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What are the challenges in assessing Circular Economy for the built environment?

A literature review on integrating LCA, LCC and S-LCA in Life Cycle Sustainability Assessment, LCSA

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ABSTRACT

The construction and real estate industry is, directly and indirectly, responsible for circa 40 percent of global greenhouse gas (GHG) emissions. Therefore, it is relevant to look upon the building sector as a focus area for a transition from Linear Economy to Circular Economy (CE), as outlined by the EU Commission through European Green Deal as a growth strategy for EU and, as a consequence of this, the EU Circular Economy Action Plan. This article aims to analyse current knowledge and methodologies for integrating life cycle thinking, namely Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) into Life Cycle Sustainability Assessment (LCSA), as an integrated assessment methodology, that can support the transition of the construction and real estate industry to a circular economy. We conducted a literature review to address this effort, including forty-two articles, thirteen of which report on integrating all three methods. Furthermore, we analysed the content of these articles and identified knowledge gaps in this area. Conclusions are, that for CE to succeed, a comprehensive and circular view upon buildings' life cycle phases is necessary to give closer attention to the service life phase and the reuse/recycle phase of buildings. Such attention will impact the building's value chain, regarding the involvement of more stakeholders, not only in the early phases of project development (decision-making) but particularly in the design phase; Further research in evaluating CE through the integration of life LCA, LCC and S-LCA into LCSA is necessary to support the transition; For this purpose, S-LCA needs even further maturation and development, as S-LCA will, through focus and development, become an essential lever for raising attention focussed upon the use phase and the reuse / recycle phase; A specific focus upon making integrated life cycle sustainability assessment operational and usable for practitioners in the building processes is necessary.

KEYWORDS

Life cycle sustainability assessment (LCSA)
Social life cycle assessment (S-LCA)
Circular Economy
Sustainable Building
Built environment

1 Background - Sustainable development and Circular Economy

Natural resources (understood as natural assets (raw materials) occurring in nature that is usable for economic production or consumption [1]) are consumed more rapidly than they are renewed. This overconsumption is fomenting significant consequences for flora and fauna – a developmental process further exacerbated by changes in our climate. At the same time, when it comes to equality, equity and wellbeing, human life is challenged globally, affecting material production and value chains regarding consumption and production of our daily needs. The prevailing linear economy growth thinking, also known as “Take, Make and Dispose”, is in this sense inadequate while requiring a resource pull beyond the earth’s capacity [2-4].

Sustainable Development aims at meeting the needs and aspirations of the present generation without compromising the ability to meet those of future generations [5] and is based on a three-pillar conception of economic, social and environmental sustainability [6], as described in the Brundtland-Report [7]. The economic, social and environmental dimensions of sustainable development reflect the assumption that the economy is dependent on the community's life, which is dependent, in turn, on the foundation of nature.

To enable sustainable development in practice and address the global challenges of ecosystem degradation, wealth concentrations, and social inequities, a change of mindset is necessary to enable sustainable development in practice. Therefore, over recent decades, more and more attention has been paid worldwide to the concept and development model of Circular Economy (CE) [8-12], applying a circular economic perspective as an alternative to the prevailing linear economy growth thinking.

The concept of CE is influenced by K. Boulding’s work [13], defining earth as a closed and circular system and calling for the equilibrated co-existence of economy and environment, and rooted in the work of Walter R. Stahel [14] on performance economy [15], alongside research work on environmental economics [16], loop and resource economy [10], ecological economics [17], natural resources economics [18], industrial ecology [10], and the concept of cradle-to-cradle [19].

The CE theoretical base is rooted in system thinking and general system theory [20] and life cycle thinking and assessment [21]. In recent years, it has become famous through the work and the definition coined by the Ellen McArthur Foundation [22-24] as "Circular economy denoting an industrial economy that is restorative by intention and design".

Construction and Real Estate describe a significant part of the built environment and play a vital role in the global economy, especially in the Global North, to such a degree that the built environment can become an engine for sustainable innovation and growth because the construction industry is, directly and indirectly, responsible for approximately 40 per cent of global greenhouse gas (GHG) emissions. The GHG emission stems from, e.g. production of building materials, transport to construction sites, construction of buildings, and when buildings are demolished and disposed of or recycled [25-27]. The production of building materials accounts for approximately 11 per cent of total GHG emissions worldwide, which is why an increase in the recycling of building materials can contribute to a significant reduction in GHG emissions and thereby can form a foundation for accelerating the transition from a linear to a circular economy, in order to increase this potential [26, 28].

The European Commission defined ‘Building and renovating in an energy and resource-efficient way' as one of eight specific focus areas while establishing European Green Deal as a growth strategy for EU and its citizens, as a response to the challenges of exceeding planetary boundaries and compromising human rights [29, 30].

Therefore there is increasing attention on CE research, both in theory [8] and in practice [31], due to the ability to couple economic growth and job creation with environmental protection, reducing resource use and externalities. CE has consequently gained momentum in policy, notably through the EU Circular Economy Action Plan [32, 33].

2 Introduction - CE in a building perspective / integrated life cycle thinking

CE is seen as a new development model creating wealth, jobs, cost savings and other significant environmental, economic and social benefits through aspiring to make a radical shift from produce-use-dispose towards the three R principles, "Reuse, Re-cycle, Recovery” [34], away from the "Take, Make and Dispose"-culture. As a result, conversion to CE will benefit the construction and real estate sector directly in the form of increased job creation and job retention by upgrading the current job force in the construction and real estate sector through the necessary changes that the sector must make in the transition from linear economy to the CE model.

Buildings are complex combinations of building materials, building components and technical installations, brought together to form a structure or service to achieve the best performance in both safety and operation for the users in the lifetime of the building [35].

The combinatorics of building materials, building components and technical installations and how this combination is planned, designed, carried out and used, are of differing interest for a series of different stakeholders in the building value chain, such as building owners, designers, consultants, end-users, contractors, producers, suppliers and demolishers, at various stages in the service life of a building.

The *stakeholder perspective* changes through the building's service life from the level of building parts to the level of combination of building parts. Also, the attention to what and when to assess sustainability are necessary is changing through the building's service life. Building materials and products are of primary interest for the producers when it comes to production and the developers and the contractors when it comes to costs, returns on investment, sales or rental and durability. On the other hand, building materials and products are of significant interest to the building owners and end-users throughout the service life of a building when it comes to health-related issues, property value and maintenance [36-38]

Although the bigger perspective of CE has a significant element of social attention regarding job creation and retention in the construction and real estate sector as such, CE appears to focus on environmental and economic aspects rather than on social aspects throughout the concrete service life of buildings; "The Circular Economy seems to prioritise the economic systems with primary benefits for the environment, and only implicit gains for social aspects", mainly when CE is considered in the broader frame of Sustainable development [38][39][40].

Life Cycle Assessment (LCA) assesses environmental and resource impacts through CE. In addition, other methodologies, such as Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA), can be used for CE's economic and social assessment. Typically social co-benefits for end-users, such as inclusiveness, health and wellbeing, are neither fully considered nor accounted for [9, 40] in the CE, nor sustainable and green-certification of the built environment. However, the quality of social sustainability in the built environment is crucial to secure the actual quality of both environmental and economic quality for the users of the built environment, taking into consideration how buildings are designed for sustainability [41] if we aim to circumvent intra- and inter-dimensional shifting of burdens during a building's lifetime.

Consequently, there is a need for a coherent and integrated approach to life cycle assessments to meet such complexity at many levels. An answer to this need can be an integration of LCA, LCC and S-LCA into a framework for Life Cycle Sustainability Assessment (LCSA), as paramount for supporting a truly sustainable implementation of CE [42] to assess CE and support a transition from linear planning of the built environment to CE.

Attempts of integration are many, but not yet mainstream, neither in research nor in practice in the building sector. In this review, we will investigate the present level of integration of the three assessment methodologies, LCA, LCC and S-LCA, into LCSA, and what knowledge gaps to uncover to succeed herein, through investigating what methodological and theoretical advancements, that are needed for a coherent and integrated approach to take place to succeed in CE, in recent scientific literature.

2.1 Environmental performance assessment – LCA

LCA is a systematic performance assessment framework for the quantitative evaluation of how the inputs and outputs of a product system induce environmental impacts.

The framework is applicable for products, projects or systems in general [43]. In terms of value chain perspective, LCA starts with the extraction of raw materials and continues downstream to production and use up to the waste treatment, typically focusing on, mainly, an entire life cycle/service life of the commodity, and LCA is thus considered as a 'cradle to grave' assessment [44]. Many ISO and EN standards deal with LCA for the built environment, namely EN ISO 14040 (Environmental management – Life cycle assessment – Principles and framework), EN ISO 14044 (Environmental management – Life cycle assessment – Requirements and guidelines), ISO 21930 (Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services), EN 15643 (Sustainability of construction works – Framework for assessment of buildings and civil engineering works), EN 15804 (Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products) and EN 15978 (Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method).

The environmental impact potentials induced by human intervention of natural systems are; 1) planetary energy balance and climate change, 2) loss of biodiversity, 3) pollution and soil erosion, and 4) water stress [45]. LCA can quantify the environmental impact potential of such production systems based on energy and material flows [37]. LCA is internationally standardised over time, DS EN ISO14040 [46] being the first of the three life cycle methodologies, and involves four distinct phases: (a) goal and scope definition, (b) life cycle inventory analysis, (c) life cycle impact assessment, and (d) interpretation of results, 'cradle-to-grave'.

LCA can be used for strategizing environmental impact reductions connected to the built environment by supporting informed decision-making in building design [43] and evaluating buildings' environmental impact. LCA is applied in the building industry through a series of sustainability certification systems of buildings, for instance, BREEAM (Building Research Establishment Environmental Assessment Method), published by the Building Research Establishment (BRE) UK), LEED (Leadership in Energy and Environmental Design Green Building Rating System), developed by the US Green Building Council (USGBC), DGNB ('Deutsche Gesellschaft für Nachhaltiges Bauen' (German Sustainable Building Council), a German sustainability certification for buildings) and HQE (Haute Qualité Environnementale (High-Quality Environmental standard), a standard for green building in France).

2.2 Economic performance assessment – LCC

LCC is a methodology for assessing the total cost of a product, project or system over time. It considers all costs, including initial costs (such as capital investment costs, purchases, and installation costs), future costs (such as energy costs, operating costs, maintenance costs, capital replacement costs, financing costs) and any resale, salvage, or disposal costs, over a lifetime, considered as 'cradle to grave' [44], of a product or a project estimated directly by one or more stakeholders in a product system [37, 47].

LCC is mainly useful for comparing economic profitability and capital investments and should ideally be analysed from both system- and end-user perspectives [45] through widely adopted LCC methodologies in the building sector. Life Cycle Costing is closely associated with the methodology known as Total Cost of Ownership (TCO), as both reveal various applicable lifetime costs resulting from the ownership and utilisation of certain types of assets.

Several proposals and standardised definitions of LCC and total cost and ownership for building owners have emerged in recent years, such as the European standard DS / EN 15643 [48] series on sustainability in construction and civil engineering and the international standard ISO 15686 Service Life Planning, Part 5, Whole Life Costing. In addition, LCC is, to an increasing extent, an effective method for making economic assessments of the built environment [49] through sustainability certification systems of buildings, such as BREEAM and DGNB.

2.3 Social performance assessment - S-LCA

S-LCA is a methodology capable of assessing the social and socio-economic aspects of services, projects, and products, accounting for both actual and potential positive and negative impacts along the life cycle.

There exist no standardised methodologies for S-LCA as of now. However, one significant step towards addressing these issues and developing a methodology that may eventually become standardised is the Guideline, published by UNEP/SETAC Life Cycle Initiative [50-53].

The S-LCA methodology provides an adequate technical framework from which a larger group of stakeholders can move towards social responsibility while assessing the lifetimes of goods and services [54]. In addition, S-LCA involves stakeholders in goal and scope definitions, data collection and interpretations, which are different from both LCA and LCC.

Indicators in S-LCA can be as diverse as sustainable behaviour, health, safety, security, number of fatalities, human rights, responsibility, architectural quality, architectural diversity, added social value, future value, historical continuity, cultural heritage, governance, socio-economic impacts, and labour policies [47, 55-58].

So far, there is no consensus on the selection of impact categories, nor are there harmonised methods or frameworks for conducting S-LCA [47, 59], except that stages in S-LCA are most often, but not always, considered equivalent to the stages in LCA, "cradle to grave", that is to say. DGNB contains social indicators for assessing social performance, and WELL, a performance-based system for measuring, certifying, and monitoring features of the built environment that impact human health and wellbeing, focuses upon social performance as such. However, S-LCA is neither considered nor applied in the building industry to assess the social impact of construction or refurbishing buildings.

2.4 Life Cycle Sustainability Assessment – LCSA

LCSA refers to the evaluation of all environmental (LCA), economic (LCC) and social (S-LCA) benefits and negative impacts in decision-making processes, with an eye trained on more sustainable products and projects throughout their life cycle.

LCSA was first introduced in 2008 [56]. LCSA describes a methodology that originates from the need to simultaneously address the three pillars of sustainable development in one aggregated methodology while preserving a classical life cycle perspective (fig. 1).

There are two main formulations of LCSA; the first one is an LCSA model for products, consisting of LCC + LCC + S-LCA [56]; the second one is an LCSA framework for sectors or whole economies, with a similar definition, but with a broader and deeper scope, addressing economic and behavioural interdependencies lying beyond technological interdependencies [60, 61].

LCSA is in the process of being applied in many sectors: transportation, energy, agriculture, manufacturing, waste treatment and building, and with this acknowledged as an assessment method to support decision making based upon sustainability. However, neither within research nor practise has LCSA broken through in the building sector.

LCSA can become a tool to bring a holistic perspective into decision-making by assessing the social and economic as well as the environmental effects of a decision. Thereby LCSA can highlight situations where CE may be too narrowly focused on the "circularity" of a specific resource and where a specific circular strategy may have to be evaluated from a broader sustainability perspective [62].

3 Methodology

3.1 Objective and research question

CE is rooted in system thinking, general system theory, and life cycle thinking and assessment. Therefore, there is a need for a coherent and integrated approach to life cycle assessments to secure CE on all levels in all phases of building processes to meet such complexity. An objective of the review at hand is to provide a summary of previous articles of integration of LCA, LCC and S-LCA into LCSA to understand current limitations and knowledge gaps regarding existing life cycle tools. Another objective is to discuss how and to what degree life cycle thinking can be integrated into the built environment life-cycle to support the implementation of CE in a sector with a high potential for sustainable development on a large scale.

We will focus upon combinatorics of building materials, building components, and technical installations into building structures and how this combination is planned, designed, carried out, and used by stakeholders and actors in the different phases of the building process at different levels.

A primary research question (RQ) and three sub-questions have guided the research:

What are the challenges in assessing Circular Economy for the built environment?

Sub-questions:

a) How does the scientific literature handle LCA, LCC, S-LCA, and LCSA building processes?
b) How well defined and described is S-LCA in the scientific literature?
c) To what extent are the findings related to usability by stakeholders in the building processes?

3.2 Method and search strategy

We have carried out a Literature Review (LR)[63]. The method follows four principles, 1. Review of scientific literature, 2. Transparent method, 3. Replicability and updatability, and 4. Summary and synthesise main subjects in the research**.**

Inclusion and exclusion criteria for the LR are described in Table 1 for screening scientific literature and defining practical reasons for justifying selection.

Search criteria	Inclusion	Exclusion
Year	2010-2021 - the circular economy has had increased political attention within the last ten years because of the accelerating human impact	Before 2010

	upon the environment, appointed by The Intergovernmental Panel on Climate Change [4]	
Language	English	Other than English, to avoid any potential bias in the interpretation of the results
Origin	Focus upon Global North context because of relevance and familiarities to and between European geography, demographic, climate, culture	Global South
Triple integration of LCA, LCC and S-LCA into LCSA	Combinatorics of building parts, building components and technical installations	Stand-alone building parts (primary and secondary (renewable and/or recycled products) building materials. This field is more often dealt with in other scientific literature
Dual integration of LCA, LCC and/or S-LCA	Do	Do
LCA	Do	Do
LCC	Do	Do
S-LCA	Do	Do
Context	Do	Do
The building process and phases	Strategic definitions, Preparation and briefing, Concept design, Spatial coordination, Handover, Use, Reuse – these phases are less dealt with in scientific literature than Technical design, Manufacturing and Construction, although being of great importance for the human impact upon the environment.	Technical design, manufacturing and construction, as these phases are often dealt with in other scientific literature.

Table 1 – Inclusion and exclusion criteria

Literature database search process: The literature search was conducted from November 2020 to June 2021 and was limited to peer-reviewed reviews, journal articles, and book chapters published in English since 2010.

We chose the scientific databases, Web of Science and SCOPUS, because they are expected and known to cover peer-reviewed articles from well-regarded sources, with appropriate geographic coverage. First, we conducted a basic search in Web of Science, based on a Boolean system setup, described below. Afterwards, we ran the exact search in SCOPUS to verify, which resulted in additional texts.

Keywords and boolean search strings: We started a general keywords search using boolean operators AND, NOT and OR. Keywords have been “LCA”, “LCC”, “S-LCA”, “SLCA”, “LCSA”, “Life Cycle Sustainability Assessment”, “circular”, “building”, “buildings”, “built environment” in the following strings:

LCSA AND OR LCA AND OR LCC AND OR S-LCA / LCA AND OR LCC AND OR S-LCA AND built environment / LCA AND OR LCC AND OR S-LCA AND circular AND economy AND building OR buildings / LCA AND OR LCC AND OR S-LCA AND circularity AND buildings OR building.

Six hundred fifty-five publications were returned from the search and included in a database established in End Notes.

The articles were reviewed, as shown in Figure 1. We reported the publications in a protocol in a spreadsheet, listing two kinds of data for the research, namely *Formal data* and *Data of specific relevance*.

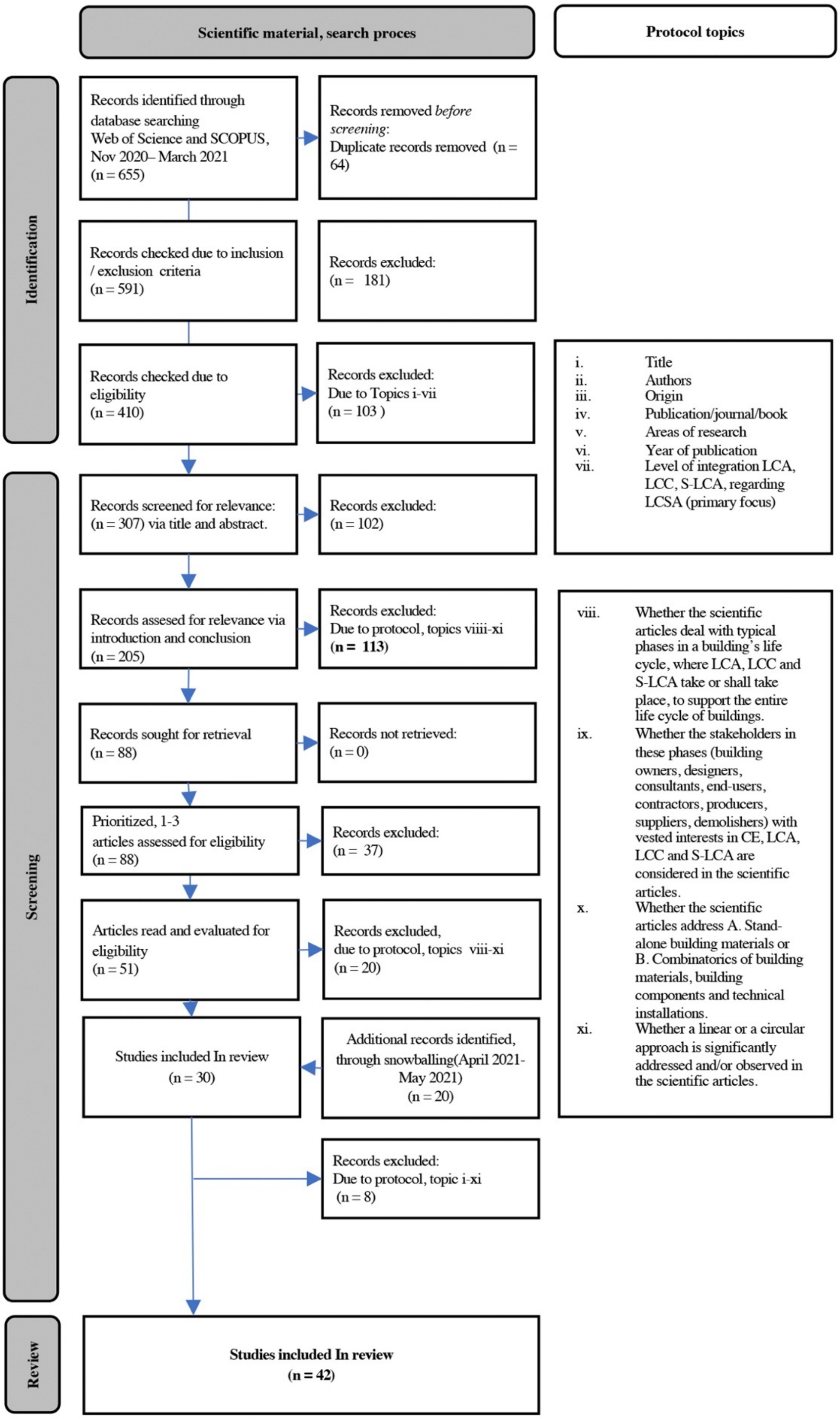

Figure 1 - Review of scientific literature, transparency

Formal data:

i. Title
ii. Authors
iii. Origin
iv. Publication/journal/book
v. Areas of research
vi. Year of publication
vii. Level of integration LCA, LCC, S-LCA, regarding LCSA (primary focus).

Due to the level of complexity of building processes [64], needs for additional data qualities such as those listed below became parts of the protocol:

Data of specific relevance, taking the overall focus of combinatorics on building materials, building components and technical installations into building structures into consideration:

viii. Whether the scientific articles deal with typical phases in a building's life cycle, where LCA, LCC and S-LCA take or shall take place, to support the entire life cycle of buildings.
ix. Whether the stakeholders in these phases (building owners, designers, consultants, end-users, contractors, producers, suppliers, demolishers) with vested interests in CE, LCA, LCC and S-LCA are considered in the scientific articles.
x. Whether the scientific articles address A. Stand-alone building materials or B. Combinatorics of building materials, building components and technical installations.
xi. Whether a linear or a circular approach is significantly addressed and/or observed in the scientific articles.

We categorised the publications in three groups in the protocol, concerning the level of complexity:

1 Articles describing triple integration of LCA, LCC and S-LCA into LCSA
2 Articles describing dual integration of LCA, LCC and/or S-LCA
3 Articles describing aspects of single standing LCA, LCC or S-LCA, that appear relevant when considering integration.

It appeared that a more flexible search design would be appropriate during the search process. Therefore, forward and backwards reference tracking and snowballing methods [65], managed by the setup presented in figure 2, were applied to prioritise the articles and to include a minor number of additional scientific literature cited in the previously identified articles.

We categorised the publications in groups, concerning the level of complexity:

1) Literature reviews on LCSA
2) Articles describing triple integration of LCA, LCC and S-LCA into LCSA
3) Articles describing dual integration of LCA, LCC and/or S-LC
4) Articles describing aspects of single standing LCA, LCC or S-LCA that appear relevant when considering integration
5) Focus upon 'Building' and 'circularity' and/or linearity

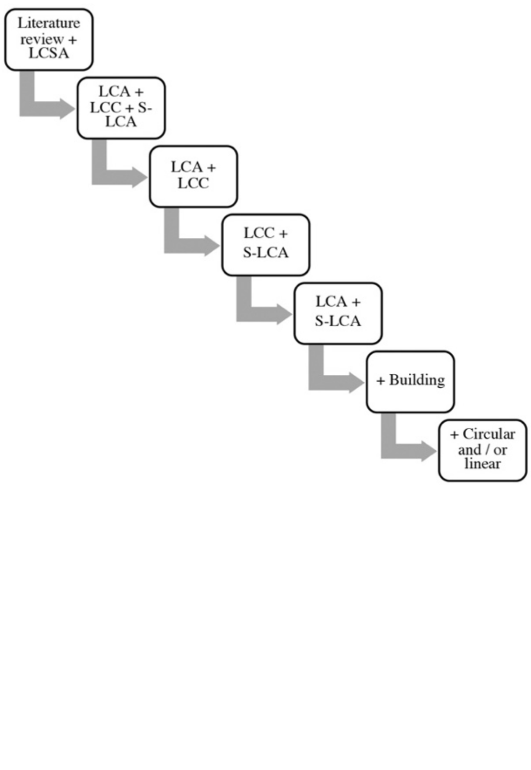

Figure 2 – Boolean system setup

In addition, we conducted further searches in Web of Science and Scopus while using specific keywords or authors that we found highlighted in the first round (such as 'social sustainability). With this action, the previously selected publications were supplemented by relevant publications earlier than 2010 to understand the product scale as a condition for the systemic scale to provide an accurate and fair representation of the concepts of S-LCA and LCSA.

4 Results

In section 4, the results are presented and elaborated upon, lining up critical findings in a descriptive analysis (4.1), along with content analysis (4.2), extracting main content, both parts being categorised here following the research questions posed in section 3.1.

4.1 Descriptive analysis

4.1.1 Overview

As mentioned, the first search strings in Web of Science returned six hundred fifty-five results, out of which forty-two were included in the LR. Table 2 describes the distribution of the total number of results per year, integrating the methodologies for sustainability assessments, respectively, over the given period in the range of 2008-2020. Thus, the total number of results dealing with integration has increased remarkably from 2015 – see Table 2, column 'Total'.

	Total	*LCSA*	*S-LCA (including grey UN reports)*	*LCA - LCC*	*LCA*	*Other approaches to integration*	*No. of publications, according to the search string*
	655	**13**	**8**	**11**	**4**	**6**	**44**
Left out	245						
Retrieved due to exclusion criteria	103						
2008	3	1	1				2
2009	6		1				1
2010	11		1				1
2011	3		1				1
2012	12	1	1				2
2013	11	2	1				3
2014	11		1				1
2015	20						0
2016	22	1	1	2	1	1	6
2017	38	1	1			2	4
2018	40	3	1				4
2019	57	2		6	1		9
2020	73	2		3	2	3	10

Table 2 – Overview of results

The forty-two included articles come from institutions based in the Global North (Europe (31), USA (7), Australia (2), Singapore (2), Canada (1), and Brazil (1)). Thirteen of the forty-two included articles deal specifically with the integration of LCA, LCC and S-LCA for LCSA purposes, and ten with dual integration of LCA and LCC. All of the articles on LCSA deal with S-LCA, and additional eight articles describe S-LCA. Six articles point at different challenges of integrating the three methodologies, and four describe development potentials for LCA when striving towards such integration.

Starting from the research question and its sub-questions (3.1), we gave special attention to the thirteen publications about LCSA and the eight articles on S-LCA.

4.1.2 Articles on integrating LCA, LCC and S-LCA into LCSA in building processes (sub-question a.)

The thirteen articles on LCSA date from 2008-2020, increasing in number since 2016. A study by Kloepffer, W. [56] dates from 2008 and is identified, in several of the other LCSA articles, as the first study, describing the concept of integrating LCA, LCC and S-LCA in an LCSA framework manner for product assessment purposes. Kloepffer thereby introduces a way of thinking integrated life cycle assessment for "simple" products, which develops in the following years and moves from 'simple' products [37, 42, 55, 66] into assembly in buildings, as shown in many of the other LCSA articles [43-45, 47, 49, 67-69]. Five out of the thirteen articles address other products and services relevant to the building sector, and eight out of the thirteen articles address the building sector directly. Table 3 presents the thirteen LCSA articles and contains notes on a primary approach to the topic of LCSA appearing in the various articles under 'Summary'. We ordered the articles due to the level of complexity ('simple' versus 'assembled') and character ('building' versus' 'refurbishment'). Three out of the thirteen LCSA articles are literature reviews:

	Title	**Topic**	**Summary**
'Simple' products	*Life cycle sustainability assessment of products [56]*	Approach to S-LCA - should be manageable and quantitative, as LCC and LCA, in order to be usable	The first study about LCSA, to which every other LCSA study refers. Focus upon the need (in 2008) for quantification and one-dimensional standardised quantifiable data, systems and structures. The picture is changing.
	Exploring the Current Challenges and Opportunities of Life Cycle Sustainability Assessment [37] (review)	LCSA is a holistic framework for decision making - challenges and research gaps – SDG	LCA / S-LCA, LCC / LCA, S-LCA / LCC - LCSA – demonstrates how the different methodologies are defined by diverse KPI's and require diverse data, which makes it challenging to integrate them seamlessly. Critical study, product level.
	A systematic review of life cycle sustainability assessment: Current state, methodological challenges, and implementation issues [55]	Premises for developing LCSA, built on methodologies that already exist and are undergoing continuous development	Define needs: coherent system boundaries, robust databases, the definition of impact categories that allow comparability between articles, impact assessment methods, uncertainty analysis, and communication strategies
	Closing the loop for packaging: finding a framework to operationalise Circular Economy strategies [42]	Combination of all three methodologies, to strive for CE	Recommendation on using the Life Cycle Sustainability Assessment framework to evaluate circularity strategies since it is the most comprehensive and still operational framework and best at preventing burden shifting between stakeholders in the value chain
	Workshop on life cycle sustainability assessment: the state of the art and research needs—November 26, 2012, Copenhagen, Denmark [66]	First Workshop on LCSA, discussing differences between LCA, LCC and S-LCA	Point out research areas such as communication, qualitative/quantitative data, combinations, potentials, goals and scopes as directions, and interpretations of results
'Assembled' products - buildings	*Towards sustainability-oriented decision making: Model development and its validation via a comparative case study on building construction methods [47]*	Building a specific sustainability assessment model: theoretically, a combination of environmental, economic and social sustainability, with a case study on choosing the most sustainable solution of the three regarding a new building.	A very straightforward model for combining LCC, LCA and S-LCA. Addresses the immaturity of S-LCA but delivers (usable) tools, references and ideas on overcoming this. Tries to accomplish these incomprehensible case articles. Is the model, in a way, too simple?
	A modelling framework to evaluate the sustainability of building construction based on LCSA [43]	LCSA for buildings. Case articles - LCA, LCC, S-LCA / EMoC, CMoC, SMoC	Developing a framework for assessing buildings - BUT: only cradle-to-end-of-construction - a key article, but not comprehensive. No considerations on the use phase.
	Integrating triple bottom line input-output analysis into a life cycle sustainability assessment framework: the case for US buildings [44]	TBL as a tool for widening the perspective of LCA - US buildings	Point out paradoxes in the choice of indicators of the methodologies.

Development of triple bottom line indicators for life cycle sustainability assessment of residential buildings [45]	Development of LCSA framework for residential buildings, including objectives, impact categories and key performance indicators (KPI's)	Identifies KPI's on all three pillars in a site-specific context. Very few observations on the discussion about qualitative and quantitative data and KPI's. Nothing on aesthetics.
Improving sustainable cultural heritage restoration work through life cycle assessment based model [67]	LCSA concerning life cycle management of cultural heritage projects.	Compares the three methods from ISO14040 to establish a sort of baseline for evaluation. However, the methods are not integrated since the three methods are regarded here as three angles, not as juxtapositions that can calculate consequences.
Life Cycle Sustainability Assessment in Building Energy Retrofitting; A Review [49]	LCSA of building **energy** retrofitting	Demonstration of assumptions, limitations and advancements in recent publications. In practice, focus upon silos, not integration, although the authors have paid attention to the necessity hereof.
Multidimensional Pareto optimisation as an approach for site-specific building refurbishment solutions applicable for life cycle sustainability assessment [68]	LCSA in the refurbishment of residential buildings.	Addresses the issues of difficulties in defining appropriate indicators for SLCA
Optimisation and LCSA-based design method for energy retrofitting of existing buildings [69]	Integration of life cycle sustainability assessment into a (digital) design process	It aims to provide a framework for integrating life cycle sustainability assessment into the design process of energy retrofitting.

Table 3 - Main content in thirteen articles addressing LCSA, identified in the LR.

4.1.3 Definition and description of S-LCA (sub-question b.)

Following UNEP report, "Guidelines for Social Life Cycle Assessment of Products" [54] and associated "Methodological Sheets for Subcategories in Social Life Cycle Assessment" [70], eight articles on methodologies of S-LCA were identified through forward referencing/snowballing from the thirteen LCSA articles and are included to discuss the level of maturity of S-LCA in terms of integration into building processes. Table 4 presents the identified articles, ordered due to the level of complexity ('simple' versus 'assembled'), and contains notes on the primary approach to S-LCA taken by each of the articles.

Although S-LCA has been given attention as a decisive parameter for sustainable buildings and urban planning [56], S-LCA is still in its infancy as a methodology, which is pointed out in Table 4. The focus is on user behaviour in buildings and refurbishments, especially regarding how buildings are designed to integrate sustainable building materials in the manufacture and construction phase and the running and maintenance hereof in the use and reuse phases.

	Title	Topic	Summary
'Simple' products	*Development of a methodological framework for the social life-cycle assessment of novel technologies [71]*	A (generic) take on S-LCA.	A way of working that allows both quantitative and qualitative indicators.
	Methodologies for social life cycle assessment [72]	The immaturity of S-LCA	Overview of tools for S-LCA on 'simple' products.
	The guidelines for social life cycle assessment of products: just in time! [51]	intro to guidelines for S-LCA – product level.	A joint article on the necessity of S-LCA, in the meaning social or socio-economic LCA, by researchers who advocates for S-LCA, and an introduction to the UN tool, Guidelines for Social Life Cycle Assessment of Products. Historical outline. Skeleton to S-LCA.
	Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA (Study) [50]	S-LCA - tools for defining KPI's of S-LCA - to be integrated into LCA	A systematic approach to defining and clustering possible KPI's of many kinds, connected to stakeholders and impact categories
	Identifying Social Impacts in Product Supply Chains: Overview and Application of the Social Hotspot Database [52]	DATABASE of essential materials regarding S-LCA	Stakeholders and impact categories in the construction sector. Categorising guidelines. There is a lack of focus on psychology, anthropology, sociology, aesthetics.
	Efficient Assessment of Social Hotspots in the Supply Chains of 100 Product Categories Using the Social Hotspots Database [53]	Indicators, social hotspots, products	More than 100 indicators for more than 100 products

'Assembled' products - buildings	*Evaluation of the social life-cycle performance of buildings: Theoretical framework and impact assessment approach [59]*	What will the guidelines look like when transformed into building/construction practice?	An attempt to adapt S-LCA to the construction industry and good reflections on this – still, there are many gaps….
	Has social sustainability left the building? The recent conceptualisation of "sustainability" in Danish buildings [73]	A conceptualisation of sustainable buildings	While earlier paradigms of sustainable buildings emphasised community building, self-provisioning, local empowerment, and shared facilities, such objectives are absent in the new types of sustainable buildings. The authors question to what extent it is possible to design sustainable settlements without social sustainability.

Table 4 – Main content in eight articles about S-LCA, identified in the LR.

4.1.4 Usability by stakeholders in the building processes (sub-question c.)

We reviewed the articles, whether they are about" simple" products as such or 'simple' products assembled as buildings (Figure 3, x). Additionally, we reviewed the articles on their approach to the typical phases in a building process (Figure 3, viii) and the main stakeholders in the respective phases (Fugure 3, ix). Finally, we reviewed the articles, whether the approach to the products and/or the processes in the articles is linear or circular (Figure 3, xi).

We used RIBA "Plan of Work" [64] to name typical building phases within which LCA, LCC and S-LCA can take place for this purpose. "Plan of Work" describes the Cradle-to-Gate approach to buildings, from 'Idea conceptualisation' to buildings' 'End of Life' (EOL). We introduced a "Reuse" phase into the series of phases, and we added a methodology for circular procurement [74], and followingly we screened the articles as to how to relate to all phases in a circular perspective (Figure 3).

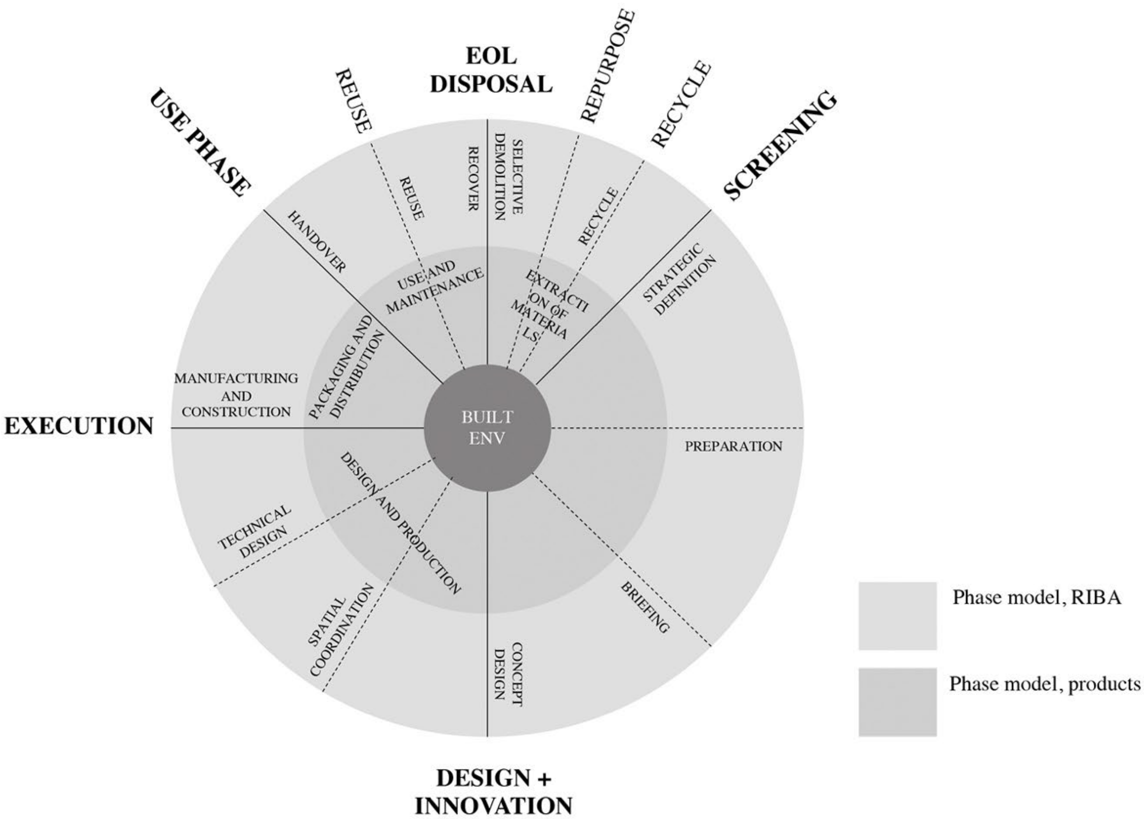

Figure 3 - Circular phase description of the phases of a building process.

Table 5 presents how the articles relate to the building phases. Most articles relate to the 'Concept Design' and the 'Manufacturing and construction' phases, while the fewest of them relate to the 'Preparation and Briefing' phase:

Phases	No of articles	Articles on assembled products in Buildings (see list of references) (x)	Articles on simple" products (see list of references) (x)
Strategic definition	15	[37, 45, 50, 59, 66-68, 75-84]	[42, 50, 51, 54, 70, 71]
Preparation and briefing	5	[37, 45, 67, 75, 78, 85]	
Concept design / Spatial coordination / technical design	21	[36, 37, 43, 45, 47, 49, 51, 59, 67, 68, 75, 76, 78-81, 83, 86-91]	[53, 71]
Manufacturing and construction	21	[36, 43, 45, 47, 49, 56, 59, 67, 68, 72, 75, 76, 78-81, 85-89, 92]	[42, 50, 51, 53, 54, 70]
Handover / Use	14	[36, 45, 47, 56, 58, 59, 67, 68, 73, 75, 78, 79, 85-88]	[53]
Reuse	8	[45, 68, 75, 76, 81, 85, 86, 88]	[42, 50, 51, 70]

Table 5 – Building process

4.2 Content analysis

The review altogether shows a series of trends. We present this series in Table 6, following the research questions.

Sub-questions	Trends identified in articles.	References
a) How does the scientific research integrate LCA, LCC, S-LCA and LCSA into building processes?	LCA - There are most articles about LCA – LCA is quantitative, quite mature, established and has standards for definitions and processes (ISO 14040). Some articles raised the discussion about LCA and the shortcomings regarding LCA as being too static. LCC - The articles covering LCC describe more diverse life cycle assessment approaches than those covering LCA. Temporality in LCC is an issue that distinguishes it from LCA. There are standards for definitions regarding LCC – but there is freedom of choice when it comes to premises because of the complex nature of LCC. Both quantitative and qualitative indicators are mentioned in order to assess Life cycle methodologies. 2/3 of the articles describe the integration of LCA, which is considered the most mature life cycle system, and LCC, which is described as a relatively mature albeit diverse methodology, based on the life cycle perspective. Thirteen articles describe intentions of combining LCA, LCC and S-LCA into LCSA and point out that S-LCA is a necessary albeit immature field, considered complex, but essential for a systemic and integrated life cycle approach. Especially after 2015, we see an increasing focus upon integrating two or three assessment methodologies. 3/4 of the articles addresses differences and challenges regarding different kinds of data in LCA, LCC and LCSA – and other life cycle tools. The discussion about different data characters and quality per methodology is mentioned in several of the articles. Until 2011, most research relating to life cycle methodologies is about "simple" products. It is pointed out that life cycle methodologies are difficult to access for practitioners of the built environment.	[36, 37, 43-45, 47, 49, 55, 56, 58, 66-68, 76, 78-82, 84, 85, 89, 90]
b) How well defined and described is S-LCA in the scientific literature?	S-LCA generally suffers from being neglected and hard to concretise but is appointed, on the other hand, as being very important and needed. S-LCA addresses societal interests in building and refurbishment, which, in terms of CE, touches upon four aspects: - Data and indicators are diverse - Data and indicators are more often qualitative than quantitative - There are no standards for S-LCA - Indicators that can be S-LCA, such as working environment, are most often linked to LCA. T here is a lack of coherency between LCA [40] and S-LCA indicators, which generally translates into some uncertainty in the requirements for impact categories to be addressed in S-LCA. These can be as diverse as sustainable behaviour, health, safety, security, number of fatalities, human rights, responsibility, architectural quality, architectural diversity, added social value, future value, historical continuity, cultural heritage, governance, socio-economic impacts, and labour policies.	[9, 43-47, 50, 52-59, 70-72]

c)	To what extend are findings related to usability by stakeholders in the building processes?	There is an overshadowing tendency to see building processes as linear rather than circular in the reviewed articles. The articles talk very little about Cradle-to-Cradle (C2C) [19] – most approaches are about Cradle-to-Gate (C2G), and there are many articles related to ISO 14044 (an international standard on environmental management and life cycle assessment) using this standard as the kick-off for anything else. Regarding linear processes and circular processes, some of the articles point out that the comprehension is not circular yet, since the standards for LCA (which are also the standards that many want to build S-LCA upon) are linear. Four out of forty-two articles address the circular C2C perspective, while the rest address three to four phases in a linear perspective. Several articles leave out phases for reasons of the delimitation of the research area. A majority of the articles stress that a focus upon decision making and policymaking in the early phases is crucial, regardless of scale (product, building, city) 2/3 of the articles address design and construction phases, less than 1/2 address the use phase, and less than 1/4 address the demolition and recycle/reuse/repurpose phases. The use phase is, in some articles, defined as essential but generally not dealt with, although it is crucial regarding LCC.	[8, 75-77, 86, 87, 91] [36, 43-45, 68, 69, 78, 88, 92, 93] [54, 58, 67, 84, 91]

Table 6 – Content analysis – Trends

5 Discussion

5.1 Sub question a) - How does the scientific research integrate LCA, LCC, S-LCA and LCSA in building processes?

There appears to be a consensus in the reviewed articles on the necessity of combining and integrating the three lifecycle-based methodologies (LCA, LCC and S-LCA) to obtain a systemic service-life perspective on products and systems in an integrated and systemic way of thinking (LCSA). However, there also appears to be a consensus in the articles that proper integration is a challenge; A vital issue is the difference between maturity and data for the three methodologies.

We synthesise the analysis of the literature as follows:

- LCA indicators are quantitative and static and account for adverse negative impacts that need to be reduced, in an environmental perspective;
- LCC indicators can be both quantitative and qualitative, are temporal over time, and dynamic, and seen from the producer's point of view;
- S-LCA indicators are primarily qualitative and dynamic, site-specific and address adverse impacts that need to be reduced, as positive benefits need to be improved, from a societal point of view.

Besides these complexities, it appears that the existing methodologies for products do not cover an entire life cycle of buildings; the use phase, recycling/reuse phase, and repurpose phase of buildings' service lives are underexposed in the literature under review.

5.2 Sub question b) - How well defined and described is S-LCA in the scientific literature?

Significant challenges and research gaps emerge when pairing LCA, LCC, and S-LCA two and two regarding the temporal issues, the different perspectives, and the indirect consequences. Additionally, the issue of quantitative versus qualitative indicators still needs to be developed to make S-LCA fully operational compared to LCA and LCC. Also, there are differences between the three methodologies, related to the moments in the processes where the evaluation takes place, in a life cycle perspective, as appointed by Fauzi et al. [37].

Recently, S-LCA has gained more attention regarding user behaviour in buildings and refurbishments stemming from linking life cycle thinking to the SDGs and CE [37]. Still, though, the selection of impact categories varies and can be site-specific, depending upon different purposes and application scenarios for S-LCA. Therefore, some will say that S-LCA needs to be strengthened, and indicators need to be tailored specifically to the building sector to provide decision-makers with a holistic basis [68]. There exist no standardised methodologies for S-LCA as of now.

Additionally, there is a need to enhance further the capabilities of evaluating social aspects besides environmental and economic aspects in CE [19, 42, 86]. In the building sector, this requires that evaluation tools are usable for practitioners and the proper involvement of stakeholders in a series of phases [64] throughout the life cycle of building and refurbishing [11].

5.3 Sub question c) - To what extent are the findings related to usability by stakeholders in the building processes?

Most of the reviewed articles address the need for integrated assessment tools for decision support in the early phases of design processes. LCSA can be developed and utilised to assess design thinking, design processes, social co-benefits and co-design, to support informed decision-making in building and refurbishment processes.

The findings in the reviewed articles can be related to the typical phases of the building processes, to some degree, as long as the focus is on stand-alone building materials that LCA can assess.

Nevertheless, the service life of stand-alone building material is not the same as the service life of a building, as the assembly of building materials and components into building structures adds several layers of complexity, relating to, e.g. assembly and technical installations maintenance and refurbishment. Furthermore, when products are assembled in buildings, more life cycle phases, besides production and construction, become equally or even more relevant regarding how building materials and components are handled by the end of life (EOL) in a linear perspective [64]. Thus, the need for assessments increases in complexity and changes while moving the attention from stand-alone building materials to complex building structures.

Figure 4 shows the critical phases of a circular perspective on building design and refurbishing, based upon the RIBA Plan of Work [64] and Circular Procurement [74], with one phase altered (from EOL to Reuse). In addition, we investigated the articles regarding which phases relevant stakeholders were described to take action.

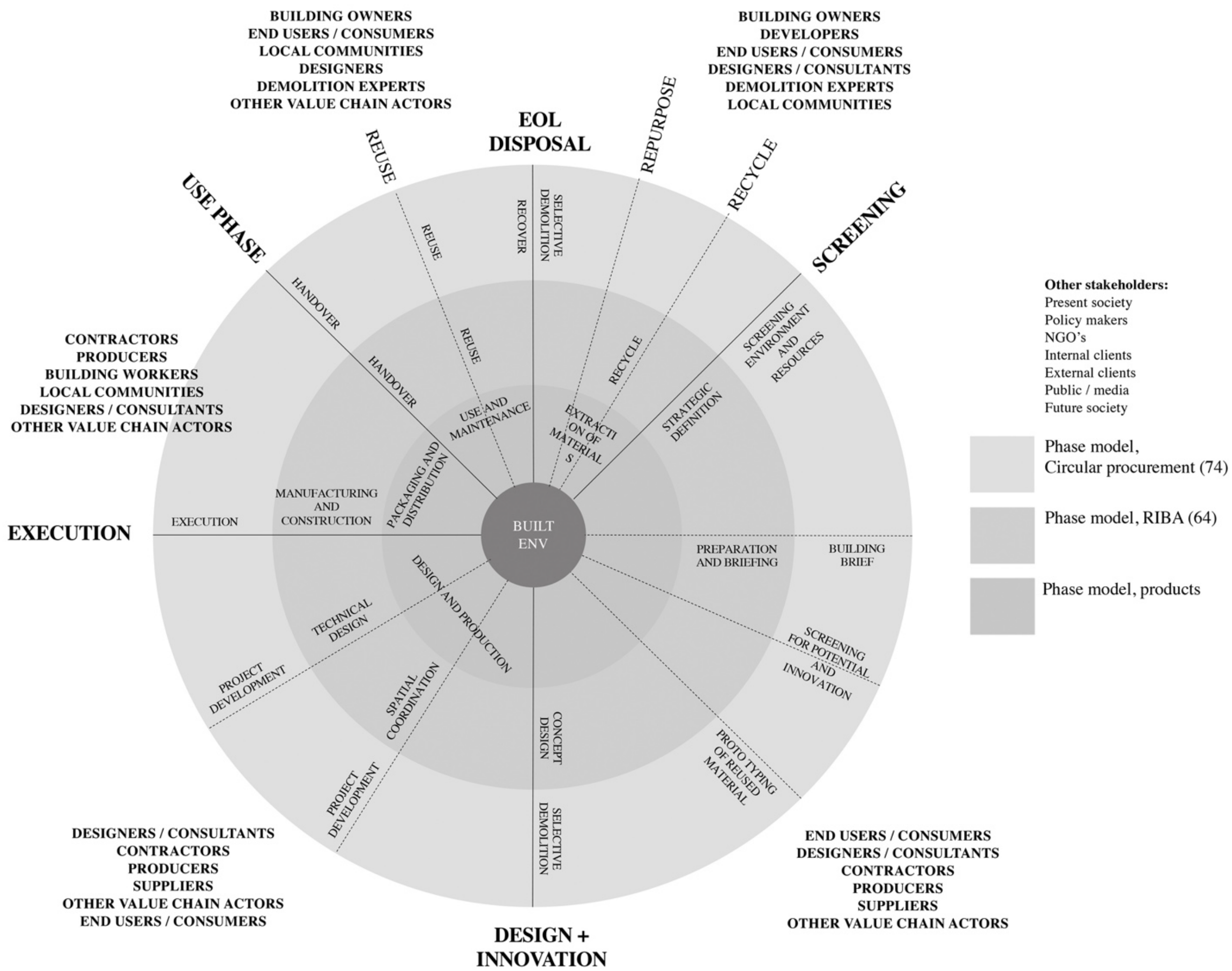

Figure 4 – life cycle phases in building – circular thinking.

Consequently, what assessment methodologies show, and what needs they meet change during a building's service life. With this, existing standards regarding defining and assessing the life cycles of complex buildings and refurbishments compared to life cycles of stand-alone building materials may be challenged.

On top of this, CE describes sustainability as originating an effort to create a restorative and regenerative economy by design, aiming to keep products, components, and materials at their highest utility and value, at all times, as well as seeking to decouple global economic development from finite resource constraints [12]. Reusing, recycling, and repurposing as phases in a building's service life, thus raising demands on how to design buildings for this and emphasising a focus upon how to use buildings sustainably, including a focus upon behaviour, which underlines the importance of user involvement in the earlier building phases.

However, the use phase and the buildings' recycling / reuse and repurpose phases are underexposed in the literature reviewed. Therefore, these phases shall have more attention to succeed in a circular economy [11, 19, 25, 73, 92, 94].

5.4 Cross-section through sub-questions.

The necessity of integrating LCA and LCC is mentioned in a significant number of the all reviewed articles, as research gaps that call for heightened attention in future research. At the same time, the diversity of data between LCA and LCC defines another issue that calls for attention when seeking to integrate the two methodologies.

S-LCA is attracting attention in several of the reviewed articles as being crucial to sustainable development, regarding focus upon user behaviour in buildings and refurbishments, especially in regards to how buildings are designed for sustainable integration of sustainable building materials in the manufacture and construction phase and running and maintenance hereof in the use and reuse phases. However, it is more challenging to handle S-LCA than to handle LCA and LCC in a building industry that traditionally favours quantitative data higher than qualitative data as a means for assessments.

Several articles address the use phase of buildings, and thereby, that involvement of stakeholders should have heightened attention. Additionally, the use and reuse phases of buildings and refurbishment and the potential in viewing buildings and refurbishments as material banks [82, 85] define aspects for sustainable building that should not be neglected.

6 Conclusion; What are the challenges in assessing Circular Economy for the built environment?

The construction and real estate sector will benefit directly in terms of enhancing new jobs creation and job retention, requiring considerations of upscaling current job force in the construction and real estate sector in line with the necessary change that the sector itself will need to undertake from a transition from the linear economy to the CE model.

The reviewed articles in this LR tells us, however, that the maturity in the building sector, regarding a systemic shift from linearity to circularity, is still not high enough when taking the challenges regarding the integration of environmental, economic and social regards and the higher level of complexity for building structure in a cradle-to-cradle perspective into consideration.

A major challenge in assessing CE for the built environment is that it is necessary to develop a comprehensive, genuinely circular view of life cycle phases, also covering the use (of buildings) phase and the reuse/recycle (of buildings and building materials) phase besides the other life cycle phases within the construction and real estate sector, to support this systemic shift.

To support the transition from linear to a circular economy, the construction and real estate sector, therefore, needs accessible working tools and methodologies for assessment so that the challenge of thinking circularly rather than linearly while developing, designing, constructing, using and recycling buildings becomes logic and straightforward for the stakeholders in the value chain of construction and refurbishment. As weighing the use phase and the reuse/recycle phase higher will impact the entire value chain of the built environment, regarding involving more stakeholders, not only in the early phases of project development (decision-making) but particularly in the design phase.

Integrated tools and methodologies for life cycle thinking need to be prioritised to assess circularity for buildings and refurbishment for this purpose (research sub-questions a-b-c):

a) Further research in the integration of LCA, LCC and S-LCA into LCSA is necessary to develop LCSA for building processes and proper assessment tools for the built environment. Furthermore, efforts should be made to harmonise the three methods and develop coherent data and KPI's, quantitative and qualitative, to secure the integration of LCA, LCC and S-LCA into a systemic LCSA framework.

b) S-LCA is still not very well defined and described in the scientific literature. Therefore, S-LCA needs even further maturation and development, whereas S-LCA can, through further focus and development, become an essential lever for raising attention that is focussed on the use phase and the reuse / recycle phase.

c) Throughout the reviewed articles stressed that life cycle methodologies are not adequately operational and usable yet, for the actors in design and construction processes in the built environment. Therefore, a specific focus upon making integrated life cycle sustainability assessment operational and usable for practitioners in the building processes is necessary to support the transition from a linear economy to CE.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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