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Service life for construction materials and products in a circular economy – a review

Lisbeth M. Ottosen, Ernst Jan de Place Hansen, Carsten Rode

Sammendrag

Hovedkonklusion:
Der er ikke fundet videnskabelig litteratur, som systematisk forholder sig til levetidsbegrebet i en cirkulær økonomi. Det er egentlig overraskende, idet levetid er helt centralt da cirkulære principper inkluderer levetidsforlængelse, genbrug (som forudsætter en restlevetid) og design af bygninger til lang levetid. I de identificerede videnskabelige artikler, er begrebet levetid anvendt i forskellige sammenhænge relateret til den cirkulære økonomi, og de diskuteres i dette manuskript.

Notatet er færdiggjort i juni 2024 som en del af afrapporteringen fra projektet 'Levetider for bygninger og bygningsdele – betydende faktorer og grundlag for modellering', gennemført i samarbejde mellem BUILD/Aalborg Universitet, DTU Sustain og DTU Construct i perioden 2021-2024. Enkelte redaktionelle rettelser er foretaget af Ernst Jan de Place Hansen i april 2025 i forbindelse med udgivelsen af notatet i VBN.

Notatet er et af fire notater, der tilsammen beskriver state-of-the art i forhold til faktorer som påvirker den faktiske levetid, sammenfattet i Ottosen et al. (2025)[1].

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[1] Ottosen, L. M., de Place Hansen, E.J., Morelli, M. & Rode, C. (2025). *Faktorer som påvirker den faktiske levetid – State-of-the-art. Sammendrag.* Kgs. Lyngby, DTU Sustain. 6 sider. DOI: 10.54337/010420252

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1. INTRODUCTION

Building and construction is pointed out as key product value chain in the transition towards a circular economy (CE) in the EU [1]. The sector requires vast amounts of resources - it accounts for about 50% of all extracted material. At the same time, the sector is responsible for more than 35% of the EU's total waste generation. Greenhouse gas emissions (GHG) from material extraction, manufacturing of construction products, construction, and renovation of buildings are estimated at 11% of total national GHG emissions [2]. Greater material efficiency is estimated to enable saving of about 80% of those emissions according to [1]. Thus there are huge incentives to transform the building and construction industry to be based on circular economy.

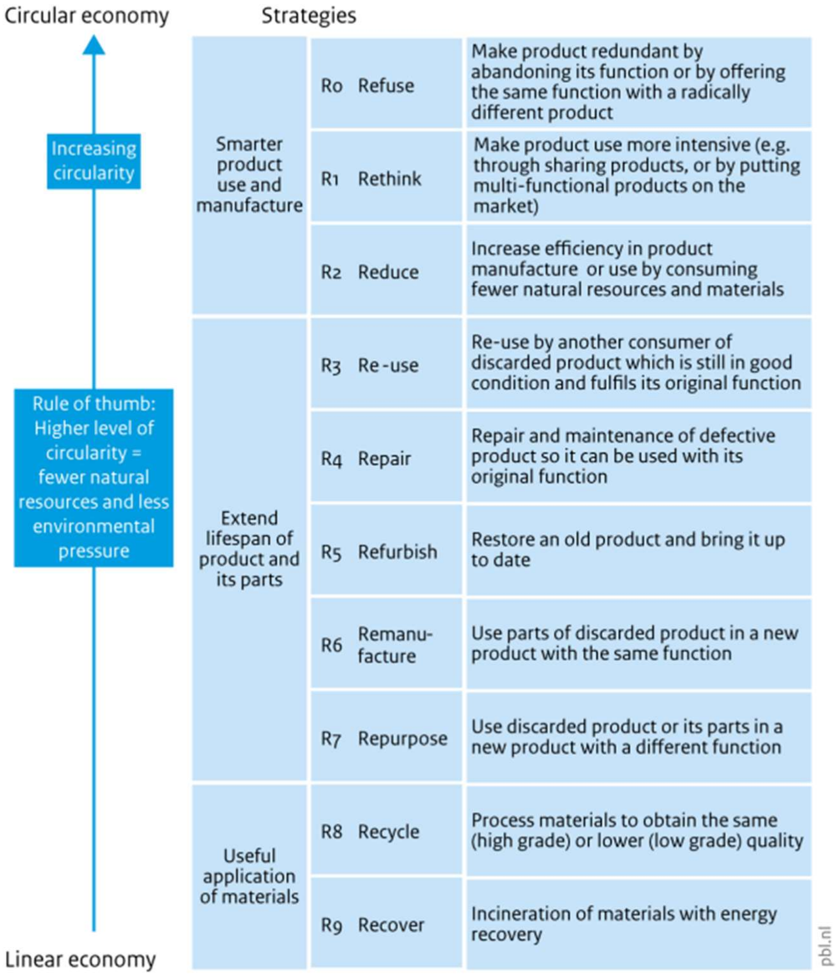
The European Parliament (2023) explains a circular economy as a model of consumption and production where the life cycle of products is extended, primarily thanks to a better environmentally friendly design that makes it easier to repair, reuse and reproduce old products, an improved durability, better waste management, and new business models based on leasing, sharing, repair and recycling. CE is defined by ISO [3] as "an economic system that uses a systemic approach to maintain a circular flow of resources by regenerating, retaining or adding to their value while contributing to sustainable development". Yet there is no agreed specific definition and terminology concerning CE in the construction sector, but European standardization is ongoing in CEN TC350/SC1. Still, it is seen from both definitions that centrally in the CE strategy is prolonging the lifetime through e.g. maintenance, remanufacturing and reuse. This calls for a new way of defining lifetime compared to the linear way of using materials and components.

To implement a circular flow of resources, it is of utmost importance to be able to evaluate the lifetime of construction materials, products, and buildings in each of multiple life cycles. In connection with this, it is of importance to develop a systematic approach combining circular construction and service life definitions. There is a need for a new terminology. *This report focuses on the research, which combines service life aspects and circularity strategies to map the current development of this terminology.*

1.1 Circularity strategies

The Waste Framework Directive [4] is the EU's legal framework for treating and managing waste in the EU. It introduces an order of preference for waste management called the "waste hierarchy": reduce>reuse>recycle>recover>landfill. Thus, the waste hierarchy forms the basis for the use of materials at the highest possible level. Waste prevention is rated the highest and products are being designed to reduce overall waste production. At the end-of-life of one life cycle, components can reenter the cycle or as the last alternative if polluted or without recycling options landfilled or used as backfill in mines, i.e. the component and materials in it are lost.

Moves forward should preferably include a shift to high-grade material recycling, and substantially higher volumes of product reuse, which is also the aim in almost all the CE Green Deal and CE Best Practice cases examined [5]. Recycling alone, and low-grade recycling, in particular, is still closely related to a linear economy. A more ambitious CE transition towards substantially lower resource and material consumption and less generation of waste will preferably be based on high circularity strategies, such as smarter manufacturing and use of products, and extending the lifetime of products and product components [5]. Potting et al. (2017) developed the "9Rs circularity strategies", which is a tool to prioritize circular options, see Figure 1.



Strategies			
Smarter product use and manufacture	R0	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1	Rethink	Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market)
	R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3	Re-use	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4	Repair	Repair and maintenance of defective product so it can be used with its original function
	R5	Refurbish	Restore an old product and bring it up to date
	R6	Remanufacture	Use parts of discarded product in a new product with the same function
	R7	Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9	Recover	Incineration of materials with energy recovery

Figure 1: The 9R2. Circularity strategies within the production chain, in order of priority. From [5]

Recognizing the need for a commonly accepted definition of circular economy, ISO published the standard "ISO/DIS 59004 Circular Economy – Terminology, Principles and Guidance for Implementation". In this standard, it is emphasized that the organization in a circular economy includes environment, social and economic systems based on the consideration that economic systems are embedded in the social systems, which in turn is embedded in the environment. The standard defines the term "circular economy" as an economic system that uses a systemic approach to maintain a circular flow of resources through recycling, maintaining or increasing their value, and which contributes to sustainable development. The mentioned standard is one in a series, the ISO 59000 series, which is designed to harmonize the understanding of the circular economy and support the implementation of quantification. The ISO 59000 series is not specific for any industry or sector. It is generic. There is a need for standards, which are sector specific for the building and construction industry, because of the special characteristics of this sector, such as the complexity of buildings and structures in e.g. the different lifetimes of components and not at least the often very long lifetime of the structural parts. In recognition of this, a number of European CEN standards are planned (under CEN TC350), which will be developed specifically for Circular Construction. Danish Standards is in charge of this work. The first of the standards "Principles, terms and framework for implementation" will come out as a draft in the spring of 2024. The scoping of the next standards in the series are expected to be initiated in the same period.

1.2 Circularity strategies and service life prediction

The service life is the period of time after installation during which materials and components meet or exceed the performance requirements [6]. The service life of materials and components can be longer than the service life of many buildings, and this difference constitutes the option for reuse. In the linear economy, service life for a material or component defines the time until the end of life (replacement, renovation or demolition). This is also the case in a circular economy, but here the material or component can have *multiple lifetimes*. Terms and definitions for this are not yet fully developed.

Different terms for service life are defined in ISO 15686 in relation to estimating or predicting the service life [6]. The *estimated service* life for a building or parts of a building is the service life that would be expected in a set of specific in-use conditions, and it is determined from reference service life data after taking into account any differences from the reference in-use conditions [6]. *The predicted service life* is predicted from performance recorded over time (in accordance with ISO 15686 Part 2: Service life prediction procedures). The *reference service life* is the service life of a product, component, assembly or system, which is known to be expected under a particular set of conditions, i.e. a reference set, of in-use conditions and which can form the basis for estimating the service life under other in use conditions [6].

Buildings and components suffer various types of depreciation throughout their life cycle, eventually leading to their obsolescence and the end of their service life. The service life is conditioned by several factors: physical deterioration, functional obsolescence, technological obsolescence, changes in the social context, aesthetic or legal obsolescence, and environmental obsolescence [7]. The concept of service life seems to be reasonably simple, although different definitions and different types of service life can be found in the literature: (a) planned service life/ design service life/design working life, (b) required service life, (c) economically reasonable working life, (d) functional service life, (e) social, aesthetic and legal service life, (f) technological service life, (g) reference service life, (h) estimated service life, and (i) predicted service life [8].

What is needed in relation to the circular economy is a service life terminology that is linked multiple use cycles and covers each cycle. If stating an estimated service life in a circular economy, it should cover both the actual use and multiple uses. In a circular economy, the ability to predict the remaining service life at a given point in the construction material or products lifetime is of utmost importance to the implementation of the circularity strategies, and especially the strategy of extending the lifespan of products and their parts (R3-R7 in Figure 1). Evaluating the remaining service life is not straight forward, as the decay of construction materials and damage of components are not linear.

1.3 Aim of review

This review outlines how the scientific literature incorporates service life prediction in circular strategies and assessments in the construction sector. ***The aim of this report is to explore if there in literature is a systematic approach on how to link terminologies for service life and circular construction and to outline the possible gaps between the two.***

2. METHOD

A systematic literature review in two parts was performed. The search words were agreed on by the authors of the report through multiple discussions. The search was designed with the base in “service life” and “construction materials”. Extra search words were added to the basic searches, and the number of publications was noted for every case. The sets of search words used can be seen in Table 1. They were service life and construction materials in combination with circular economy or circularity, and further reuse, maintenance, aging, degradation, durability, transformation, renovation, and LCA. The term “service life” was used in most searches as this is the term used in ISO 15686-1 [6]. However, a few additional searches on remaining lifetime or lifetime in combination with construction materials and circular economy were also conducted.

After narrowing the number of publications into a manageable number in a search string by extending the string by relevant keywords, the abstracts were read. This resulted in some of the papers being excluded, as they were found irrelevant to the topic. The papers selected as relevant were those with a focus on lifetime prediction related to a circular strategy.

The literature search was finalized on 20. October 2022 using DTU FindIt, the library database of the Technical University of Denmark, which covers approximately 190 million articles from scientific journals and subject databases, 530,000 e-books, and a printed collection of 308,000 books. The search covered papers in international journals.

3. RESULTS AND DISCUSSION

3.1 Overall results – selected papers

The overall outcome of the literature search is given in Table 1. It is seen that as soon as the search string includes the term circular economy, the number of papers is limited.

The aim and major conclusions of the selected papers stated in Table 1 can be found in Appendix A. *None of the papers presented a systematic approach (or part of an approach) in combining circular strategies and service life terminology.* However, in one of the papers it was stated that “time-dependent technical-functional quality functions should be developed further, as they require a dedicated approach for each material separately” [22] which points at the need for a new system, when dealing with circular solutions.

Table 1: Search words and strings, hits, and selected papers based on the reading of abstracts. Italic marks when the reference is new compared to earlier search strings in the table ("-" marks that neither of the papers was evaluated as relevant to the present investigation).

Search strings	**Hits**	**Selected papers based on abstract**
Service life, construction materials	9398	
Service life, construction materials, reuse	231	
Service life, construction materials, reuse, circular economy	32	In total 15 papers: [9][10][11][12][13][14][15][16][17][18][19] [20][21] [22] [23]
Service life, construction materials, circular economy	77	In total 23 papers – 9 new [9] [10] [11] [13] [14] [15][16] [17] [18] [19] [20] [21] [22] [23] [24][25] [26] [27][28] [29] [30] [31][32]
Service life, construction materials, circular	111	
Service life, construction materials, circularity, reuse	27	[9][10][11] [12] [13][14] [15] [16] [17][18] [19][21] [20] [33]
Service life, construction materials, maintenance	1397	
Service life, construction materials, maintenance, circular economy	9	[20]
Service life, construction materials, ageing	1112	
Service life, construction materials, ageing, circular economy	7	[9]
Service life, construction materials, degradation	706	
Service life, construction materials, degradation, circular economy	7	-
Service life, construction materials, degradation	198	
Service life, construction materials, degradation, reuse	9	-
Service life, construction materials, transformation	340	
Service life, construction materials, transformation, reuse	7	[10][13]
Service life, construction materials, renovation	87	
Service life, construction materials, renovation, reuse	10	[17][21] [33][34] [35][36][37][38]
Service life, construction materials, LCA	279	
Service life, construction materials, LCA, reuse	23	[12] [17][18][20][37] [39][40][41]
Service life, construction materials, LCA, circular economy	14	[16][17][18][20] [24] [42]
Remaining lifetime, construction materials	361	
Remaining lifetime, construction materials, reuse	11	[10] [34][43][44][45][46]
Lifetime, construction materials	5533	
Lifetime prediction, construction materials	634	
Lifetime prediction, construction materials, circular economy	3	-
Lifetime, construction, circular economy	36	[43][45][47][48] [49][50]

3.2 Perspectives on service life and circular economy from literature

The identified literature contained very little relating circular principles to terms related to lifetime. *Since the interest and implementation of in reuse of components at large scale have had no focus until recently in the industrialized construction sector, the knowledge on the status of the construction materials and components is limited at the end-of-life, and thus inputs to estimate the remaining service life based on current knowledge are limited.* This observation is in accordance with [36]: too little focus on either a building's serviceability, or the management of its service life (i.e. the service lives of its parts and elements) is given.

Some discussions in the selected papers point to the very different needs for terminology in the circular and linear systems related to lifetimes. Some major differences are listed here:

- *Design for multiple lives*

In a circular economy, design must enable maintenance and reparability to extend lifetime in each of multiple uses. An efficient process for the recovery and reuse of construction materials should include a design proposal that takes into consideration the parameters determined from an inspection of the condition of the debris, an assessment of the potential environmental impacts, and an estimation of the related costs. Such a design can be instrumental in offering a less costly and more environmentally friendly alternative to landfills [40]. Deconstruction recommendations, with methods and strategies to apply independently on the different constructive systems and materials, that can enable more sustainable solutions for the end of life of buildings, in a construction sector where buildings are mostly designed to be demolished and not deconstructed [1]. Subtle changes in the core facility function, such as in products' purchase approach, delivery of ongoing maintenance and refurbishment of building assets, and end-of-life management, possess the potential to enable circularity. Thus, within the buildings' operation realm, a dedicated service stream, such as the facility service, can contribute to realizing circularity for facility service providers' commercial clients [31].

- *Temporary buildings*

In a circular economy, temporary buildings must be designed for reuse. The cases have been selected according to three basic issues, which characterize each of them: temporariness [28]. The case project concerns a temporary building made of leased materials and building components such as shipping containers, scaffolding materials, and lifts. The major research question for the case is how the supplier's continued ownership of the building materials influences the sustainability of such buildings [39].

- *Design for durability*

Design for durability can be an important term. A focus is currently neither on a building's serviceability, or the management of its service life (i.e. the service lives of its parts and elements), nor is there much evidence of a serious life care replacement practice that optimizes on the durability properties of the supply chains specified or used [36]. Finding circular technologies suitable for enhancing a building's service life and closing material loops is important [26]. Proposal of a Total Value of Ownership (TVO) method to evaluate the financial performance of a building energy retrofit in terms of Net Present Value, comparing a matrix of scenarios was given in [29].

3.3 LCA and service life

According to EN 15978:2012 and DIN EN 15804:2014, the LCA information is structured in the lifecycle sections of buildings and the materials used therein. This specifies the exact time expected within the life cycle, as well as the extent to which certain effects can be quantified from the use of buildings or the building products. The LCA information is subdivided into the environmental impacts of the building, through to the completion of a building (module A), the environmental impacts during its use (module B), and the expenses at the end of the buildings life cycle (module C). An additional module D summarizes all benefits and loads outside the system boundaries. Module D declares the advantages or loads associated with raw material properties due to reuse, recovery, or recycling of a construction product.

Service life prediction is an inevitable part of life cycle assessment and is aligned with life cycle costing [42]. LCA shows that durability, in terms of service life, is directly related to the environmental impact [37]

There is a lack of reliable LCA data for the most critical stages in reuse such as deconstruction, sorting, quality check and re-distribution of materials and components. These gaps in lifecycle inventory databases have to be addressed in the future [33]. The potential benefit of reusing and recycling the materials and components is not gained immediately but at the point of future retrieval [27]. What is not obvious, however, is the future circumstances in which the environmental impacts and future reuse or recycling will occur along with how long these material loops can be maintained as the changes in the inherent properties of the materials resulting from *reuse and recycling are not taken into account as it is still not determined how to account for it within LCA* [27].

In a circular economy, a combination of LCA and material flow analysis (MFA) is needed in order to account for all the Rs between R4 and R9 in the assessment. MFAs are made to determine how waste reduction, reuse and recycling of mineral construction and demolition waste is generated [21]. The high levels of uncertainty for long-lived products propagates to the analysis of the material flows. The same product category can have very different lifetimes depending on the country or circumstances, which makes it problematic to use data obtained in one area to another [45]. The estimated service life of buildings is necessary in order to foresee the available materials and components for reuse and plan the next constructions and renovations with these. The availability of a methodology is crucial in asserting critical data regarding the waste volume generation and thus enabling CDW recycling as a viable economic activity [48].

3.4 Base for a systematic approach to circular strategies and service life terminology

None of the papers presented a systematic approach (or part of an approach) in combining circular strategies and service life terminology. However, in one of the papers it was stated that "time-dependent technical-functional quality functions should be developed further, as they require a dedicated approach for each material separately" [22], which points to the need for such a systematic approach.

In a circular economy, single lifetimes do not exist (if so, it would be a linear economy). The service life as we know it from the linear system cannot cover the circular principles (Figure 1) with multiple lifetimes, and lifetime extensions. Since we did not identify a systematic approach combining service life terms and circular strategies and principles in the literature review, we will here present a preliminary take on the issue:

1) *Before a life cycle* starts, reused components have served in other buildings, and new components are planned for multiple life cycles e.g. through strategies for design for disassembly, design for deconstruction and design of temporary buildings. There is no service life terminology and concept which covers this.
2) *A life cycle* starts when a component (new or reused) is placed in a building. The life cycle ends when it is removed from the same building. The period in between is the service life for the actual life cycle. The concepts from the linear system could possibly be used to cover each single life cycle separately.
3) *During the lifecycle* maintenance and repair of components and parts are carried out to extend the technical lifetime (as often done in the linear system). This influences the possible lifetime in the next cycle.
4) *End of life (of multiple cycles)* In relation to remanufacture and repurpose reuse, parts of the product/building are used in new products/buildings, and this means the end-of-life cycle of the original product, and that the materials or component parts are released as raw materials for production of new components. There might be a need for terms showing that the new component contains parts which have already been through multiple lifetimes. Such a term would enable the choice of such components over components made solely from primary raw materials.

Our system combines the circular strategies R3 to R7 (Table 1) and different types of service life (listed in [8]). In relation to recovery of materials (e.g. recycled concrete aggregates or wood for fiberboards), this is considered as end-of-life for the products and components, and the raw materials are entering a new (multiple) life cycle in the new product, where they are used, and the products starts their service life.

Table 2: Circular economy principles (from 9Rs) and different service lives.

Circular principle	**Type of service life relevant**	**Comment**
Reuse by another consumer of discarded products which is still in good condition and fulfils its original function (R3)	**Predicted lifetime** - service life predicted from recorded performance over time [6]	The predicted lifetime is highly relevant related to reuse because it is important to be able to evaluate the *predicted lifetime at the start of the reuse cycle* to decide if the reused product fits the purpose. A *predicted lifetime over multiple uses* is also necessary in order to compare different products.
Repair and maintenance of defective product so it can be used with its original function (R4)	**Estimated service** life that a building or parts of a building would be expected to have in a set of specific in-use conditions, calculated by adjusting the reference in-use conditions in terms of materials, design, environment, use and maintenance [6]	The estimated service life can support the planning of repair and maintenance actions. It can also support if the component has a sufficient estimated lifetime to fulfill the requirements from the next use, or how it can possibly be reused.
Refurbish to restore an old product and bring it up to date (R5)	**Technical service life** period of time after construction until the building is no longer technologically superior to the existing alternatives [6]	The technical service life determines when end-of-life (for all cycles) is reached, however, in the circular construction, it should be investigated if refurbishment might be possible, and hereby enable more cycles.
Remanufacture is to use parts of discarded product in a new product with the same function (R6)		In relation to remanufacture, repurpose and reuse, parts of the product/building are used in new products/buildings, and this means the end of the original life cycle. They are instead incorporated in new products. A terminology might be needed to cover this status to distinguish the raw material from discarded products from new.
Repurpose is to us discarded products or its parts in a new product with a different function (R7)		

4. CONCLUSION

There is yet no systematic approach in scientific literature that combines the principles in a circular economy and the terminology and principles related to different definitions for service life. Nevertheless, *it is important to develop such a systematic approach since implementation of the circular economy principles is central in the European strategy* for the future sustainable developments. There is a need for new terms covering e.g. lifetime, when a component passes several use phases and to open the term estimated lifetime to being both the starting point in a new use phase and being the base for repair and maintenance plans in the actual use.

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Appendix A- Aim and key conclusions in the selected papers

Aim	Key conclusion	Ref.
Deconstruction recommendations, with methods and strategies to apply independently on the different constructive systems and materials that can enable more sustainable solutions for the end of life of buildings.	Building deconstruction can be achieved by defining the following key points during the building planning and design process, independently from the constructive system type. (1) The reduction of building complexity, minimizing the number of components and types, favoring the modularity and lightness of the components, as well as the use of prefabrication and the simplification of the connections between the structural and non-structural elements. (2) Smart choice of the materials to be used for the construction, favoring the use of reusable and eco-compatible materials and minimizing the use of hazardous materials and compositions. (3) allow the access to the information regarding building construction and deconstruction, with the instructions to follow for the correct identification and dismantling of components and the following instructions about their possible reuse or recycle. (4) Define a deconstruction methodology for the whole planning process to include deconstruction principles at every lifecycle stage, so as to ascertain the potential for deconstruction and reuse at each stage of the process (design, production, construction, use, and end of life).	[9]
Create value from remanufacturing products of buildings at end of service life into high value durable products with minimal re-processing.	Whilst there are considerable challenges in reclaiming structural products that re-designed circular building and construction system could transform the value of end of service life buildings and the offers new opportunities for circular innovation and the circulation of materials and products at their highest value for the longest period.	[10]
Structured information for the basis of organizing the future cities through circular economy	The number of different and sometimes optional CE solutions to be applied in built environment is large and growing with accelerating speed, highlighting multidisciplinarity and complexity of the field. To stay up to date on development of the paradigm, cities need a database that consists of an interconnected and continuously supplemented set of best practices along with proper evaluation methods. The value in the CE paradigm is strengthening communication on practices and broadly shared vision for sustainable cities.	[11]
Quantify potential environmental and economic benefits of designing the buildings concrete structure for disassembly, with the purpose of reuse, as well as to exemplify how circular economy can be applied in future building projects.	The study demonstrates an improved environmental performance of the office building when designed for disassembly. Furthermore, the choice of building materials has a noteworthy influence on the building's embodied environmental impacts. From the results obtained in this study it is estimated that the potential environmental impact savings as well as economic benefits can be further increased through a higher degree of design for disassembly.	[12]

Compare algorithmic formulations for reuse-driven design.	Introduces a new Grasshopper-based tool that implements them, and demonstrating their application on a case study. Both flexible design space exploration and efficient optimization are obtained by the use of the Hungarian Algorithm in a nested loop workflow. For small problems, the material reuse efficiency is computed in real time; for larger problems in a few seconds. The potential of this approach and tool are demonstrated on a real world case study that will be explored through physical experiments in future work.	[13]
Develop and demonstrate an integrated systemic “service” composed of different circular technical solutions in the current housing value chain.	The current building sector’s business model must be redesigned to include the application of new and improved methods, solutions and innovative services, and advance a positive transition from a linear economy to a circular economy. The demonstration will include technologies to circulate all process flows while reducing the overall energy demand. (The paper describes the project.)	[14]
Reuse of blocks cut out of obsolete cast-in-place concrete walls for a new structural application	A 10 m-long posttensioned segmented arch footbridge.A comparative life cycle assessment shows that the arch construction presents a significantly lower global warming potential then recycled concrete (~ 71%) or steel (~ 74%) alternatives and is very competitive to a timber one (+9%). In conclusion, the project proves the feasibility of a new circular economy application for the construction industry, in which new and reliable concrete structures are built with little to no cement inputs.	[15]
Assesses the embodied GHG emission reduction potential of the reuse solutions from the Resource Block: when virgin materials in the new buildings are substituted with secondary materials from the existing buildings.	The results show that reuse of these elements may on average potentially save 49% of the new buildings’ greenhouse gas emissions compared to building solely with virgin materials depending on the availability and degree of reuse and which types of virgin materials the reuse is combined with.	[16]
Promote the transition of Danish affordable housing to a CE by developing a framework for assessment, evaluation, and cost-benefit analysis of the efficiency and effectiveness of CE while integrating environmental, economic and social co-benefits.	Part of an overall research project called "Circular transition of affordable housing: Generating environmental, economic and social co-benefits by design". We critically discuss the concept of CE and aim to understand how and when integrated life cycle assessment could occur in a circular construction process to support evidence-based decision making and contribute to the transition to a circular economy for the affordable housing sector. Below this aim is another aim to identify the type, time and format of information that can support housing associations’ and architects’ decision-making at the various design stages in a social cost-benefit analysis regarding efficiency and effectiveness of CE.	[17]

Quantified assessment of the potential environmental and financial benefits and burdens of introducing circular design alternatives for internal wall assemblies.	Reviews the methodological implications on the results of a consequential life cycle assessment (LCA) and a life cycle costing (LCC), acknowledging the time dependence and closed-loop nature of those circular design alternatives. Altogether, this case study points out the potential benefits of introducing demountable and reusable walls, but highlights at the same time the need for a comprehensive sustainability assessment before responsible conclusions can be drawn.	[18]
Maintaining the circularity of the building materials through optimal deconstruction.	the central analyses focus on deconstruction properties, EoL paths of the sorted deconstructed building materials and the material compatibility of building materials remaining in the composite. With the focus on design guidance in the evaluation steps and the transparent presentation of the intermediate results, central influences on the circularity of buildings are revealed: the choice of materials and the choice of the installation situation. If materials are chosen whose end-of-life scenarios are similar, the installation situation can fade into the background. However, if one material within a composite significantly influences the EoL scenario of another material, the an alternative construction method has to be considered and a disassembly-oriented design has to be worked out. Furthermore, the question is raised whether there are alternative material combinations that yield a more valuable end-of life scenario.	[19]
Examine the relevant literature on construction circularity to address the knowledge gap.	Internal drivers were identified to consist of BIM (Building Information Modelling)-based design and evaluation, IoT (Internet of Things)-based material tracking, predictive data analytics, and logistics network optimization. External drivers included material certifications and legislation, financial incentives, market maturity and material flow balance, and social engagement. The review revealed that the BIM-based and LCA-based methods have been widely used; however, logistics network optimization to allow industrial symbiosis was not adequately addressed in the existing literature. The strategies and drivers were also composed into a framework to guide the future implementation of circular construction projects. The framework could help construction researchers and project participants clearly understand circular resource flows across various construction supply chain stages and thus help them to keep up with the global action of “Net Zero Emission” by 2050.	[20]
Use of material flow analysis to determine how waste reduction, re-use and recycling of mineral CDW generated in a city can contribute to reduce the demand of raw material imports for construction minerals	Case study of the city of Vienna. The results show that the annual consumption of construction minerals of 4.5 million tons can be reduced by 32% to 3 million tons by implementing the waste hierarchy to CDW. The most important measures are the use of recycling materials from mineral construction and demolition waste as recycling aggregate in concrete (575,000 t/yr), followed by the use of recycling material to substitute gravel in unbound form (463,000 t/yr), avoiding the demolition of historical buildings by extending their service life (230,000 t/yr),	[21]

	asphalt recycling (85,000 t/yr), and substitution of raw-mix in cement by recycling material from debris (84,000 t/yr). Reuse of full bricks (17,000 t/yr) is of lesser relevance. To implement this enhanced circularity scenario, however, efforts in installed technology, construction and demolition waste management as well as legal and entrepreneurial measures are required.	
A comprehensive Circular Construction Indicator (CCI) is introduced. First, an investigation of the state-of-the-art is performed to find partial indicators that can contribute to the CCI. In addition, existing partial indicators are amended, and new ways to measure certain aspects are introduced.	In this study, a new CCI framework is introduced. Contrary to previously developed CIs, it allows one to evaluate the circularity of a complete construction project by making a diversification between the design, construction, and EoL phases. For each phase, the aspects of circularity that are relevant in the concerning phase are considered. The contribution of this CCI framework over previously proposed CIs is that it presents methodologies to objectively evaluate the reusability of components in the EoL phase, both in the case where the construction has reached its design service life, as in the case where the construction would be disassembled at a different point in time. Future research will need to focus on establishing weighting factors to combine the different reusability indicators. Moreover, time-dependent technical-functional quality functions should be developed further, as they require a dedicated approach for each material separately.	[22]
This paper reports industrial joint research to develop an integrated platform-based digital tool that seamlessly incorporates circular economy principles into construction processes, focusing on circular resource utilization in the building envelope components life cycle.	By combining different platforms and services from the previous research, this study's results enhance and integrate comprehensive thinking approaches and services. These include promoting raw material substitution, reducing supply chain arrangement time, minimizing waste throughout the building component lifecycle, enhancing disassembly processes, and improving life cycle environmental assessments. The tool design was informed by user-driven narratives and requirements, and demo case testing procedures, ensuring usability and industry relevance. Furthermore, integration with product lifecycle management software and data management platforms enhanced data sharing and accuracy. This study highlights the potential of integrated tools to revolutionize supply chains and promote circular economy, transforming construction paradigms. They can contribute to the reshaping of material management towards environmental consciousness, fostering resource-efficient green building solutions, and enabling more circularity in the construction industry.	[23]
An integrated assessment method that considers indicators for environmental impacts and economic benefits by combining Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) with	We demonstrate its benefits and limitations taking the Swiss canton of Aargovia as an example. We analyze which processes in the material flow system of construction minerals are decisive for formulating mass-related or financial policies encouraging a CE.We show that a shift toward a CE can only be captured by combining material and money flows in a joined model, because a significant increase of services—mainly waste management—is a core element in this	[24]

Input-Output Analysis (IOA) as the connecting element.	development. It can only be covered sufficiently by combining environmental and economic assessment. Our model captures the degree to which a regional economy is advanced in the transition toward a CE to compare different regions or analyze scenarios of future developments.	
Analyze and compare approaches regarding the different methodologies proposed for structural pavement rehabilitation with recycled materials.	The results demonstrate that the implementation of pavement rehabilitation techniques using recycled materials and based on a circular economy approach is the most advantageous and sustainable strategy and can be considered at design level. Using a simplified analysis, it is possible to overcome the limitation in resources toward making the best decision.	[25]
Finding circular technologies suitable for enhancing a building's service life and closing material loops.	The study's assumption is that synthetic and reliable indicators for that purpose could be based on reversibility and durability features. The paper provides an overview of building design issues within the circular economy perspective, highlighting the difficulty in finding circular technologies which are suitable to enhance buildings' service life while closing material loops. The results identify reversibility and durability as potential indicators for assessing circular building technologies. The second part highlights, from the literature overview conducted, the difficulties in finding circular technologies suitable for enhancing a building's service life and closing material loops. Reversibility and durability are then proposed in the third part (results) as possible indicators for assessing the circular potential of building technologies, while the next research stage is aimed at further developing the rating of both construction materials and whole buildings through the application of Circular Design strategies. Reversibility and durability are then proposed in the third part (results) as possible indicators for assessing the circular potential of building technologies, while the next research stage is aimed at further developing the rating of both construction materials and whole buildings through the application of Circular Design strategies.	[26]
Demonstrating variations in life cycle environmental impacts and material flows when supplying buildings with linear components compared to prospective circular designed building components for reuse and recycling and how they are modelled in life cycle assessments	It becomes clear that the potential benefit of reusing and recycling the materials and components is not gained immediately but at the point of future retrieval i.e. in the case of the column this happens 80 years into the future. What is not obvious, however, is the future circumstances in which the environmental impacts and future reuse or recycling will occur along with how long these material loops can be maintained as the changes in the inherent properties of the materials resulting from reuse and recycling are not taken into account as it is still not determined how to account for it within LCA	[27]

Critical collection of case studies and design experiments of buildings which have technological characteristics and design qualities which allow, regardless of their different uses or intervention contexts, consideration as buildings with a circular potential and are therefore prepared for the transition to the circular economy.	The cases have been selected according to three basic issues, which characterize each of them: temporariness, Low Tech and circularity. The collection is organized by grouping the cases into three areas which refer to the main scopes affected by the solutions adopted in each case: design, building and living. The overall objective of this survey is to highlight the development of new technical and living models in building design and production, triggered by the need to save resources and reduce waste.	[28]
Total Value of Ownership as method to evaluate the financial performance of a building energy retrofit in terms of Net Present Value, comparing a matrix of scenarios.	Proposes a Total Value of Ownership method to evaluate the financial performance of a building energy retrofit in terms of Net Present Value, comparing a matrix of scenarios. Results show that – when accounting for capital and opportunity costs tied to alternative investments, internalising externalities, and monetising soft values such as user productivity and property value – a PSS model can deliver the highest NPV. Furthermore, results show that a PSS alternative can act as a positive future-proofing strategy to safeguard the building owner's position in the face of uncertain future market indicators and carbon taxation. Recommendations for policymakers, investors, financiers, building owners, and end-users are presented to identify the economic value of PSS contracts, leading to better-informed decisions which can accelerate deep energy retrofit of the building stock.	[29]
The study formulates and validates a novel BCI called the Whole-Building Circularity Indicator (WBCI), built upon a critical analysis of existing literature and previous methodologies.	This paper has developed and validated an innovative circularity assessment model called the Whole-Building Circularity Indicator (WBCI) through a comprehensive review of existing tools, mathematical modeling, and a case study of an existing building.	[30]
To explore the fundamental basis necessary to conceptualise circular economy in facility management practices and identify areas for circularity-oriented actions.	As key findings, subtle changes in the core facility function, such as in products' purchase approach, delivery of ongoing maintenance and refurbishment of building assets, and end-of-life management, possess the potential to enable circularity. Thus, within the buildings' operation realm, a dedicated service stream, such as the facility service, can contribute to realising circularity for facility service providers' commercial clients.	[31]
This study focused on the expected product lifetime and constructed a framework to analyze this potential, using air conditioners in Japan as a case study.	When the expected product lifetime increased by 1, 2, and 3 years, the mean actual product lifetime rose by 0.9, 1.8, and 2.72 years, respectively, whose values can be sufficiently recognized as potentials for product lifetime extension. The results indicate that products and services for product lifetime extension can actually be used by consumers. Therefore, business strategies for product lifetime extension can increase resource efficiency and potentially strengthen competitiveness in future resource constraint economies.	[32]

Create a better understanding of the end-of-life scenarios of building structures and the possible ways in which the environmental, economic and cultural values of their components can be preserved.	Approach all aspects of sustainability equally as well as all aspects of the major building materials.The standardization process and the recent changes in the environmental certification systems indicate that the importance of life-cycle assessment of buildings and components will grow in the near future. However, there is a lack of reliable LCA data for the most critical stages in re-use such as deconstruction, sorting, quality check and re-distribution of materials and components. These gaps in lifecycle inventory databases have to be addressed in the future.	[33]
Quantify the mitigation potential of material efficiency strategies, through a developed model that simulates the temporal material flows and greenhouse gas embodied emissions of the material use in the construction and renovation activities of a neighborhood by combining life-cycle assessment with dynamic material-flow analysis methods.	Although 52% of the total GEEs are caused by material use during initial construction, the remaining 48% are due to material replacements in a larger timeframe of 45 years. Hence, it is urgent to act now and design for ME over the whole service life of buildings. GEEs occurring far into the future will, however, have a reduced intensity because of future technology improvements, which we found to have a mitigation potential of 20%. A combination of ME strategies at different points in time will best mitigate overall GEEs. In the planning phase, encouraging thresholds on floor area per inhabitant can be set, materials with low GEEs must be chosen, and the buildings should be designed for ME and in a way that allows for re-use of elements. Over time, good maintenance of buildings will postpone the renovation needs and extend the building lifetime.	[34]
Investigates how component design and different construction methods influence the salvage ability for reuse in order to avoid down-cycling.	The results show that the single brick itself has great potential as a reusable component. Simplicity and small scale provide a unique architectural flexibility, which increases the potential for a second service life.	[35]
Building's serviceability, or the management of its service life (i.e. the service lives of its parts and elements)	Too little focus on either a building's serviceability, or the management of its service life (i.e. the service lives of its parts and elements) is given, nor is there much evidence of a serious life care replacement practice that optimises on the durability properties of the supply chains specified or used. There must be an understanding that the design vivendi proposed applies equally to new and existing buildings. Concluding, adopting a 'design for durability' approach should encourage client organisations and their design and project teams to improve the reliability and whole life cost management of their buildings. But, the major players may well tun out to be those involved in life care and building life management and those that fund or insure buildings underpinned by this new vivendi for design for durability with manufacturers offering service life products.	[36]
Eco-efficiency and building optimization potential of prefabricated structures to be used in new buildings are studied, focusing on the analysis of a novel dry	LCA shows that durability, in terms of service life, is directly related to the environmental impact. However, other design options, such us re-using, have less repercussion in the impact categories (i.e. Global Warming Potential and Embodied Energy), and in the global cost.	[37]

precast beam-column connection under different durability and re-using scenarios.	Results from this research could contribute to the implementation of prefabricated elements in the building stock promoting eco-efficiency	
How the component design influences the reusability.	Case study. Massive wood is considered to be an environmentally beneficial building material, however it is not common to design components for a second service life. The criteria used are: limited material selection, durable design, high generality, flexible connections, and access and in-formation. The results indicate that there are great potentials to improve the reusability for the most commonly used components types. Improved generality of the components will give architectural flexibility in a second service life, which is crucial to increase the likelihood of reuse.	[38]
Improve the sustainability of temporary buildings, a Product/Service-System (PSS) strategy is here applied to a case project.	The case project concerns a temporary building made of leased materials and building components such as shipping containers, scaffolding materials and lifts. The major research question for the case is how the supplier's continued ownership of the building materials influences the sustainability of such buildings. The validation of the improved sustainability of the PSS-based building solution is achieved by comparing the PSS with a corresponding conventional approach for the temporary building through a comparative Life Cycle Assessment (LCA). The results show that over the entire life cycle, the aggregated environmental impact score for the PSS solution is 27% lower than the conventional solution when including operational energy and 37% lower when operational energy is excluded.	[39]
Quantify the potential environmental impacts and the economic feasibility of reusing waste material in new constructions with an applicable design solution.	This study demonstrated that an efficient process for the recovery and reuse of such materials should include a design proposal that takes into consideration the parameters determined from an inspection of the condition of the debris, an assessment of the potential environmental impacts, and an estimation of the related costs. It was further determined that such a design can be instrumental in offering a less costly and more environmentally friendly alternative to dumping the rubble into landfills. The findings of this study will help fill the current gap in the literature regarding the LCA of walls, with a focus on the strength and condition of the wall material after demolition has taken place.	[40]
A method to design reticular structures with minimal environmental impact made from reused and new elements.	The LCA carried out in this work accounts for impacts generated from sourcing reclaimed elements to the assembly of the structure. Structural optimization is subject to stress constraints on element capacity and deflection limits for serviceability. The formulation given in this paper is based on a combination of LCA and discrete structural optimization.	[41]

This study adopts a systematic literature review method to find a total scope of key approaches to CE.	Despite the great potentials of CE strategies, past research focused on investigating the LCA methods or experts' opinions to partially identify the benefits and drawbacks of the specific CE approach adopted in construction projects. An overview of exactly what and how the different available approaches could contribute to CE remains missing from the existing body of knowledge but requires systematic investigations. Service life prediction is an inevitable part of life cycle assessment and is aligned with life cycle costing. The building lifespan has significant effects on the overall environmental performance of a building. For example, the longer the lifespan and more reuse cycles, the less embodied environmental impacts. Therefore, an accurate prediction of the life span of building elements and the number of life cycles is considered essential to allow a reliable planning process for CE. Detailed mathematical prediction models were not seen from the selected articles, but it is likely they were excluded earlier during the literature search. However, many LCA-related case studies in the selected literature referred to norms and standards (e.g., ISO 15686) to predict the service life of building elements.	[42]
Current state of knowledge regarding GHG abatement through material efficiency, focusing on products groups for which material efficiency strategies are particularly relevant: buildings, vehicles, and electrical and electronic equipment.	Review. The focus on the product perspective was chosen because consumers, producers, and policy directly relate to them. Numerous studies explored the potential reductions in resource demands by extending building lifespans, which directly reduce upstream energy demands. The literature supports a strong role for ME as an avenue for reducing GHG emissions connected to material-intensive systems, including buildings and light-duty vehicles, while evidence for emission reductions within EEE is more limited. There is a significant potential to reduce the substantial emissions connected to producing materials used in buildings and vehicles.	[43]
Indicators for urban mining feasibility based on planning stages, process change, behavioural practices and reuse-driven economic considerations.	Based on urban mining of over 350 building components from Singapore. Develops an empirical research approach to measure urban mining feasibility and applies it to demolition-ready urban residential buildings stock in Singapore with semi-skilled construction workers.	[44]
Explores the connections between the circular economy and the reduction of embodied carbon	A move to whole life costing will help a greater number of projects to see the economic benefits of these strategies.	[45]
A case study for the increasingly prevalent, yet under-studied area of net zero carbon refurbishments and does so using detailed field data, which is rarely available to researchers.	We calculated embodied carbon of the Brick Works Kiln Building restoration, using primary construction site data and modeled with datapoints from the One Click LCA database, assuming a 60-year serviceable life, as 1250 tCO2e. The scope of the study excludes all pre-existing building elements. Use phase operational emissions are estimated, based on data from the literature, to add around 90 tCO2e/y to the life cycle emissions of the building. Estimated	[46]

	savings in operational energy due to the installation of renewable energy systems and improved building envelope are forecast to balance the embodied carbon invested in the building retrofit within 8 years of operation. This value should be viewed as a rough estimate because it is based on the highly uncertain scoping of operational energy consumption. Once all retrofits are complete and the building is operational, monitoring the building's actual energy consumption will indicate when carbon neutrality is achieved.	
Method and an overall transfer function for steel in the UK.	In principle it is possible, given the inflows and outflows, to compute a transfer function which describes the probability distribution of the delay between an inflow and its release as an outflow, following use and discard. We have presented a novel method for the top-down determination of the lifetime distribution of products, which takes as an input trade data, which is of high quality, and widely available for many countries but highly aggregated. A transfer function is identified using a genetic algorithm, and using external information on recycling rates, the transfer function can be, by inspection, transformed to a lifetime probability distribution for the classes of product of interest. Using our proposed method we could identify the lifetime of buildings in the UK for which there exists no good bottom-up data.We have compared our results with cars where bottom-up data are available, and found that the method found average lifetimes with very good agreement with the bottom-up data, but was less precise when considering the spread of the lifetime distribution. Overall, this gives confidence that the method can reliably usedwhen no bottom-up data are available.We hope this new method will make it possible to dowide-ranging, cross-country and time, comparisons of product lifetimes, using only top-down data, while still highlighting important insights into the lifetime distributions of products.	[47]
Propose an analysis tool for strategic decision-making in CDW management.	As the construction sector is shifting towards circular economy models, the role of mineral construction materials as main waste fraction in terms of volumes is crucial. A characterization of this mineral stock, as well as the waste derived from it is decisive in ensuring the application of the best practices of circular economy. This paper describes a methodology for assessing the mineral building stock through a combination of geospatial and image analysis. By analysing old topographic maps, buildings are grouped according to their building age into different typologies and based on these maps the construction and demolition activity is evaluated. The mineral stock is assessed and estimations of the mineral construction and demolition waste (CDW) is generated for different stochastic scenarios. This methodology is applied exemplarily on the country of Luxembourg. It was found that the total mineral construction stock for	[48]

	Luxembourg is 276.75 Mt and has been growing at a rate of 20.81%–24.39% in the last 30 years. Furthermore, the study identified a mean age of the urban building stock of about 60 years and a typical maximum building lifetime of 122 years. Based on the stochastic projections the mineral CDW generated from the existing building stock is expected to be up to 226.9 Mt by 2100, while if future building scenarios are considered, it can be as high as 885.3 Mt. The annual CDW production is expected to be sufficient for a viable concrete recycling activity if regulations on the waste volume flows are made available.	
Assess the environmental performance of a flexible and reversible building design in comparison with a conventional, monolithic building design.	Due to severe sustainability problems caused by the built environment, calls for adopting circular economy principles in building design, such as flexibility and reversibility, are increasing. However, there is still a lack of quantitative studies on the corresponding environmental benefits in this regard. In the present study, a life cycle assessment of a multi-storey residential reference building is carried out, comparing a flexible, reversible building design using a load-bearing steel structure and wooden ceiling elements to a conventional, monolithic design based on reinforced concrete. The assessment is carried out on a whole building level, including construction, operation, maintenance, and the end-of-life phase. Both building designs show similar results for a regular life cycle of 60 years without major refurbishment (13 and 14.5 kg CO2-eq/m2 per operational year). When longer building lifetimes are considered, the environmental impact of the reference building per operational year decreases significantly. In this context, flexible building design is advantageous as it facilitates the refurbishment of buildings, while monolithic building design often leads to premature demolition due to low adaptability. Further advantages of reversible building design include the increased potential of materials to be recirculated at the end-of-life stage of a building and in the potential reuse of structural elements. This study shows that 14% of the embodied greenhouse gas emissions of the flexible building can be avoided if the foundation, load-bearing structure and ceiling elements are kept in place for a subsequent building. Such direct reuse leads to a substantially higher environmental value retention than recycling of the same materials.	[49]
An analysis methodology for refurbishing the glazed buildings of the modern heritage. The aims is to evaluate a building through its energetic aspects and establish refurbishment strategies that contribute to	Among the objectives of this research, we have imposed the preservation of the modern exterior image devised by Modernism, extending and improving the building's lifetime, implementing comfort conditions in accordance with current habitability requirements.	[50]

more sustainable development, respecting the historical and architectural value.		
Analytical review the applications of life cycle assessment in circular economy for the built environment.	The necessity of incorporating life cycle assessment in circular economy is highlighted. It is found in the review that adoption of life cycle assessment enhances the comprehensiveness and transparency of circular economy implementation in the built environment. To overcome the inherent limitations of life cycle assessment methods that hinder their applications in circular economy, practitioners need to constantly improve the consistency of functional unit and system boundary, the accessibility and quality of life cycle inventory data as well as the reliability of impact allocation methods. It is also found that dynamic life cycle assessment that considers the time factor can increase the applicability of life cycle assessment in circular economy. The main contribution of this review is a proposal for the transition of the built environment towards a circular and sustainable future.	[51]
Demonstrate the environmental gains of CE in a competitive way, by bringing together in an industrial symbiosis action - the pulp and paper industry and concrete construction sector.	Sustainability evaluation based on a life cycle and circular approach is presented and discussed using a simple case study performed at real industrial scale. The lime ash waste from the pulp and paper industry is used to replace 100% of the natural filler used in precast concrete production and the impacts and benefits from the technical, environmental, economic and social level were assessed. It was demonstrated that this simple action causes positive impacts in the evaluated dimensions of sustainability without causing any changes in production time and causes no degradation on relevant concrete properties.	[52]