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Building design and construction strategies for a circular economy

Leonora Charlotte Malabi Eberhardt [a*], Morten Birkved [b] and Harpa Birgisdottir [a]

[a]Department of the Built Environment, Aalborg University, Copenhagen SV, Denmark; [b]Department of Chemical Engineering, SDU Life Cycle Engineering, Biotechnology and Environmental Technology University of Southern Denmark, Odense-M, Denmark

ABSTRACT

The considerable environmental impacts, resource consumption and waste generation emanating from buildings are a cause of great concern and political attention. Interest in the circular economy (CE) concept of slowing, narrowing and closing material loops through CE strategies (reuse, repair, refurbish, recycle and recover) has grown in recent years to facilitate minimising these unresolved issues emanating from the building industry. Although CE initiatives are proliferating within the industry, wide-scale adoption of CE is still lacking, and the current development and implementation of CE building design and construction strategies is fragmented. Through a systematic literature review (SLR), this study assesses which design and construction strategies are being linked to the concept of CE for new buildings, and their level of application and readiness in a building context. On this basis, the study offers insight into how this field of research is developing and provides directions for future research. From the SLR, a taxonomy is presented that groups the strategies together into 16 overarching building design and construction strategies. An important gap preventing a greater CE uptake within the industry was found to include the lack of knowledge about the environmental performance and related benefits of the various building design and construction strategies. Thus, it is suggested that conveying more comprehensive and uniform adoption of CE in the building industry requires the development of a new design typology to facilitate CE-oriented decision-making in a building context and that prioritises the strategies according to their potential in terms of minimising building-related environmental impacts.

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Circular economy (CE); built environment; buildings; design strategies; environmental performance

Introduction

Globally, buildings are responsible for 40% of all waste generated (by volume), 40% of all material resource use (by volume) and 33% of all human-induced emissions (United Nations Environment Programme, 2012; World Resources Institute, 2016). At the same time, a great amount of all materials ever extracted in human history are located in the built environment (Sanchez & Haas, 2018a), suggesting that buildings will become a major temporary material stock to supply future demand.

CONTACT Malabi Eberhardt lcl@build.aau.dk; lcl@sbi.aau.dk Department of the Built Environment, Aalborg University, A. C. Meyers Vænge 15, Copenhagen SV 2450, Denmark; Department of the Built Environment, Department of Energy Efficiency, Indoor Climate and Sustainability, Aalborg University, A. C. Meyers Vænge 15, Copenhagen SV 2450, Denmark
*Affiliation where the research was conducted: Department of the Built Environment.
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Continued inefficient use of non-renewable materials will almost certainly cause significant natural-resource depletion (Hossain & Ng, 2018). Consequently, the European Union aims at net zero (emissions) buildings by 2050 (European Commission, 2019b).

The circular economy (CE) concept promises an alternative to the current linear economy of 'take-make-use-dispose'. CE is a restorative and regenerative system in which resource use, waste, and emissions are minimised by narrowing (efficient resource use), slowing (temporally extended use) and closing (cycling) material loops (Reike, Vermeulen, & Witjes, 2018). CE is operationalised through CE strategies such as reuse, repair, refurbish, recycle and recover (Ellen MacArthur Foundation, World Economic Forum, & The Boston Consulting Group, 2016). Despite the growing interest in CE in recent years (Advisory Board for Cirkulær Økonomi, 2017; Ellen MacArthur Foundation, 2016b; European Commission, 2017; The Danish Government, 2018) the bulk of new building projects is not yet moving towards CE. Although, CE building design and construction strategies are increasingly being developed and implemented, the process has so far been incoherent and without a commonly acknowledged or established direction across the building industry.

This lack of CE orientation leads to the question: in which direction is the building industry actually moving in terms of designing and constructing buildings for a CE? Accordingly, through a systematic literature review (SLR), the study aims to provide an overview of the state-of-the-art design and construction strategies being applied in relation to the concept of CE within the building industry. Furthermore, to qualitatively assess these strategies' level of application and readiness in the building industry in order to provide insight into how this sector is developing and thereby provide directions for the future research needed to promote a more comprehensive CE adoption in the sector.

The paper is structured in five sections. Section 2 introduces CE developments in the building industry. Section 3 presents the research methodology. Section 4 presents the results of the descriptive and comparative analysis and identifies pertaining gaps. Section 5 provides a discussion on the research limitations and proposes an agenda to address future research needs. Finally, section 6 concludes by recapping the research contribution and limitations.

Background

The European building industry has largely focused on lowering operational energy consumption in order to minimise the environmental impacts induced by buildings (Malmqvist et al., 2018). However, as buildings become more energy efficient, the embodied environmental impacts stemming from production, construction, maintenance and disposal of building materials represent an increasing share of a buildings' total environmental burden (Röck et al., 2020). In view of this development, CE is regarded as an important step towards continuing efforts to reduce buildings' environmental burdens (Pomponi & Moncaster, 2017). The CE concept gained a stronger foothold within the industry after the Ellen MacArthur Foundation published a series of reports (Ellen MacArthur Foundation [EMF], 2012, 2013, 2014, 2015, 2016b), among other things promoting the opportunities and benefits of a CE in the building industry. In recent years, the EU has planned a series of actions and legislative proposals including plans for future reuse and recycling targets for construction and demolition waste (European Commission, 2019a). Due to increasing political focus on inefficient use and depletion of natural resources, and expected legislative demands in the future (Advisory Board for Cirkulær Økonomi, 2017; European Commission, 2017; The Danish Government, 2018), there is a proliferation of CE-concept awareness (Adams, Osmani, Thorpe, & Thornback, 2017), publications (Ghisellini, Ripa, & Ulgiati, 2018) and CE building projects within the building industry (EMF, 2016b). Many different definitions of CE exist (Kirchherr, Reike, & Hekkert, 2017) and there is still no clear and accepted definition within the building industry (Hart, Adams, Giesekam, Tingley, & Pomponi, 2019). Thus, CE initiatives seem to be going in many different directions and with different focus areas (EMF, 2014) (e.g. design for disassembly, flexibility, secondary materials, etc.). This fragmented development potentially prevents universal adoption of CE in the building industry.

A large body of pre-existing work already exists behind the CE concept, as the concept tries to bring together pre-existing concepts with shared qualities and characteristics under one name (Blomsma & Brennan, 2017; Hart et al., 2019). Thus, the origin of CE can be traced back to earlier scientific and economic schools of thought (Boulding, 1996; Braungart & McDonough, 2002; Brezet & van Hemel, 1997; Frosch & Gallopoulos, 1989; Pearce & Turner, 1990; Stahel, 1982). Even though the building industry is consolidating previous knowledge in the field (Cheshire, 2016; Geldermans, 2016; Ness & Xing, 2017) 'business as usual' is still deeply entrenched within the industry. In addition, many literature reviews on CE (Blomsma & Brennan, 2017; Ghisellini, Cialani, & Ulgiati, 2015, 2016; Kirchherr et al., 2017; Lieder & Rashid, 2016) and different CE frameworks (Blomsma, Kjaer, Pigosso, McAloone, & Lloyd, 2018; Bocken, de Pauw, Bakker, & van der Grinten, 2016; Mestre & Cooper, 2017; Potting, Hekkert, Worrell, & Hanemaaijer, 2017) have emerged, including BS 8001, the world's first standard on CE (Pomponi & Moncaster, 2019). Additional CE standards are on their way from the International Organisation for Standardisation (ISO, 2019). While undoubtedly adding to the body of knowledge on CE, most of these publications are not specifically targeted at the building industry and it's complex nature: instead they are targeted at the CE concept in general or focused on short- and medium-lived consumer goods (Hart et al., 2019). In comparison, buildings are often complex, dynamic, unique long-lived products consisting of a multitude of different components and materials, each with their own lifecycle, functions and characteristics while simultaneously interacting with the entire building system (Hart et al., 2019; Pomponi & Moncaster, 2017). Moreover, during their service life buildings are exposed to changing use and a changing multiplicity of actors with diverging and/or conflicting incentives, and this leads to increased uncertainty about future circumstances for reuse of building materials and components, for example (Hart et al., 2019; Pomponi & Moncaster, 2017, 2019). For these reasons, the environmental performance of buildings depends on several different interlinked attributes such as building design, material choice, operation and maintenance (Maslesa, Jensen, & Birkved, 2018). In addition, the building industry has its own design process, manufacturing techniques, supply chain and financial arrangements (Hart et al., 2019). In other words, existing guidance falls short as it fails to match the complex nature of the building industry, resulting in inadequate use/development of CE-focused design and collaboration tools, and poor information and metrics that hinder CE progress in the building industry (Hart et al., 2019).

In summary, knowledge and guidelines supporting effective design and construction for a CE in the built environment are still lacking (Adams et al., 2017; Hart et al., 2019; Ness & Xing, 2017; Pomponi & Moncaster, 2017). As more and more CE initiatives appear with no common direction, there is an obvious need to understand current developments in the building industry in order to conceptualise and define the CE concept more specifically within the complex context of the building industry for more comprehensive and consistent adoption of the CE concept.

Method

The SLR approach used to review the existing literature ensures rigour and objectivity in the selected studies and replicability of the study (de Almeida Biolchini, Mian, Natali, Conte, & Travassos, 2007) and has been used by other recent CE studies (Pagoropoulos, Pigosso, & McAloone, 2017; Pieroni, McAloone, & Pigosso, 2019). A review protocol was carefully developed in line with the objective of the study (see supplementary material) (de Almeida Biolchini et al., 2007). The SLR was not intended as an exhaustive study, but rather as a representation of the state-of-the-art building design and construction strategies for a CE in the building industry. Furthermore, the CE builds on a large body of pre-existing work that the building industry is consolidating. Thus, the literature search was conducted using a very specific set of keywords related to the CE, buildings, strategies and their synonyms: (*'circular economy' OR 'circle economy') AND ('built environment' OR building OR construction OR 'civil engineering') AND (approach OR method OR strategy OR concept OR framework OR principle OR taxonomy OR guideline OR guide*). The search string was searched applying four criteria:

(1) Publications must contain at least one building design and construction strategy that is explicitly related to the CE concept
(2) The strategy/strategies must focus on optimising the building's resource consumption, waste generation and/or embodied environmental impacts in accordance with the CE concept (Reike et al., 2018)
(3) The strategy/strategies must focus solely on the design and construction of new buildings i.e. strategies related to building renovation as well as building extensions are excluded
(4) The study must provide a sufficient level of information about the building design and construction strategy/strategies and their application

The different search engines used returned a total of 506 publications. Review of the title, abstract and keywords against the selection criteria stated in the protocol and excluding irrelevant subject areas and duplicates reduced the number of publications to 54. Further reading of the introduction and conclusion, resulted in the selection of 19 publications. As CE has to large extent been developed in grey literature, 12 grey literature publications, some of which were known *a priori* by the authors to meet the scope and selection criteria of the study, were also included. Additionally, backward snowballing (Wohlin, 2014) was performed between these papers, resulting in the inclusion of 3 additional papers. In total 34 publications were analysed in full-text for the synthesis (see supplementary material). The outline of the study method is shown in Figure 1.

The design and construction strategies were extracted from the 34 publications and added one by one to a spreadsheet as the search progressed. If a study contained several building design and construction strategies, each of these were registered individually. Similarly, as some studies contained several case studies mentioning the building design and construction strategies several times in

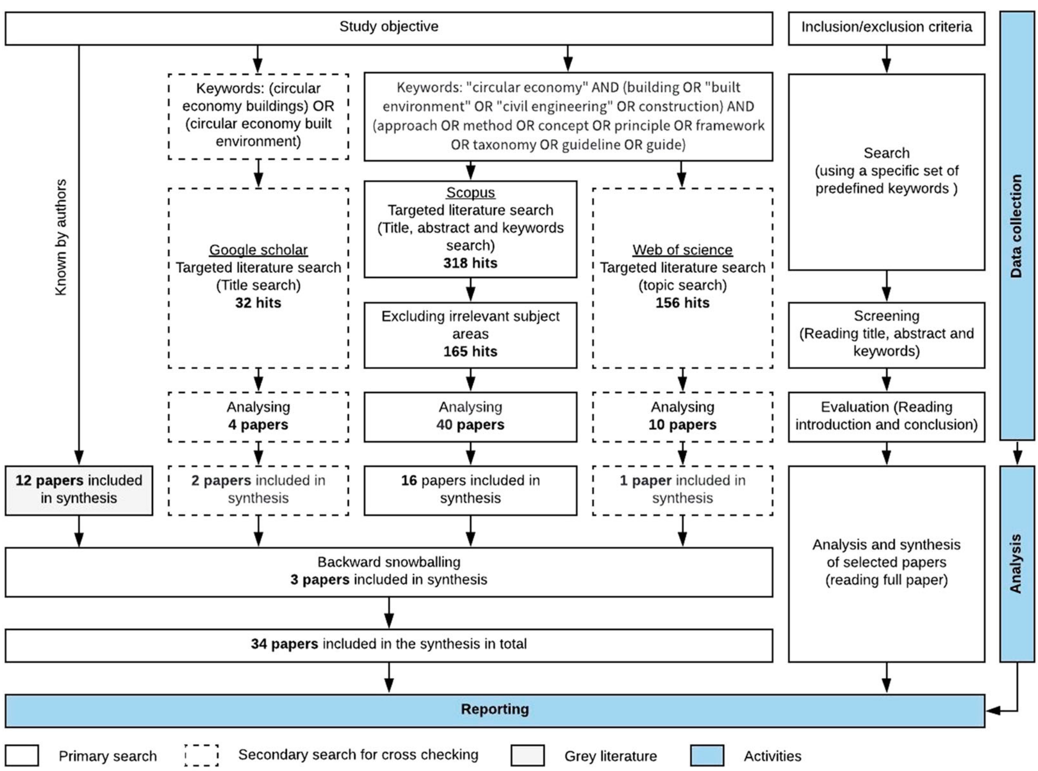

Figure 1. Outline of the study methodology.

relation to different cases, these were counted for each case. During the search, it was found that the building design and construction strategies were interpreted and practised in different ways, with different goals, and with different names in the literature. To make sense of the multitude of design and construction initiatives found from the selected literature, we focused on essential shared practices, quality and characteristics of each strategy in order to group the strategies into overarching design and construction strategies. For example, it was found that the strategy 'flexibility' and 'adaptability' reflect the same thing. In total, 16 overarching design and construction strategies were identified (see Table 1). Based on the overall objective of the study, the following information was registered for each strategy:

(a) Number of occurrences
(b) Relation to CE strategies (i.e. reduce, reuse, repair, refurbish, remanufacture, recycle and recover (Ellen MacArthur Foundation et al., 2016))
(c) If stated, relation to project stage(s) from planning and design to decommissioning
(d) If relevant, relation to building type e.g. school, office, hospital, residential, etc.
(e) Level of application in buildings (i.e. if the strategy addresses the overall building level, component level and/or material level or in general terms)
(f) Level of readiness

Using a simplified scale (see Table 1), (f) leans on the principle of Technology Readiness Level (TRL) used in projects funded by the EU Horizon 2020 to measure/indicate the maturity level of a given technology (European Commission, 2019c) – in our case the maturity level of the building design and construction strategies.

The linkage of different design strategies was also registered as interconnectivity between the design strategies was found from the literature i.e. one design and construction strategy may enhance or enable another strategy.

Based on the overall objective of the study a taxonomy summarising the 16 building design strategies identified was developed to provide an overview, systemise and enable comparison between state-of-the-art building design and construction strategies for a CE (see Table 1). The strategies were organised according to (a), (e) and (f), aiming to provide a simple overarching scheme of different strategies and how they are applied in terms of buildings and their level of readiness.

Results

Descriptive findings

The 34 publications were all published between 2013 and 2019 (see Figure 2(c)), the same period as the Ellen MacArthur Foundation published a series of reports (EMF, 2013, 2014, 2015, 2016b, 2017). An emerging trend is observed after 2015 correlating with the recently increasing environmental concerns expressed by the building industry and evident from the increasing political (European Parliament and the Council of the European Union, 2018) as well as academic attention (Hossain & Ng, 2018; Pomponi & Moncaster, 2017).

24/34 publications originate from Europe, while Asia, Canada, Australia and the USA account for 3/34, 2/34, 2/34 and 1/34, respectively. The origin of the 2 remaining studies is unknown (see Figure 2(b)).

Several different research methods have been used in the studies, including systematic literature reviews, literature reviews, case studies, use or development of frameworks and tools, life cycle assessment, surveys, workshops and expert interviews (see Figure 2(a)). Several studies combined different methodologies. Most studies combined case studies with a literature review. Combinations of literature review or case studies with existing frameworks or the development of a new framework

Table 1. Overview of building design strategies from the literature and their level of application and level of readiness ranked according to occurrences within the selected literature

Occurrences	Design and construction strategy	Level of application			Level of readiness			Description in literature	Source (see Appendix)
		Building	Component	Material	Theoretical	Experimental	Consolidated		
32	Assembly/ disassembly							Is used to design the building, components or materials to be easily assembled/disassembled to enable e.g. direct reuse or recycling, ease of maintenance/operation and ease of adaptability/flexibility. A precondition is reversible connections.	1, 4, 6, 5, 7, 8, 10, 11, 13,14, 16, 17, 19, 21, 22, 23, 25, 26, 27, 28, 29, 30, 33, 34
25	Material selection/ substitution							Choosing or substituting materials for materials that are e.g. local, renewable, natural/eco/bio, have lower environmental impact, of high quality, durable, easy assembly/disassembly, reusable and recyclable, C2C certified, pure, maintenance free, retain or increase their value, match the performance lifespan, non-toxic/ hazardous etc.	2, 5, 6, 7, 8, 10, 11, 14, 18, 22, 24, 23, 30, 33, 34
21	Adaptability/ flexibility							Designing to be able to e.g. adapt to available materials, accommodate changes in future use/ function requiring modifications/remodelling/ expansion, secure easy and low cost operation/ maintenance, prolong the lifespan of the building, components or materials, reuse and recycle, enable/enhance design for disassembly, close materials loops, distinguish between long- and short-life materials as well as low- and high-value materials.	2, 7, 5, 6, 10, 12, 14, 17, 20, 21, 22, 24, 27, 33, 16, 29, 30, 34
17	Modularity							Is used to e.g. allow for easier building/ component adaptability/flexibility (upgrade, demounting/disassembly, replacement, reconfiguration, reuse and recycling), build cheaper standard buildings and lean production.	5, 7, 6, 10, 12, 15, 19, 22, 25, 26, 29, 30, 33
17	Prefabrication							Also known as off-site construction. Is used to ensure e.g. reclamation, reusability and recyclability, construction time optimisation, enhanced assembly and disassembly, enhanced adaptability, avoidance of off-cut materials etc. e.g. wooden components such as glue-laminated timber.	2, 5, 6, 7, 8, 10, 15, 16, 17, 24, 25, 30, 33, 34
15	Secondary materials							Integrating materials that are recycled in order to slow and close resource loops. E.g. recycled insulation materials, textiles, cellular glass, plywood etc.	3, 5, 7, 15, 17, 18, 24, 26, 28, 30, 31, 33, 34

13	Durability							Designing or using high quality durable long performance lifespan components and materials that are easy to maintain and upgrade and can handle several service lives.	5, 6, 7, 17, 20, 27, 29, 30, 32, 33, 34
12	Standardisation							Is used to e.g. maximise recovery of materials at end-of-life, ensure reuse and recycling options, limit the number of different components used, avoid material off-cuts, prolong product lifespan etc. (Geldermans, 2016) suggests that the dimensions of the elements do not necessarily need to be standardised if the connections between elements are.	2, 6, 7, 8, 10, 11, 14, 16, 19, 25, 26, 33
11	Component and material optimisation							Reducing the amount of materials used as well as the number of different types of components and materials used. E.g. reducing the use of concrete and reducing excavation by choosing a shallow raft foundation.	2, 5, 6, 7, 15,16, 29, 32, 33
11	Reusing existing building/ components/ materials							Is used to directly reuse existing buildings, components or materials for new construction projects. E.g. reusing existing buildings on the site, floor boards, cement tiles, rubble, steel beams etc.	5, 9, 15, 16, 17, 28, 29, 33, 34
10	Optimised shapes/ dimensions							Design to precise material measurements specification in order to: suit appropriate means of handling components and materials, enhance/enable future adaptability/flexibility by e.g. avoid over ordering and onsite material cut-offs. E.g. by simplifying the building form, using lightweight structures or reducing the customers' spatial needs by optimising floor areas.	5, 6, 9, 14, 16, 18, 19, 25, 29
8	Accessibility							Also known as 'open design'. Used to provide good access to connections between components to enhance design for assembly/ disassembly, to ease maintenance, maximise recovery of materials at end-of-life. E.g. accessible technical building services for easy service and maintenance, demountable and reconfigurable façade systems.	6, 10, 16, 22, 25, 29, 33
6	Layer independence							Is used to make building components and materials independent from each other's lifespan for easier operation and maintenance, material recovery, separation and adaptability/	6, 8, 10, 14, 22, 33

(*Continued*)

Table 1. Continued.

Occurrences	Design and construction strategy	Level of application: Building	Component	Material	Level of readiness: Theoretical	Experimental	Consolidated	Description in literature	Source (see Appendix)
								flexibility. E.g. by making the long-lasting building elements flexible so that short-lasting elements can be easily changed. Clear definitions are required of which components belong to which 'shearing layer', with specific attention to intersection-zones.	
5	Material storage							Is used to design buildings as material deposits to avoid degradation of material quality over time by temporarily storing the materials in the building and minimising in-between stockholding that may damage materials by using principles such as just-in-time delivery of the materials to subsequent building projects.	5, 16
3	Short use							Opposite of *10 Design for durability:* the building is only designed for its specific use and performance span. Material and product choices are adjusted accordingly. E.g. Brummen Town Hall in the Netherlands is designed for a building lifespan of 20 years, after which it will be relocated to accommodate shifting municipal borders (Ellen MacArthur Foundation, 2016a). Another example is the Queen Elizabeth Olympic Park in the UK, which was constructed for hosting the Olympics, after which is was taken apart for other purposes (Ellen MacArthur Foundation, 2016a).	5, 14
2	Symbiosis/sharing							Is used to utilise residual resource outputs from one building as feedstock for another, often in relation to industrial parks e.g. sharing/ outsourcing surplus water, waste and energy.	2, 18

Note: Legend – Theoretical: theoretical research e.g. conceptual studies; Experimental: research with a practical application e.g. prototypes and test-/pilot projects; Consolidated: applied in a 'real-life' building project. Black icon: level in which the given strategy is most pronounced, grey icon: level in which the strategy has also been mentioned in relation to, no icon: the strategy has not been represented within the given level.

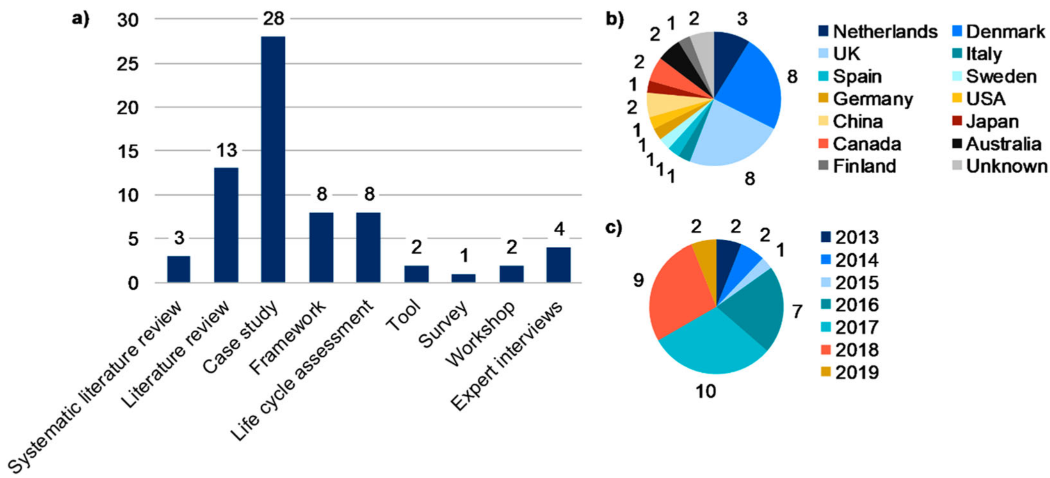

Figure 2. (a) research methods, (b) spatial and (c) temporal trends. The figure shows the number of incidents registered.

were also found. Only 8/34 studies performed an environmental impact performance assessment to confirm environmental benefits of design and construction strategies.

Systematic comparison of building design and construction strategies

The following section presents the results of the SLR shown in Figure 3 leading to the developed taxonomy and the comparative analysis of the 16 building design and construction strategies presented in Table 1.

Popularity

Figure 3(a) shows that the most encountered strategy in the literature is assembly/disassembly with 32 occurrences. Perhaps, this reflects that this strategy has been developed and gained foothold in the building industry over the course of the last decade due to expectations that it can facilitate/enable high-quality reuse of recovered materials beyond end-of-pipe solutions (Geldermans, 2016). The second-most encountered design and construction strategy is material selection/substitution with 25 counts, perhaps indicating an increasing awareness of the material choice in relation to implementing a CE in building design. The third-most encountered strategy is adaptability and flexibility with 21 counts, possibly because it is generally believed that a shift towards adaptable buildings has significant advantages for investors (by adding long-term value to investments), as well as users (by adding value through extensive customisation possibilities) (EMF, 2016b; Geldermans, 2016; Ness & Xing, 2017).

Relation to CE strategies

As the CE strategies i.e. reduce, reuse, recycle, etc. (Ellen MacArthur Foundation et al., 2016) were added as they occurred in the literature the CE strategies stated in Figure 3(b) should not be viewed as an exhaustive list.

The design and construction strategies were predominantly applied in relation to *reduce, reuse and recycle,* most likely because these are the most commonly known and practised CE strategies within the industry (Esa, Halog, & Rigamonti, 2017). Of these three, design and construction strategies were primarily related to the CE strategy *reuse,* with a total of 111 counts, and especially *assembly/disassembly* with 23 counts. This indicates that the literature has a predominant focus on direct reuse, i.e. extending resource life either by slowing or closing resource loops, as the CE concept has also

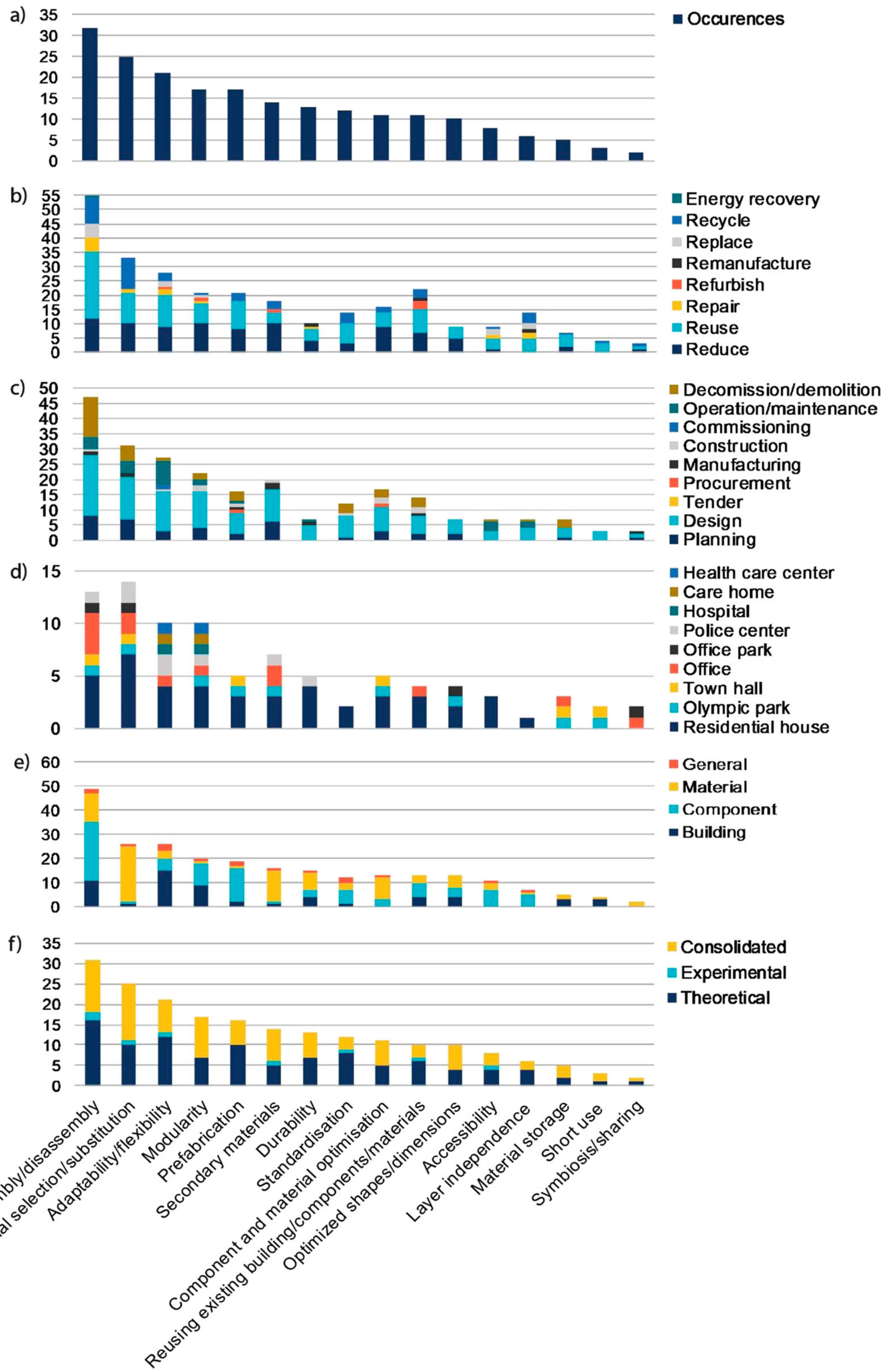

Figure 3. The design strategies' (a) number of occurrences, relation to (b) CE, (c) project stages, (d) building types, (e) application level and (f) readiness level.

been defined by Blomsma and Brennan (2017). *Reuse* is followed by 92 occurrences of *reduce* in terms or reducing or avoiding environmental impacts, resource consumption and waste generation, as well as lowering the total cost of construction and construction time. In relation to *reduce* the most commonly mentioned design and construction strategy was *assembly/disassembly and secondary materials,* with 12 and 10 counts respectively. *Recycle* returned 47 counts, where *material selection/substitution* had the most counts, with 11 occurrences. Energy recovery is only mentioned once in relation to *assembly/disassembly* perhaps because energy recovery is at the bottom of the waste pyramid (European Commission, 2008) and CE aims at higher utilisation and value of products (Esa et al., 2017). Furthermore, *repair*, *refurbish* and *remanufacture* are only mentioned 13, 6 and 3 times, respectively in connection to the design strategies.

Previous research and practice within the building industry has mainly focused on end-of-pipe solutions, i.e. recycling to manage construction and demolition waste (Adams et al., 2017; European Commission, 2008; Ghisellini, Ripa, et al., 2018). However, the findings of this study suggest that more ambitious preventive developments are occurring within both research and industry related to up-front reuse and recycling. Thus, strategies that integrate recycling and reuse in the design and construction of buildings and/or use components and materials that are reusable/recyclable at a later stage of a buildings' life cycle. This is in accordance with the design and construction strategies *material selection, secondary materials* and *reusing existing buildings, components and materials.* The design and construction strategies identified are also mostly related to the CE strategy *reuse,* which is associated with a higher utilisation and value than *recycle* according to the CE concept. For example, the design strategies most often encountered in the literature, i.e. *assembly/disassembly, material selection/substitution* and *adaptability/flexibility,* also have the most counts in relation to *reuse,* perhaps indicating a growing focus on direct reuse of buildings, components and/or materials in the future.

Project stages

The design and construction strategies are not always mentioned in the literature in relation to specific project stages and not all project stages are mentioned, e.g. the tender phase. Figure 3(c) shows that the design strategies have mostly been related to *planning, design, operation/maintenance* and *decommission/demolition,* with 40, 122, 25 and 38 counts, respectively. In other words, the design strategies were either used as preventive strategies in the early project stages i.e. planning and design of a building project, or management strategies in the later project stages *operation/maintenance* and *decommission/demolition*. Examples of preventive strategies and management strategies are *material optimisation* and *assembly/disassembly* respectively. However, all the design and construction strategies were mentioned in terms of the planning and design stage in accordance with the SLR selection criteria. This also matches the findings of recent research that suggests that environmental benefits of CE strategies are maximised by focusing on preventive strategies particularly during the early design stages (Akanbi et al., 2018; Ghisellini, Ji, Liu, & Ulgiati, 2018). Those design strategies most mentioned in the design stage are *assembly/disassembly* and *material selection/substitution,* with 20 and 14 counts, respectively.

Building types

Building typologies were added as they appeared from the literature, and for that reason Figure 3(d) does not capture the many other existing building typologies these design and construction strategies may also apply to. In general, it is seen that few studies mentioned the design and construction strategies in relation to specific building typologies, as seen from the few counts in Figure 3(d). However, the most common relations made between strategies and building typologies were for *residential houses* and *offices,* with 44 and 13 counts, respectively.

Although, the design strategies in the collected literature have been related to specific CE strategies, project stages and building types, the design strategies will most likely help achieve most

CE strategies, as depicted by Cheshire (2016), and they will be relevant in most project stages and building types.

Level of application

Figure 3(e) shows that most of the design and construction strategies address both the building, component and material level. However, for some strategies specific levels are more pronounced than others. For example, for the three most commonly encountered strategies, *assembly/disassembly, material selection/substitution* and *adaptability/flexibility* the component, material and building level is more pronounced, respectively.

Interconnectivity between the strategies

Table 2 shows the identified interdependencies between the individual strategies. Many of the design and construction strategies are mentioned as enabling or enhancing *assembly/disassembly* and *adaptability/flexibility*. However, as the table only reflects the connections made in the literature collected for this review, many more unrecorded connections may exist. Relations that were not captured from the collected literature, and potentially missing (in the authors' perception) are shown in Table 2 based on the description of each design and construction strategy in the literature. For example, *standardisation* is believed to potentially enable *adaptability/ flexibility,* but this was not recorded in the literature. As seen from the counts in Table 2, several potential missing relations have been identified for most of the design and construction strategies. Most of the relations identified from the literature are located in the first half of the table, while the potential missing relations indicate that the relations are more evenly spread throughout the table.

Level of readiness

Figure 3(f) shows that the studies predominantly work with design and construction strategies on a theoretical and consolidated level. These two levels are approximately equally represented, whereas the experimental level in-between is almost not represented at all. Thus, it seems that developments in both research and industry are occurring, but independently of one another. This could indicate a missing link between research and practice. This indication is strengthened by the fact that choices of design and construction strategies in the publications were most often found to be based on intuition rather than well-founded scientific facts and data, for example the environmental performance of strategies. For example, in most of the reviewed publications the environmental impact performance of the design and construction strategies were often not assessed. Only 8/34 studies quantified how the design and construction strategies potentially improved the environmental performance of the building or its components using life cycle assessment. If the environmental effects are unknown there is a potential risk of focusing/selecting the 'wrong' strategies. The lack of knowledge about the strategies' environmental performance and related potentially hinders a more unified development/ effort towards a circular built environment.

Thus, we suggest further developing a new design typology that structures and prioritises the design and construction strategies from Table 1 according to which strategies are most promising for minimising building-related environmental impacts. In the following section, we discuss what further work is required to convey such a new typology.

Discussion

Suggestion for future research

Geldermans (2016), also found that many envisioned design solutions for the implementation of circular material flows have fallen short due to their relatively one-sided nature, taking insufficient account of how environmental factors are integrated in practice. Thus, assessing the potential environmental performance of each building design and construction strategy is a fundamental

Table 2. Overview of how the design and engineering strategies enable or enhance one another.

Rank	Rank	1 Assembly/ disassembly	2 Material selection/ substitution	3 Adaptability/ flexibility	4 Modularity	5 Secondary materials	6 Prefabri- cation	7 Standardi- sation	8 Optimised shapes/ dimensions	9 Dura- bility	10 Component and material optimisation	11 Accessi- bility	12 Reusing existing building/ components/ materials	13 Layers independence	14 Material storage	15 Symbiosis/ sharing	16 Short use	Count x/o
1	Assembly/ disassembly		x	x	o	x	x	o	o	x	o	o	x	o	o	o	o	5/8
2	Material selection/ substitution	x		x		x	o	o	o	x	o		x	o	o	o	o	5/7
3	Adaptability/ flexibility	x			x		x	o	o	x		o	x	o	o		o	5/5
4	Modularity	x		x			o	o	o	x	o	o		o			o	3/6
5	Secondary materials		o							x	o					o	o	1/3
6	Prefabrication	x		x	x	x		o	o	o	o	o	o	o			o	4/7
7	Standardisation	x		o	x		o		o	o	o	o		o	o		o	2/9
8	Optimised shapes/ dimensions	x		x	o		o	x			o	o			o		o	3/6
9	Durability	x		x									o		o	o		2/2
10	Component and material optimisation	x		x	o		o	x										3/2
11	Accessibility	x		x	o				o	o			o	o	o			2/5
12	Reusing existing building/ components/ materials	x		x		o			o		o				o	o		2/4
13	Layer independence	x		x	o				o	x	o	o	o		o		o	3/6
14	Material storage									o			o				o	0/3
15	Symbiosis/ sharing					o							o					0/2
16	Short use	x		o									o	o				1/3
Count x/o	12/0	1/1	10/2	3/5	3/2	2/5	2/5	0/9	5/4	0/7	0/4	3/4	0/8	0/9	0/3	0/10		

Note: x = relations recorded from the collected literature, o = possibly missing relations not recorded from the collected literature according to the authors.

step towards establishing a new design typology. Studies seeking to prove environmental benefits of a CE exist (Cooper et al., 2017; Eberhardt, Birgisdóttir, & Birkved, 2019; Ghisellini, Ripa, et al., 2018; Nasir, Genovese, Acquaye, Koh, & Yamoah, 2017). For example, Rasmussen, Birkved, and Birgisdóttir (2018) demonstrated how a Danish 'design for disassembly' building potentially reduced its' embodied greenhouse gas emissions from reusing the building components. It was found that 'design for disassembly' could reduce the buildings embodied greenhouse gas emissions by 36% if the concrete elements were subsequently reused (Rasmussen et al., 2018). In addition, another Danish 'upcycling' building showed 46% lower embodied greenhouse gas emission compared to the 'design for disassembly' building when building components and materials were reused and recycled up-front for the construction of the building (Rasmussen et al., 2018). Similarly, Eberhardt et al. (2019) found a potential 15% and 21% embodied greenhouse gas emissions reduction from a Danish office building when using the prefabricated concrete structure in one and two subsequent buildings respectively. However, there is still inadequate knowledge about the environmental implications of CE strategies (Adams et al., 2017; Eberhardt et al., 2019; Hossain & Ng, 2018; Ness & Xing, 2017). This is most likely due to the complex nature of buildings. For example, Eberhardt et al. (2019) demonstrate how the environmental performance of different building components and materials varies between different impact categories and, hence, the material composition has a significant influence on the building's overall environmental performance. The potential of the different building design and construction strategies will therefore most likely differ between different buildings, components and materials. Thus, design and construction strategies should differentiate between the flow of different buildings, components and material groups. Geldermans (2016) suggests an inventory matrix to help link different building components and materials to relevant biological and technical cycles. Potentially, this also means that it is not the environmental performance of the individual component or material that will be the determining factor in terms of CE, but rather it is how the component or material is used i.e. the use cycle. In addition, possible use cycles greatly depend on the quality, characteristics and value of the components and materials. This requires a better understanding of buildings' material metabolism.

Limitations of the study

As the publications that formed the basis for the SLR contained a wide range of literature that also included other literature reviews as well as systematic literature reviews (see Figure 2), we argue that the sample is large enough to capture the general research directions and different considerations in the field. Furthermore, we argue that using keywords related to CE, buildings and strategies captures building design and construction strategies currently perceived to enhance or enable CE in a building context, and this helps provide insight into how this field of research is developing and directions for future research (see Tables 1 and 2).

As CE is a concept that seeks to bring together pre-existing concepts with shared qualities and characteristics under one name (Blomsma & Brennan, 2017), other potentially relevant publications may have been excluded from this study as a result of only using keywords relating to CE. Thus, the 16 overarching building design strategies found from the reviewed literature should not be viewed as an exhaustive list. Hence, broadening the keyword synonyms to include pre-existing concepts such as eco-design, industrial ecology, cradle to cradle, etc. (EMF, 2016a) is suggested as future research to get a larger sample of studies to capture other relevant missing strategies that may have been overlooked by the industry. Furthermore, this will also help understand the evolution in the field, how CE has contributed to it, and where additional gaps may exist.

The study at hand overlooks parallel developments in science, policy and practices outside of the building industry that may also be important to consider. For example, it should be noted that other CE frameworks have been developed outside of the building industry aimed at product design and the manufacturing industry (Blomsma et al., 2018; Bocken et al., 2016; Mestre & Cooper, 2017; Reike et al., 2018). Although, these do not fit the complex nature of buildings, they may serve as valuable inspiration in the development of a new design typology for the building industry.

As previously mentioned, the building design and construction strategies were found to be interpreted and practised in different ways, with different goals across the reviewed publications. It cannot be ruled out that the design strategies found can be understood or used differently from what has been found in the publications reviewed. Hence, as many technical aspects of the individual strategies are still very unclear, there is still a need to establish a common terminology facilitating the understanding of each design and construction strategy.

Many of the design strategies overlap, i.e. they enable/enhance other strategies to a degree that cannot be ignored (see Table 2), and are believed to be related in ways that may not have been captured by this SLR. The apparent relation between the design and construction strategies suggests that multiple design strategies will be needed to support the move towards implementing CE in the building industry. This falls in line with the findings of Blomsma et al. (2018), who also demonstrates the related nature of various CE strategies. Blomsma et al. (2018) argue that the CE concept implies a shift away from implementing and assessing singular strategies towards assessing different configurations, i.e. situations where two or more strategies work together in sequence or in parallel. This fits well with the fact that most of the studies considered several different strategies as well as synergetic combinations between different strategies rather than focusing on a single strategy to reach CE goals. For example, the Circle House project used a combination of several of the strategies identified in Table 1 to reach a goal of 90% reuse or recycling of materials at the buildings' or components' end-of-life without loss of value (Partners Circle House, 2018). However, the literature did not give any insight into whether one design and construction strategy may potentially be limited or excluded by another strategy. Nor was there any insight into rebound effects from conflicting strategies such as *durability,* which aims at long or several performance-lives and *short use,* which aims at designing for specific use and shorter performance lifespans, see Table 1. *Assembly/disassembly* is the most commonly mentioned design and construction strategy in the selected literature. It is also the strategy likely to be enabled through most of the other identified strategies. Some of the selected literature viewed *assembly/disassembly* as the main design and construction strategy in terms of CE were the other strategies were means to reach this strategy (Rios, Chong, & Grau, 2015; Sommer & Guldager, 2016). Related to this, Geldermans (2016) found that circularity-values emerge at the intersection of specific intrinsic properties (material and product characteristics) and relational properties (building design and use characteristics). This also suggests that materials and products need to fulfil specific criteria in order to facilitate a CE. Some recent research has identified specific sets of conditions for individual strategies. For example, InnoByg (2018) and Geldermans (2016) identified preconditions for the performance of materials, products and buildings in relation to *assembly/disassembly*. The findings of this study also indicate that certain strategies are more relevant for some levels than others, i.e. building, component and/or material level. Further research is needed to better understand the strategies' nature and under which conditions strategy combinations contribute to an effective CE in the built environment to help establish a new design typology.

From the literature gathered it becomes apparent that a new design typology cannot stand alone, as there are multiple barriers hindering the adoption of CE in the building industry. For example, there are organisational, cultural and legal aspects, and these have been addressed in some recent literature (Adams et al., 2017; Hart et al., 2019; Leising, Quist, & Bocken, 2018; Mahpour, 2018). Thus, development of a new design typology should keep in mind the current barriers and drivers/enablers that have been identified in recent research. Some of the reasons why the CE concept has still not gained the impetus to catalyse the transition of the building industry include a lack of willingness to pursue CE due to strict work environment and health and safety rules, low productivity and high risk. In addition, one of the major challenges is that building projects consist of multiple processes, functions and stakeholders that are subject to change over time (Geldermans, 2016) and do not necessarily run in sequence but in parallel. Thus, facilitating a new design typology successfully means new framing around the problem, as the scope has been extended to include the whole building life-cycle. An important driver is the incentive to design for the whole building life-cycle, requiring new market mechanisms and business models, multidisciplinary industry mechanisms throughout the value chain. For example, early supply chain collaboration, new customer behaviours and resource management practices, as well as new distribution of responsibilities to identify synergies and possibilities to innovate (Adams et al., 2017; EMF, 2016b; Geldermans, 2016; Hossain & Ng, 2018; Leising et al., 2018; Sanchez & Haas, 2018b). In conclusion, this means that a completely different design process is needed, where focus is not on selecting building parties, but rather it is on selecting different disciplines needed to work closely together to reach CE objectives within the project (Leising et al., 2018). This could provide a well-defined project definition, potentially corresponding to a higher probability of project success in terms of sustainability (Sanchez & Haas, 2018b). However, it also requires trust as a cultural element in new supply chain dynamics and this includes non-traditional contracts in which collective aims and benefits are key instead of detailed specifications and distributed responsibility creating fragmented incentives to make the highest margins from one's own services (Leising et al., 2018). Hence, the success of a new design typology will potentially entail aligning different stakeholder interests throughout the value chain with environmental objectives.

Conclusion

Applying a SLR this article derived a taxonomy containing 16 overarching building design and construction strategies for a CE. Based on the analysis key findings outlined that developments in relation to the identified strategies are occurring, both in the scientific community as well as within the industry. However, these developments are happening independently of one another and this potentially indicates a missing link between research and practice. Thus, the choice of design and construction strategies in the publications were most often based on intuition as a result of the lack of knowledge about the environmental performance and related benefits of the strategies, i.e. which strategies have the biggest potential of minimising buildings' environmental impacts. This gap potentially hinders a more focused effort as well as a greater CE uptake in the building industry. To close this gap, we recommend developing a new design typology that structures and prioritises the strategies from Table 1 according to which strategies are promising for minimising building-related environmental impacts. To convey such a design typology to prioritise efforts, we suggest further research is needed:

- to assess the environmental performance of each of the different design and construction strategies in relation to the CE concept (i.e. whether the strategies minimise building-related environmental impacts)

We suggest that research is also needed:

- to capture potentially overlooked strategies from pre-existing concepts
- to explore parallel developments in science, policy and practise
- to establish a common understanding of each of the strategies identified and their technical aspects
- to further explore the interaction between different design and construction strategies
- to explore strategy combinations and determine under which conditions these combinations contribute to an effective CE in the built environment
- to link barriers and drivers/enablers in the development of such a new design typology

By systematising a comprehensive collection of building design and construction strategies for a CE, the research presented in the study at hand provides contributions for practitioners, with an overview of existing strategies for a CE in the building industry. The study also provides researcher with an understanding of the current developments and guidance on where to focus future research to conceptualise and advance the CE concept within the context of the building industry and further the discussion about CE in the built environment.

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ORCID

Leonora Charlotte Malabi Eberhardt http://orcid.org/0000-0002-8974-4537
Morten Birkved http://orcid.org/0000-0001-6989-1647
Harpa Birgisdottir http://orcid.org/0000-0001-7642-4107

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Appendix

No.	References	Location	Method(s)
1	Azcárate-Aguerre, Den Heijer, and Klein (2018)	Netherlands	Literature review Expert interview
2	Esa et al. (2017)	Japan	Systematic literature review Case study Framework
3	Nasir et al. (2017)	England	Literature review Case study Life cycle assessment
4	Chau, Xu, Leung, and Ng (2017)	China	Case study Life cycle assessment
5	Ellen MacArthur Foundation (2016b)	Unknown	Case study
6	Cheshire (2016)	England	Case study
7	Adams et al. (2017)	England	Survey Workshop
8	Akanbi et al. (2018)	England	Literature review Case study
9	Cooper et al. (2017)	England	Literature review Framework Tool
10	Sommer and Guldager (2016)	Denmark	Case study
11	Circle House Partners (2018)	Denmark	Case study
12	Kyrö, Jylhä, and Peltokorpi (2019)	Finland	Literature review Case study Framework
13	Fregonara, Giordano, Ferrando, and Pattono (2017)	Italy	Case study
14	Geldermans (2016)	Netherlands	Workshop
15	Ghisellini, Ji, et al. (2018)	China	Systematic literature review
16	Gálvez-Martos, Styles, Schoenberger, and Zeschmar-Lahl (2018)	Spain	Literature review
17	Hopkinson, Chen, Zhou, Wang, and Lam (2019)	England	Literature review
18	Leising et al. (2018)	Netherlands	Case study Framework Tool
19	Kurdve and De Goey (2017)	Sweden	Literature review Case study
20	Sanchez and Haas (2018a)	Canada	Framework
21	Sanchez and Haas (2018b)	Canada	Literature review Case study
22	Zimmermann, O'Brian, Hargrave, and Morrell (2016)	England	Case study Framework
23	van Sante (2017)	Unknown	Case study
24	Minunno, O'Grady, Morrison, Gruner, and Colling (2018)	Australia	Literature review Framework

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No.	References	Location	Method(s)
25	Rios et al. (2015)	USA	Literature review
26	Nußholz and Milios (2017)	Germany	Literature review Case study
27	Ness and Xing (2017)	Australia	Literature review Framework
28	Vandkunsten Architects (2017)	Denmark	Case study Life cycle assessment
29	Kleis (2013b)	Denmark	Case study Life cycle assessment
30	Kleis (2014b)	Denmark	Case study Life cycle assessment
31	Kleis (2013a)	Denmark	Case study Life cycle assessment
32	Kleis (2014a)	Denmark	Case study Life cycle assessment
33	Innobyg (2018)	Denmark	Case study
34	Pomponi and Moncaster (2016)	UK	Systematic literature review