol. 106, 2017.

[63] Brand S. How Buildings Learn: What Happens after They're Built. London: Penguin Books; 1994.

[64] Mouilek S. Design for Adaptability and Deconstruction (DfAD). 2009.

[65] Webster M. D. Structural Design for Adaptability and Deconstruction: A Strategy for Closing the Materials Loop and Increasing Building Value. Proc. New Horizons Better Pract., Long Beach: 2007, p. 1–6.

[66] Tebbatt Adams K, Osmani M, Thorpe T, Thornback J. Circular Economy in Construction: Current Awareness, Challenges and Enablers. Proc. Inst. Civ. Eng. - Waste Resour. Manag., vol. 170, 2017, p. 15–24.

[67] Jones P, Comfort D. The Construction Industry and the Circular Economy. Int J Manag Cases 2018;20:4–15.

[68] Sonego M, Soares Echeveste ME, Galvan Debarba H. The Role of Modularity in Sustainable Design: A Systematic Review. J Clean Prod 2018;176:196–209.

[69] CE100. Circularity in the Built Environment: Case Studies. 2016.

[70] Bouwer M, Jonk M, Szuppinger P, Lusser H, Berman T, Bersani R, et al. Green Public Procurement in Europe. 2006.

[71] European Commission. What is GPP 2019. https://ec.europa.eu/environment/gpp/what_en.htm (accessed August 22, 2019).

[72] Lazarevic D, Kautto P, Antikainen R. Finland's Wood-Frame Multi-Storey Construction Innovation System: Analysing Motors of Creative Destruction. For Policy Econ 2019:1–11.

[73] Ramage MH, Burridge H, Busse-Wicher M, Fereday G, Reynolds T, Shah DU, et al. The Wood from the Trees: The Use of Timber in Construction. Renew Sustain Energy Rev 2017;68:333–59.

[74] Parisi Kern A, Vargas Amor L, Cirelli Angulo S, Montelongo A. Factors Influencing Temporary Wood Waste Generation in High-Rise Building Construction. Waste Manag 2018;78:446–55.

[75] Stichting Bouwkwaliteit. Bepalingsmethode Milieuprestatie Gebouwen en GWW-werken. 2011.

[76] Beco. Vergelijkende LCA Studie bruggen. 2013.

[77] Jarre M, Petit-Boix A, Priefer C, Meyer R, Leipold S. Transforming the Bio-Based Sector towards a Circular Economy - What Can We Learn from Wood Cascading? For Policy Econ 2019:1–12.

[78] Radić J, Kušter Marić M. Aesthetics and Sustainability of Arch Bridges. 7th Int. Conf. Arch Bridg. Arch '13, 2013, p. 1–9.

[79] Long AE, Basheer PAM, Taylor SE, Rankin BGI, Kirkpatrick J. Sustainable Bridge Construction through Innovative Advances. Bridg Eng 2008;161:183–8.

[80] García-segura T, Yepes V, Frangopol DM, Yang DY. Lifetime Reliability-Based Optimization of Post-Tensioned Box-Girder Bridges. Eng Struct 2017;145:381–91.

[81] Hegger J, Curbach M, Stark A, Wilhelm S, Farwig K. Innovative Design Concepts: Application of Textile Reinforced Concrete to Shell Structures. Struct Concr 2018;19:637–46.

[82] Shibata T, Kata K, Kasuga A, Sakai K. Sustainability Evaluation of Butterfly Web Bridge. Struct Concr 2017;19:422–39.

[83] Enfedaque A, Alberti MG, Gálvez JC, Rivera M, Simón-Talero JM. Can Polyolefin Fibre

Reinforced Concrete Improve the Sustainability of a Flyover Bridge? Sustain 2018;10:1–18.

[84] Awan AB. A Framework for Assessing Sustainability in the Design of Michigan Bridges and Life Cycle Cost Analysis. 2012.

[85] O'Born R. Life Cycle Assessment of Large Scale Timber Bridges: A Case Study from the World's Longest Timber Bridge Design in Norway. Transp Res Part D Transp Environ 2018;59:301–12.

[86] Navarro IJ, Yepes V, Martí J V., González-Vidosa F. Life Cycle Impact Assessment of Corrosion Preventive Designs Applied to Prestressed Concrete Bridge Decks. J Clean Prod 2018;196:698–713.

[87] Gervásio H, Dimova S, Pinto A. 21.15: Resource efficiency in the building sector: Application to steel buildings. Ce/Papers 2017;1:4620–9.

[88] Zastrow P, Molina-Moreno F, García-Segura T, Martí J V., Yepes V. Life Cycle Assessment of Cost-Optimized Buttress Earth-Retaining Walls: A Parametric Study. J Clean Prod 2017;140:1037–48.

[89] Penadés-Plà V, García-Segura T, Martí J V., Yepes V. An Optimization-LCA of a Prestressed Concrete Precast Bridge. Sustainability 2018;10.

[90] Ingenieursbureau Stadsontwikkeling Rotterdam. Ontwerpen van Duurzame Bruggen - Handleiding voor een Milieubewust Ontwerp van Parkbruggen. 2013.

[91] Buyle M, Braet J, Audenaert A. Life Cycle Assessment in the Construction Sector: A Review. Renew Sustain Energy Rev 2013;26:379–88.

[92] Pacheco P, Adão da Fonseca AP, Resende A, Campos R. Sustainability in bridge construction processes. Clean Technol Environ Policy 2010;12:75–82.

[93] Dinas A, Nikolaidis TN, Baniotopoulos CC. Sustainable Restoration Criteria for a Historical Steel Railway Bridge. Int. Conf. Sustain. Synerg. from Build. to Urban Scale, SBE16, The Author(s); 2017, p. 578–85.

[94] Van den Broek M. Design of Sustainable Bridges - Manual for Civil Engineers. 2012.

[95] Keoleian GA, Kendall A, Chandler R, Helfand GE, Lepech M, Li VC. Life Cycle Cost Model for Evaluating the Sustainability of Bridge Decks. Adv. Life-Cycle Cost Anal. Des. Civ. Infrastruct. Syst., 2004, p. 143–50.

[96] Fernando D, Mirzaei Z, Adey BT, Ellis RM. A Paper Submitted for Presentation at the 2012 Annual Meeting of the Transportation Research Board and Publication in the Transportation Research Record. Transp. Res. Rec., 2012.

[97] dos Santos Gervásio HM, Simões da Silva LAP. A Design Approach for Sustainable Bridges - Part 1: Methodology. Eng Sustain 2013;166:191–200.

[98] Popa N, Charlier M, Tibolt M, Rademacher D, Ryjáček P, Jehlicka P, et al. Holistic Approach to Sustainability of Bridges. Steel Constr 2018;11:179–83.

[99] Verma P, Raghubanshi AS. Urban Sustainability Indicators: Challenges and Opportunities. Ecol Indic 2018;93:282–91.

[100] Brundage MP, Bernstein WZ, Hoffenson S, Chang Q, Nishi H, Kliks T, et al. Analyzing Environmental Sustainability Methods for Use Earlier in the Product Lifecycle. J Clean Prod 2018;187:877–92.

[101] Markelj J, Kuzman MK, Grošelj P, Zbašnik-Senegačnik M. A Simplified Method for Evaluating

Building Sustainability in the Early Design Phase for Architects. Sustainability 2014;6:8775–95.

[102] Ahmad S, Wong KY, Tseng ML, Wong WP. Sustainable Product Design and Development: A Review of Tools, Applications and Research Prospects. Resour Conserv Recycl 2018;132:49–61.

[103] Dalla Mora T, Bolzonello E, Peron F, Carbonari A. Integration of LCA Tools in BIM toward a Regenerative Design. PLEA 2018 Hong Kong, Hong Kong: 2018.

[104] García-Segura T, Yepes V, Martí J V., Alcalá J. Optimization of Concrete I-Beams Using a New Hybrid Glowworm Swarm Algorithm. Lat Am J Solids Struct 2014;11:1190–205.

[105] Yepes V, Martí J V., García-Segura T. Cost and CO2 Emission Optimization of Precast-Prestressed Concrete U-Beam Road Bridges by a Hybrid Glowworm Swarm Algorithm. Autom Constr 2015;49:123–34.

[106] García-Segura T, Yepes V, Alcalá J, Pérez-López E. Hybrid Harmony Search for Sustainable Design of Post-Tensioned Concrete Box-Girder Pedestrian Bridges. Eng Struct 2015;92:112–22.

[107] Penadés-Plà V, García-Segura T, Martí J V., Yepes V. A Review of Multi-Criteria Decision-Making Methods Applied to the Sustainable Bridge Design. Sustainability 2016;8.

[108] García-Segura T, Yepes V. Multiobjective Optimization of Post-Tensioned Concrete Box-Girder Road Bridges Considering Cost, CO2 Emissions, and Safety. Eng Struct 2016;125:325–36.

[109] García-Segura T, Penadés-Plà V, Yepes V. Sustainable Bridge Design by Metamodel-Assisted Multi-Objective Optimization and Decision-Making under Uncertainty. J Clean Prod 2018;202:904–15.

[110] Lavagna M, Baldassarri C, Campioli A, Giorgi S, Dalla Valle A, Castellani V, et al. Benchmarks for Environmental Impact of Housing in Europe: Definition of Archetypes and LCA of the Residential Building Stock. Build Environ 2018;145:260–75.

[111] Hossain MU, NG ST. Critical Consideration of Buildings' Environmental Impact Assessment towards Adoption of Circular Economy: An Analytical Review. J Clean Prod 2018;205:763–80.

[112] Kylili A, Fokaides PA. Policy Trends for the Sustainability Assessment of Construction Materials: A Review. Sustain Cities Soc 2017;35:280–8.

[113] Lehnert T. Special Heavy Plate Solutions for Bridges. Steel Constr 2018;11:192–5.

[114] European Commission. Energy Efficiency and CO2 Reduction in the Cement Industry. 2013.

[115] Simon F. 'Invisible' Cement Polluters Urged to Double Climate Efforts 2018. https://www.euractiv.com/section/climate-environment/news/invisible-cement-polluters-urged-to-double-climate-efforts/ (accessed April 3, 2019).

[116] Gimenez M. CO2 Uses in the Cement Industry 2019. https://setis.ec.europa.eu/setis-reports/setis-magazine/carbon-capture-utilisation-and-storage/co2-uses-cement-industry (accessed April 3, 2019).

[117] Timperley J. If the Cement Industry Were a Country, It Would Be the Third Largest Emitter in the World. 2018. https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change (accessed April 3, 2019).

[118] Harvey C. Cement Producers Are Developing a Plan to Reduce CO2 Emissions 2018. https://www.scientificamerican.com/article/cement-producers-are-developing-a-plan-to-reduce-co2-emissions/ (accessed April 3, 2019).

[119] Saarela J. Pilot investigations of surface parts of three closed landfills and factors affecting them. Environ Monit Assess 2003;84:183–92.

[120] Matthias B, Waldo G, Wim D, Amaryllis A. Sustainability Assessment of Circular Building Alternatives: Consequential LCA and LCC for Internal Wall Assemblies as a Case Study in a Belgian Context. J Clean Prod 2019;218.

[121] Van der Voet E, Van Oers L, Verboon M, Kuipers K. Environmental Implications of Future Demand Scenarios for Metals: Methodology and Application to the Case of Seven Major Metals. J Ind Ecol 2019;23:141–55.

[122] Kayal B, Abu-ghunmi D, Abu-ghunmi L, Archenti A, Nicolescu M, Larkin C, et al. An Economic Index for Measuring Firm's Circularity : The Case of Water Industry. J Behav Exp Financ 2018.

[123] Ellen MacArthur Foundation, Granta Design, Life. Circularity Indicators - An Apporach to Measuring Circularity. 2015.

[124] Wang N, Chi Kin Lee J, Zhang J, Chen H, Li H. Evaluation of Urban Circular Economy Development : An Empirical Research of 40 Cities in China. J Clean Prod 2018;180:876–87.

[125] Leising E, Quist J, Bocken N. Circular Economy in the Building Sector: Three Cases and a Collaboration Tool. J Clean Prod 2018;176:976–89.

[126] Núñez-cacho P, Górecki J, Molina V, Corpas-Iglesias FA. New Measures of Circular Economy Thinking In Construction Companies. J EU Res Bus 2018;2018.