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RESEARCH ARTICLE

3DCP-CI: Developing a Circularity Indicator for Assessing 3D Concrete Printed Architectural Designs

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Abstract

3D Concrete Printing (3DCP) is considered a promising technology for circularity and sustainability in construction through material-efficient designs and processes. While life cycle analysis has been applied to 3DCP materials and processes to test this view, circularity assessments covering the full life cycle of 3DCP designs remain understudied. Existing assessment methods are not designed for, and are difficult to apply within, the 3DCP context. To address this gap, this article introduces 3DCP-CI, a framework developed to systematically assess the circularity potential of 3DCP designs. Existing circularity indicators and their assessment methods were reviewed and synthesised to create 3DCP-CI. Four key performance indicators were identified for 3DCP: adaptability, disassemblability, reusability, and recyclability. Using 3DCP-CI, the Project Milestone was evaluated to improve, validate, and demonstrate the framework's applicability. The assessment of the Project Milestone indicated that while the separation of building layers and the use of reversible connections significantly influence the final score, the use of non-virgin materials improves the circularity score noticeably. The framework aims to encourage designers to make more circular decisions when applying 3DCP. Furthermore, areas in which the research or practice of circular 3DCP applications can be advanced are expected to emerge through the use of 3DCP-CI.

Keywords: Circular Design · Circularity Indicator · 3D Concrete Printing · Circularity

1. Introduction

The construction industry has used conventional construction methods for decades. While these methods have proved to be robust, they are also resource-inefficient, since they originate from the linear economic model of "take-make-dispose." Construction and demolition waste is almost 40% of the total waste generated in the European Union (EU) (European Commission, 2024). The construction sector, excluding the use phase of the built environment, is responsible for 5–12% of the EU's total greenhouse gas emissions and 50% of all of its raw material consumption annually (European Environment Agency, 2024). In response, the concept of circular economy was introduced and has become a key topic of political agendas in the EU (European Commission, 2024; European Commission & Directorate-General for Environment, 2020).

In its most accepted definition, by the Ellen MacArthur Foundation (2013), circular economy has three main principles: designing out waste and pollution, preserving products and materials in use, and restoring natural systems (Kirchherr et al., 2017; Saidani et al., 2019). 3DCP-CI, the framework presented in this article, focuses on the first two principles. These principles can be overlaid on the stages of the design lifecycle, which are depicted in Figure 1. To design out waste and pollution, circular design aims to use and waste as little virgin material as possible in the product and construction process stages of a design lifecycle

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(A1–5). 3D Concrete Printing (3DCP) is considered a novel and promising manufacturing method to create optimised geometries without the use of formwork, which could help reduce waste and pollution (García de Soto et al., 2018; Khan et al., 2020). However, material reduction and waste elimination during manufacturing only cover the product and construction-process stages (A1–5). To achieve holistic circularity, we need to think beyond. To preserve products and materials, design should aim to extend the use stage (stages B1–7) and ensure that designs are still valuable and useful at the End of Life (EoL) stage (stages C1-4).

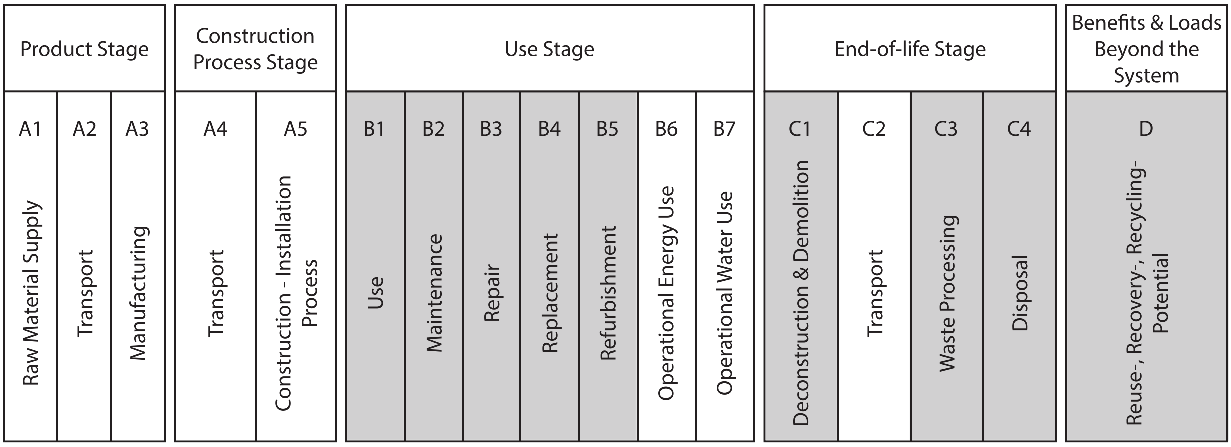

Figure 1. Life cycle stages of the built environment. The figure is redrawn based on EN 15804:2012 + A1:2013 (NEN-EN 15804, 2019). The stages included in the proposed framework are highlighted in grey.

According to Habibi et al. (2024) and to the best of our knowledge, Life Cycle Assessment (LCA) is the only environmental assessment method employed in the context of 3DCP (Agustí-Juan, 2018; Kuzmenko et al., 2020, 2021, 2022; Roux et al., 2023). Although LCA is invaluable for understanding the environmental impact of printed designs through the impact of materials and processes, it is not sufficient to evaluate the design itself for its use and the EoL stages. There is a separate set of assessment methods named Circularity Indicators (c-indicators) that include these stages. Samani (2023) and Khadim et al. (2025) make a distinction between the sustainability assessment and circularity assessment methods, in which LCA belongs to the former and the c-indicator to the latter. Samani (2023) says LCA's main goal is "to identify environmental hotspots, advantages, and burdens to make the system more sustainable," while c-indicators are aligned "with the principles of the circular economy, and focus on the EoL stage of products and services." This lacuna in LCA was demonstrated by Kuzmenko et al. (2021), where an additional assessment of the reuse potential was implemented in LCA. Although this was a good initial step, the implementation was limited to reusability and relied on visual observation of the elements after the use phase.

To define and highlight the necessary circular design strategies and to be able to analyse designs for their circularity potential, a collection of c-indicators was developed over the years. According to Khadim et al. (2022), there are at least 35 indicators on the material-to-building scale. Some are designed for specific contexts, such as bridges (Coenen et al., 2021), building envelopes (Finch et al., 2021), or heritage buildings (Valdebenito et al., 2021). Others are more generalist frameworks, such as the efforts of Platform CB'23 (2023) to develop a national circular construction framework or of Verberne, J. J. H. (2016) to create a holistic Building Circularity Indicator (BCI). While it is undesirable for the construction industry to have a large collection of c-indicators, the diversity of indicators reflects the difficulty of creating a single framework for the varying contexts of the built environment.

Despite the large variation in indicators, Cottafava and Ritzen (2021) and Khadim et al. (2022) suggest that most of the indicators are derived from existing "base indicators" as it is easier to build on top of an existing framework. On the material scale, the Material Circularity Indicator (MCI) (Ellen MacArthur Foundation, 2019) remains the most influential base indicator. Another base indicator, BCI (Verberne, J. J. H., 2016), which is based on MCI, remains important in assessing the technical cycle of different building layers and scales. Further research was carried out to improve BCI; van Vliet (2018) improved the disassembly metrics of BCI, and Khadim et al. (2025) implemented further assessment factors to improve BCI in Whole Building Circularity Indicator (WBCI).

This research conducted a targeted review of existing circularity indicators to identify their applicability to 3DCP. Table 1 summarises the main c-indicators considered, highlighting their original scope and the extent to which their concepts were integrated into the proposed 3DCP-CI framework.

1.1. Problem

Many articles on 3DCP projects claim that the technology could enable more sustainable and circular designs by saving materials and eliminating waste (Wangler et al., 2016). However, as criticised by Flatt and Wangler (2022), the empirical evidence for this argument is unclear. After a comprehensive study on sustainability in the context of 3DCP, Habibi et al. (2024) found that the only sustainability assessment conducted in 3DCP research is LCA and concluded that "integrating Circular Economy (CE) principles into 3DCP technology can enhance the industry's sustainability, innovation and cost-effectiveness."

Table 1. Overview of the reviewed c-indicators for the built environment, their scope and their relevance to the proposed 3DCP-CI framework.

Reference	Scope & Limitations	3DCP-CI Relevance
Durmisevic (2006)	Focuses on assessing building disassembly. Uses building scales but not layers.	Some of its KPIs were used to assess the disassembly potential of systems and the reusability of elements.
Ellen MacArthur Foundation (2015)	Focuses on material circularity assessment. Not limited to the built environment, but applicable to most products. Does not use building layers or scales.	Partially used for assessing recyclability and material circularity.
Verberne, J. J. H. (2016)	Focuses on building circularity assessment. Uses building layers and scales. Employs MCI for material circularity and Durmisevic (2006) for disassembly assessment. Its strong emphasis on material circularity makes it less suitable for 3DCP.	The overall structure of building scales and the assessment calculation method for element (ECI), and system (SCI) levels were adapted.
Geraedts (2016)	Focuses on building adaptability and uses building layers. Provides clear guidelines for assessment.	The assessment of system adaptability for relevant layers was adopted from this framework.
van Vliet (2018)	Improves upon Verberne, J. J. H. (2016) and implements Durmisevic (2006). Builds on building layers and scales.	Its disassembly assessment was instrumental for the 3DCP-CI.
Madaster (2018)	Focuses on building circularity assessment. Similar to the BCI, using building layers and MCI. Follows a similar approach to assessment calculation.	Although it did not directly inform the 3DCP-CI framework, it confirmed the use of MCI and building layers.
van Schaik (2019)	Focuses on foundation circularity—an area largely outside 3DCP capabilities. Uses building scales (material, element, and system) similar to 3DCP-CI, and some KPIs from Durmisevic (2006) for element reusability.	Although it did not directly influence 3DCP-CI development, it validated the use of specific building scales and reusability assessments.
Zhai (2020)	Focuses on BIM-based implementation of existing frameworks. Uses building scales and layers, MCI, disassembly assessment from Durmisevic (2006), and the assessment method of BCI.	While it did not directly influence 3DCP-CI development, it confirmed the use of building layers, scales, and disassembly assessment implementation.
Kamp (2021)	Focuses on assessing the reuse potential of existing concrete.	Used to define reuse for concrete and assess the reuse potential of concrete elements.
Kentie (2021)	Focuses on the reusability potential of building elements and uses building layers.	Although not fully integrated into 3DCP-CI, its findings informed the reusability assessment.

Table 1 (Cont.). Overview of the reviewed c-indicators for the built environment, their scope and their relevance to the proposed 3DCP-CI framework.

Reference	Scope & Limitations	3DCP-CI Relevance
Finch et al. (2021)	Focuses on façade circularity.	The framework's narrow application scope limits its relevance to 3DCP.
Dodd et al. (2021)	Level(s) is a comprehensive EU framework extending beyond building design.	Its high complexity made it difficult to implement in this version, but it may be considered for future iterations.
Dams et al. (2021)	Focuses on circular construction evaluation with emphasis on disassembly and adaptability. Uses building layers and scales but in a different structure than Verberne, J. J. H. (2016).	Although its KPIs align with 3DCP-CI, its unconventional structure led to its exclusion.
Cottafava and Ritzen (2021)	Focuses on the relationship between embodied energy, carbon, and circularity in residential buildings, based on Verberne, J. J. H. (2016).	Since embodied energy and carbon are outside the scope of this study, they were not included in 3DCP-CI.
Coenen et al. (2021)	Focuses on bridge circularity. Uses building scales similar to Verberne, J. J. H. (2016) (MCI–ECI–SCI). Designed with concrete in mind.	As it was developed for longer lifespans, its material circularity calculation was well-suited for 3DCP and was incorporated into 3DCP-CI.
Zhang et al. (2021)	Primarily focuses on material circularity and material flow.	Since material options for 3DCP-CI are limited, this framework was considered outside its scope.
Lei et al. (2022)	Focuses on probabilistic embodied energy and carbon emissions in EoL scenarios.	It is designed for different materials and, therefore, not suitable for 3DCP-CI.
Platform CB'23 (2023)	Focuses on circular design principles in the construction industry but provides limited assessment methods.	Excluded from 3DCP-CI development due to its limited assessment capabilities.
Khadim et al. (2023)	Builds upon van Vliet (2018) and Verberne, J. J. H. (2016) and implements Geraedts (2016) for adaptability assessment. Uses building layers and scales.	The adaptability assessment, overall framework structure, and disassembly assessment played an integral role in 3DCP-CI development.
Anastasiades et al. (2023)	Focuses on design, construction, and EoL. Uses building scales and MCI as a basis.	While it shares a similar design and EoL scope and structure, it is a highly material-focused indicator that does not align well with 3DCP-CI.

Meanwhile, in the present study, attempts to evaluate 3DCP for circularity using existing methods were not successful. Many frameworks are designed to assess the circularity of entire buildings that use various materials, whereas 3DCP research concerns a single material and technology applied only to specific parts of buildings. Furthermore, many c-indicators try to encourage the designer to use circular materials, placing less emphasis on extending the lifespan of the design.

In this article, a framework is proposed to systematically evaluate the circularity of designs manufactured by 3DCP, focusing on the use and EoL stages. It is hypothesised that the application of the following principles: adaptability, modularity, and disassembly, significantly influences overall performance. By translating these principles into measurable indicators and assessment methods tailored to 3DCP, the framework aims to enhance their practical implementation. While the primary goal is to create a framework that assesses designs manufactured by 3DCP for circularity and thus encourages designers to make more circular decisions, another goal is to identify obstacles for achieving greater circularity in future research.

1.2. Methodology

For this study, a similar methodology to Khadim et al. (2023), van Vliet (2018), Verberne, J. J. H. (2016), and Zhai (2020) was adopted. All four studies were designed to improve an existing c-indicator, a goal that aligns with 3DCP-CI's intentions. Each of these studies consists of three main parts: exploratory research, model design, and a validation process. While Khadim et al. (2023) and Zhai (2020) utilised literature review, van Vliet (2018) and Verberne, J. J. H. (2016) additionally benefited from expert interviews.

This study follows the same three-part structure (see Figure 2), which begins with exploratory research on existing c-indicators for the built environment. To inform this process, a systematic SCOPUS search (2020–2025) was conducted for English-language studies on circularity indicators and assessment frameworks, and insights were also drawn from two recent review papers by Askar et al. (2022) and Khadim et al. (2022) focused on circularity and adaptability frameworks. For this review, frameworks related to demolition or heritage were excluded; specific implementations of existing frameworks such as BIM or LCA were not considered; frameworks not related to design but to construction, regulations, circular businesses, or economic/social circularity were omitted; frameworks designed for the neighbourhood or urban scale, as well as those whose methodology is not publicly available, were also excluded. Both the structure and the assessment methods of the new framework were derived from existing c-indicators.

First, the structure of the framework was selected according to the most preferred option in the literature, to ensure that it could support the integration of different assessment methods. Then, the relevant Key Performance Indicators (KPIs) were identified, and the existing frameworks were filtered based on these KPIs and on their applicability to the overall structure of the framework. The methodology for selecting KPIs is described in Chapter 2.3 Key Performance Indicators (KPIs). The resulting approach reflects a hybrid framework, based on existing methods but customised to suit the context of 3DCP. A mixed-method approach was utilised to develop the framework, synthesising qualitative assessment methods for adaptability, disassembly, and reusability and quantitative assessment methods for recyclability. Finally, these methods were integrated into a quantitative assessment calculation method derived from existing frameworks.

Once the framework design matured, its applicability was validated by assessing a design using 3DCP- CI. The framework development and validation followed an iterative process aimed at refining 3DCP-CI, as illustrated by the double-arrow in Figure 2. Based on the feedback from the assessment process, the framework was improved. For this phase, Project Milestone (Wolfs et al., 2023) was chosen for its large-scale application, multi-functionality of elements (skin and structure) and data availability. The assessment presented in Chapter 3 represents the final iteration of this validation process and demonstrates the framework's application.

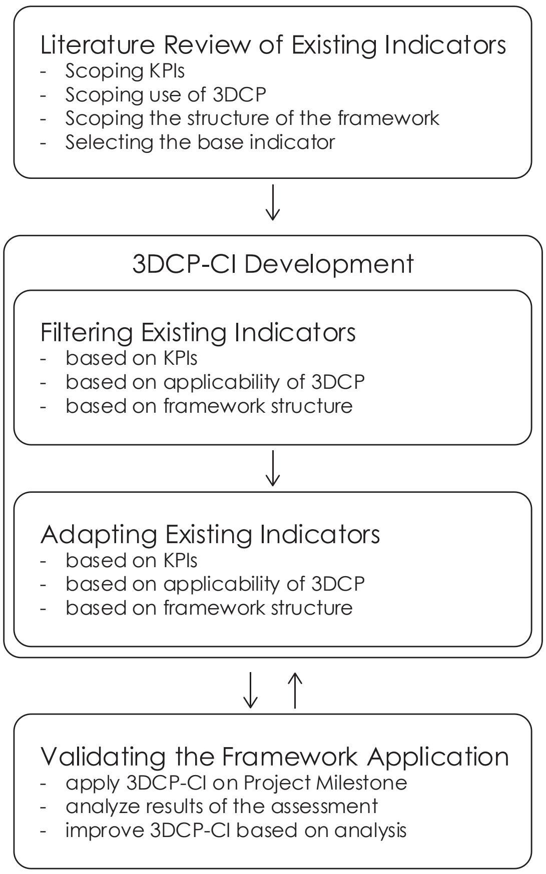

Figure 2. The steps of the methodology used to develop 3DCP-CI.

2. Circularity Framework

This section explains the theoretical development of the circularity framework.

2.1. Framework Structure

The framework structure involves two main ideas: building layers and building scales. Layers refer to the functionalities in the built environment, based on the analysis of Brand (1995) on how buildings evolve.

Brand (1995) identifies six distinct layers with different lifespans: site (eternal), structure (30–300 years but typically under 60 years), skin (20 years), services (7–15 years), space plan (3–30 years) and stuff (3–10 years) (see Figure 3). Many c-indicators in the built environment use this analysis to categorise the functions of elements and systems as well as their respective expected lifespans (Geraedts, 2016; Kentie, 2021; Khadim et al., 2023; van Vliet, 2018; Verberne, J.J.H., 2016). Having these layers physically and functionally independent from one another is the desired scenario for achieving circularity, as it allows adaptability and maintainability (Dams et al., 2021; Mlote et al., 2024; Ottenhaus et al., 2023).

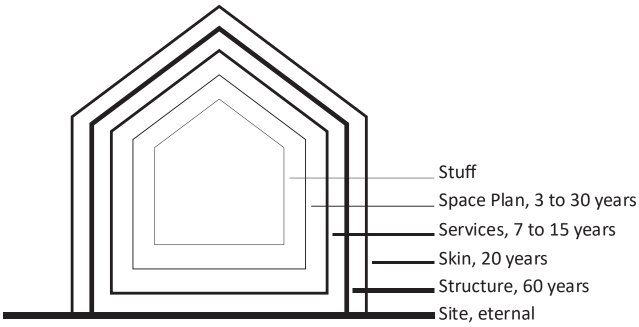

Figure 3. Layers of buildings and their respective approximate service lives, redrawn from Brand (1995)

The scales help break down buildings into their parts. The seminal work of Durmisevic (2006) elaborated on these scales for design disassembly, and was referenced in other c-indicators (Cottafava & Ritzen, 2021; Khadim et al., 2023; van Vliet, 2018; Verberne, J. J. H., 2016). From low to high, these scales are material, element, system, and building. The step from one scale to the next is always an assembly or disassembly process, and often one or more sub-assemblies are involved. Ideally, where building layers are separated, the system scale would refer to one of these layers, such as the structural system, façade system, etc. The relationship between the scales and the layers of buildings is shown in Figure 4.

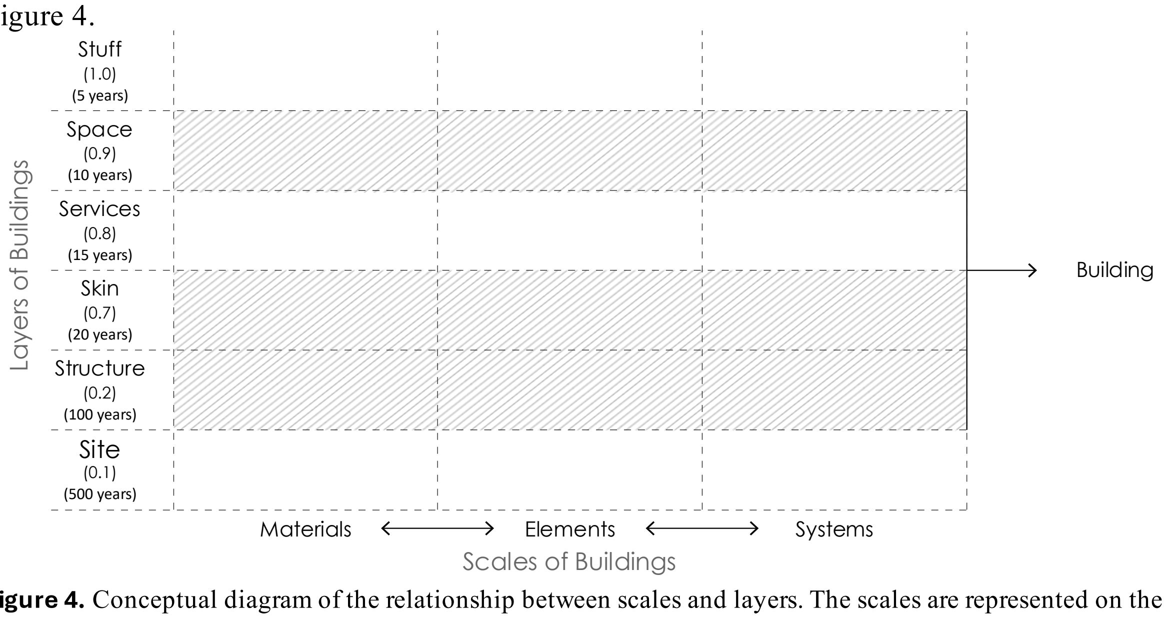

Figure 4. Conceptual diagram of the relationship between scales and layers. The scales are represented on the x-axis, the layers on the y-axis. The hatches show the scope of 3DCP-CI both on building layers (structure, skin, space —excluding site, services, stuff) and scales (materials, elements, systems —excluding building).

2.2. The Scope & Assumptions

3DCP is typically used in structural elements, and in both interior and exterior walls. Therefore, only three building layers were included: structure, skin, and space. The use of 3DCP in furniture design is not uncommon, but this layer is excluded from this framework because it is not considered part of the buildings.

The building scale, the culmination of all systems, was excluded, as it includes different layers and materials that cannot be manufactured with 3DCP, such as windows or service pipes. Since this framework focuses solely on a single material and manufacturing technology, only materials, elements, systems, and combinations of systems manufactured by 3DCP were included.

When demonstrating the framework, it was assumed that the concrete elements could be reused. Alternatively, concrete is recycled to be used as aggregates or wasted at the end of its lifecycle (Gebremariam et al., 2020). Although there are studies on scenarios for concrete recycling (Coenen et al., 2021; Gebremariam et al., 2020), these are not considered general practice. While the steel reinforcement is often recycled, it is only possible to recycle concrete by crushing it with high energy, resulting in non-reusable, down-cycled, or wasted concrete.

Given the EoL scenarios available to concrete, the framework assumes that the goal for designing with concrete is to extend its lifetime. Ellen MacArthur Foundation et al. (2019) define the lifetime of a product as “the total amount of time a product is in use, including the potential reuse of the whole product”, a timeline that can be extended through repair and maintenance. WBCI considers the lifetime of an element as the lowest value of the technical and functional lifetime (Khadim et al., 2023). The functional lifetime “refers to the lifetime the product meets the user’s requirements”, whereas the technical lifetime “refers to the lifetime that the product meets the technical requirements” (Zhai, 2020). Considering the durable nature of concrete, 3DCP-CI assumes that extending functional lifetime through design will improve the circularity potential of designs.

2.3. Key Performance Indicators (KPIs)

C-indicators use different KPIs to assess and hierarchise performance and to exhibit circularity visions and ambitions (Verberne, J. J. H., 2016). Khadim et al. (2022) identify twelve KPIs that have been used in various c-indicators developed for the built environment. These KPIs were neither consistent in each c-indicator nor prioritised equally, but instead tailored to the context of the given c-indicator. They were categorised as material content and process, operational impact, EoL scenarios, and social impact (See Table 2).

Table 2. A list of KPIs defined by Khadim et al. (2022) based on the existing c-indicators, and their further categorisation of impact. Operational impact and EoL scenario indicators are considered for the context of 3DCP.

Category	KPI
Material Content & Process Indicator	Technical Cycle Biological/Renewable Energy Emission Water
Operational Impact Indicator	Adaptability Functional Lifetime Energy Emission Water
EoL Scenario Indicator	Disassembly Reusability Recycling Efficiency

Table 2 (Cont.). A list of KPIs defined by Khadim et al. (2022) based on the existing c-indicators, and their further categorisation of impact. Operational impact and EoL scenario indicators are considered for the context of 3DCP.

Category	KPI
Social Impact Indicator	Heritage Economy

Energy, emissions, and water can be categorised as both material content and process, and also operational impact indicators. However, these KPIs are not included in 3DCP-CI because they can be evaluated through other frameworks like LCA, LEED, and BREEAM. Heritage will be avoided for the simplicity of the framework. However, it could be added to future versions. Economy encapsulates a picture larger than the designs using a single material and technology. Therefore, this KPI is also excluded from the 3DCP-CI.

As described in 2.2 The Scope & Assumptions, maximisation of functional lifetime is the main goal of 3DCP-CI. Khadim et al. (2022) defined functional lifetime as a KPI in c-indicator by Alba Concept (2018), van Schaik (2019), and Zhai (2020). The first two sources do not provide a clear method for assessing, calculating, or determining functional lifetime, and the last source is no longer available. Although functional lifetime is not a KPI that can be assessed alone, the three remaining KPIs— adaptability, disassembly, and reusability— would extend the functional lifetime of concrete. In addition to these three KPIs, 3DCP-CI contains a circularity assessment on recycling efficiency at the material level.

These KPIs for 3DCP-CI are integrated into the framework structure based on an ideal scenario that would receive a full score, where projects consist of separate and independent systems as building layers. Each system should be flexible and adaptable to future changes. Therefore, each system is subjected to a system adaptability assessment according to the layer(s) to which it belongs. When adaptation is no longer possible, the system should still be easily disassembled into its elements. This capacity is evaluated through a system disassembly assessment. The disassembled elements should be reusable if the material lifespan allows it, and so each element is assessed for its reusability. Finally, when the element is not reusable, the element should be separated into its materials for recycling or other circular EoL scenarios. Hence, each element is analysed for material recyclability. Figure 5 illustrates the relationships between different scales and the relevant KPIs.

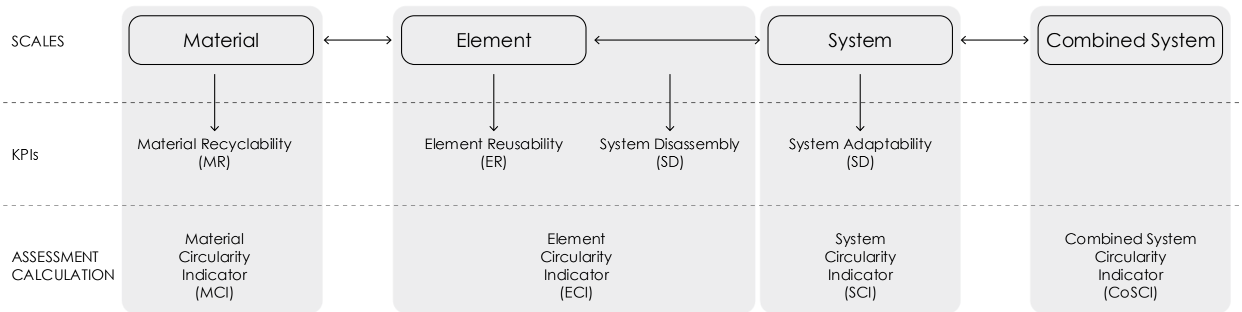

Figure 5. The relationships between scales, in-between scales, KPIs, and their calculation methods for 3DCP- CI.

2.3.1. System Adaptability (SA) Adaptability is "the inherent properties of a building that give it the ability to change" (Heidrich et al., 2017). The characteristics of an adaptable system change based on its layer type (structure, skin, and space plan for 3DCP). Askar et al. (2022) identify eight adaptability frameworks: ARP (Langston et al., 2008), ABD (Allahaim et al., 2010), IconCur (Langston & Smith, 2012), AdaptSTAR (Conejos et al., 2013), PAAM (Wilkinson, 2014), FLEX 4.0 (Geraedts, 2016), SAGA (Herthogs et al., 2019), and ARAM (Mehr & Wilkinson, 2021). Some of these frameworks focus on existing buildings (ARP, IconCUR, PAAM, ARAM), while others focus on specific typologies, such as commercial (ABD) or residential (SAGA) (Askar et al., 2022).

Khadim et al. (2023) adopt FLEX 4.0 (Geraedts, 2016) for WBCI, a framework to determine the adaptability of new buildings of all typologies. FLEX 4.0 follows the structure of the building layers (Brand, 1995).

Its universality for building programs and easy implementation through the building layers make it suitable for 3DCP-CI implementation. FLEX 4.0 uses two sets of detailed KPIs to assess adaptability: one is applicable for all buildings, and a second is for more specific scenarios. Both are divided into building layers. The relevant FLEX 4.0 KPIs for 3DCP-CI were selected and shown in Table 3. Although FLEX 4.0 includes KPIs for disassembly, they were excluded because the assessment of disassembly is a separate step on 3DCP-CI.

Table 3. Adaptability rating table redrawn based on FLEX 4.0 for the KPIs relevant to Geraedts (2016).

Layer	KPI	Explanation	Assessment Values
Structure	Surplus of building floor	Is there a surplus of the needed usable floor space? This enables easy rearrangement or transformation to other functions.	1. Not oversized 2. 10–30% oversized 3. 30–50% oversized 4. > 50% oversized
	Surplus of free floor height	How much is the net free floor height? Higher floor heights enable rearrangement/transformation to other functions and changing demands of facilities and quality.	1. < 2.6 m (Bad) 2. 2.60–3.00 (Normal) 3. 3.00–3.40 (Better) 4. > 3.40 (Best)
	Positioning obstacles/ columns	Is the adaptation of the building obstructed by load-bearing obstacles, walls, or columns?	1. The entire building is 2. < 50% of the building is 3. < 10% of the building is 4. No building space is obstructed by difficult-to-replace load bearing elements.
	Surplus of load-bearing capacity	How large is the load-bearing capacity of the floors in the building?	1. < 3 kN/m2 2. 3–3.5 kN/m2 3. 3.5–4 kN/m2 4. > 4 kN/m2
	Extendible building/ units horizontal	Is it possible to expand the building horizontally for a new extension?	1. Not possible at all 2. Very limited 3. Limited 4. Easily possible
	Extendible building/ units vertical	Is it possible to expand the building vertically for a new extension?	1. Not possible at all 2. Very limited 3. Limited 4. Easily possible
Skin	Location/ shape daylight	The more regular open surfaces in the façade according to the planning grid, the better a building can meet changing demands in functions, quality, and finishing of the building.	1. Large, closed surfaces 2. Small horizontal open surfaces 3. Large open surfaces with different heights 4. Large continuous horizontal openings, connections according to the planning grid.
	Insulation of façade	Higher thermal and acoustic insulation enables easier adaptations to changing user demands.	1. Not meet current demands 2. Meets demands for office buildings. 3. Meets demands for housing and care. 4. Meets 10% above the current demand for offices, housing, and care.
Space	Distinction between support – infill	The more construction components belong to the infill, the easier a building can be rearranged/transformed to other functions, the better a building can meet changing demands	1. <10% 2. 10–30% 3. 30–50% 4. >50% of building is divided into a support and infill part

Each indicator has four possible ratings (the highest score is 4 and the lowest is 1) based on how well the design performs for that specific indicator. In addition to evaluating the design based on the indicator, the assessor must rate the importance of the specific KPI with a weight factor between 1 and 4. In FLEX4.0's implementation to WBCI, the second rating was omitted. The same practice for 3DCP-CI was followed under the assumption that each KPI is equally important. Once the designs are rated, the assessor can normalise the value based on the possible lowest and highest scores, a process that will result in the final adaptability score of the overall system design.

2.3.2. System Disassembly / Element Assembly (SD) System disassembly is the potential of a system to be disassembled into its smaller elements and materials. The disassembly of a system also increases its adaptability. It is also a crucial criterion for its elements to be reusable.

The seminal work of Durmisevic (2006) outlined a framework to assess disassembly in the built environment. This framework is used in other c-indicators, including BCI and WBCI. Durmisevic (2006) identified 17 different Design Determining Factors (DDFs) and weighed them using fuzzy logic. Although both Khadim et al. (2023) and Verberne, J. J. H. (2016) chose seven of these DDFs to be used in the BCI and the WBCI, respectively, van Vliet (2018), through surveys, concluded that 12 DDFs are the most important. Of these 12 DDFs of van Vliet (2018), five were newly introduced. The list of these DDFs and the comparison of frameworks by Khadim et al. (2023), van Vliet (2018), and Verberne, J. J. H. (2016) can be found in Table 4.

Table 4. Comparison of DDFs between Durmisevic (2006), Khadim et al. (2023), van Vliet (2018), and Verberne, J. J. H. (2016). The uses of different names for DDFs in van Vliet (2018) are marked with an *.

DDF Durmisevic (2006)	Verberne, J. J. H. (2016) & Khadim et al. (2023)	van Vliet (2018)	3DCP-CI
Functional separation	X		
Functional dependence*	X	X	X
Structure of material levels			
Type of clustering			
Type of base element			
Use lifecycle coordination	X		
Technical lifecycle coordination	X		
Coordination of lifecycles and use			
Type of relational pattern		X	
Assembly direction	X		
Assembly sequences		X	
Geometry of product edge*	X	X	X
Standardisation of product edge*	X	X	X
Type of connections	X	X	X
Accessibility to fixings*	X	X	X
Tolerance			
Morphology of joints			
	Disassembly costs		
	Deconstruction safety		
	Disassembly Instructions		
	Number of Operations		
	Disassembler Expertise		

All four frameworks by Durmisevic (2006), Khadim et al. (2023), van Vliet (2018), and Verberne, J. J. H. (2016) agree on the importance of functional dependence, product edge geometry, product edge standardisation, type of connections, and accessibility to fixings. These are also relevant DDFs for 3DCP-CI. However, the standardisation of product edge will be addressed later in this article in chapter 2.3.3 Element Reusability (ER). The remaining DDFs fall into the category of system disassembly.

Functional dependence —also named functional autonomy by Durmisevic (2006) and independency by van Vliet (2018)— refers to the separation of different building layers. Durmisevic (2006) identifies four scenarios: total or unplanned integration, unplanned interpenetration, planned interpenetration, and total independence.

"Type of connections" refers to the connection types between the elements, which van Vliet (2018) concluded is the most crucial aspect of disassembly. Durmisevic (2006) identified three types of connections: direct (integral), indirect (accessory), and filled. Accessory connections refer to connections that require an additional element to connect two elements. Depending on the location of this connection, Durmisevic (2006) concludes that these as the most favourable. Integral connections refer to interlocking connections. These are criticised for their assembly sequence, as it is often hard to remove a single element from the interlocking assembly. Filled connections refer to chemical connections. These are considered to be the least favourable (Durmisevic, 2006).

The "accessibility of connections" plays a significant role in disassembly. It is important to be able to access the connections without damaging the elements. This is especially important for the reusability of the elements.

Although left out of the BCI (Verberne, J. J. H., 2016) and WBCI (Khadim et al., 2023), assembly sequences were rated among the most important DDFs by van Vliet (2018). Assessment of the assembly sequence consists of two levels: assembly direction based on the assembly type and assembly sequences with respect to the material levels (Durmisevic, 2006). Although the latter was deemed important in van Vliet (2018), assembly direction plays a more significant role in the context of 3DCP, considering concrete elements' size, weight, and difficulty of handling. Therefore, for this DDF in 3DCP-CI, the assembly direction is referred to. Durmisevic (2006) identifies five scenarios in the assembly direction: parallel assembly, sequential assembly, interlock, closed circle, and base element. The diagram, scores, and definitions of these assemblies can be found in Figure 6.

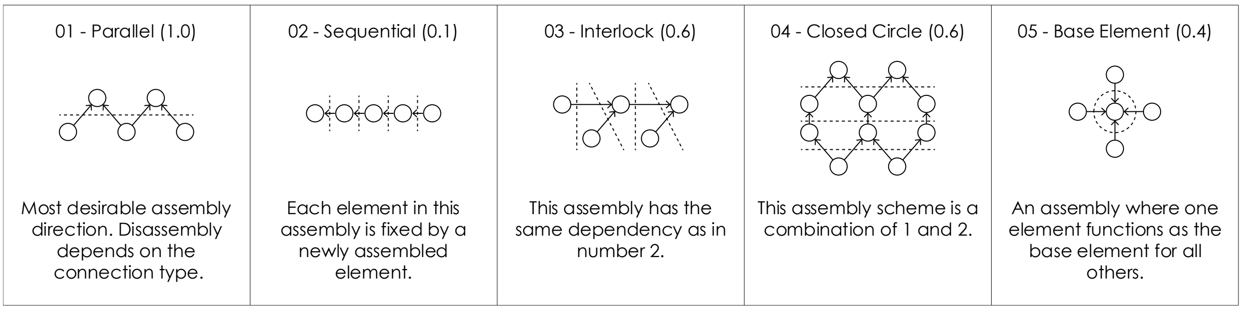

Figure 6. Assembly direction diagrams, descriptions and corresponding grading (Durmisevic, 2006).

Four KPIs were introduced to determine the system disassembly potential in Table 5. The average of these four KPIs results in the disassembly value. If the assembly scores "direct chemical connection" on the type of connection or "not accessible/total damage" on elements with accessibility to the fixings, the elements are considered "cannot be disassembled". Hence, these elements cannot be evaluated for reusability but should be directly evaluated for material recyclability.

Table 5. Grading for system disassembly based on four Design Determining Factors DDFs. Redrawn based on the work of Durmisevic (2006). An asterisk indicates non-reusability.

DDF	Scenario	Grading
Functional Dependence	Total independence	1.0
	Planned interpenetrating for different solutions (overcapacity)	0.8
	Planned interpenetrating for one solution	0.4
	Unplanned integration	0.2
	Total dependence*	0.1

Table 5 (Cont.). Grading for system disassembly based on four Design Determining Factors DDFs. Redrawn based on the work of Durmisevic (2006). An asterisk indicates non-reusability.

DDF	Scenario	Grading
Type of Connection	Accessory external connection of the connection system	1.0
	Direct connection with additional fixing devices	0.8
	Direct integral connection with inserts (pin)	0.6
	Direct integral connection	0.5
	Accessory internal connection	0.4
	Filled soft chemical connection	0.2
	Filled hard chemical connection	0.1
	Direct chemical connection*	0.1
Accessibility to Connections	Accessible	1.0
	Accessible with additional operation, causes no damage	0.8
	Accessible with additional operation, causes reparable damage	0.5
	Accessible with additional operation, causes partly reparable damage	0.4
	Not accessible/total damage of elements*	0.1
Assembly Sequence	Parallel – open assembly	1.0
	Stuck assembly	0.6
	Base element in stuck assembly	0.4
	Sequential assembly	0.1

2.3.3. Element Reusability (ER) Reuse was defined as the "operation by which a product, its components, or materials can be used again for the same purpose/function for which they were conceived" (Kamp, 2021). In line with this definition, Kamp (2021) describes the "reuse potential" for concrete as "possibility to reuse a harvested concrete element in the design of a new building, considering the process of 'Deconstruct & Reuse'."

Excluding frameworks on adaptive reuse or material recyclability, only two frameworks aligned with 3DCP-CI's aims and context: "Reusability Potential in the Building Circularity" (Kentie, 2021) and "Assessment of the Reuse Potential of Existing Concrete" (Kamp, 2021). These two frameworks were synthesised to create the element reusability assessment.

Kentie (2021) identifies nine measurable and essential KPIs to assess reuse potential: disassembly, toxicity, logistics, data management, standardisation, quality, financial value, over-dimensioning, and contracting. As "disassembly" is already implemented at the system level, it would be redundant to include this KPI at the element level. The "toxicity" of concrete can be ignored due to the material properties. "Data management" is assumed to be adequately provided due to the nature of digital manufacturing. The 'quality' and 'financial value' of an element are KPIs that can be determined on the day of disassembly or reuse, not on the day of manufacture. Therefore, these KPIs were also excluded in 3DCP-CI. "Over-dimensioning" is difficult to determine in the case of 3DCP, as regulations for this technology are under development and many real-life projects are built with extra safety margins (Bos et al., 2022; Wolfs et al., 2023). 'Contracting' refers to "the return guarantee of a building product", which is a legal condition rather than a design feature and therefore was also excluded. This leaves us with logistics and standardisation.

The logistics of an element refer to the difficulty in removing an element from the site. This factor is influenced by the dimensions and weight of the element (Kamp, 2021; Kentie, 2021). The reusability of an element is diminished as soon as it becomes too difficult to relocate it. Kentie (2021) identifies three categories of logistics: normal transportation, specific transportation, and no transportation. Normal transportation is transportation by road. This requires the element to be within 3.00 m x 4.00 m x 22.00 m with a total mass of 50 tons (50,000 kg), including the transport vehicle (Kamp, 2021; Kentie, 2021). Specific transportation is provided for exceptional cases with high historical or cultural value. In these cases, the dimensions are 27.50 m x 3.50 m x 4.25 m, and the weight is less than 100 tons (100,000 kg). Any element that falls outside of these limitations will be considered untransportable. No transportation option categorises the element as non-reusable regardless of all other characteristics of the design.

As mentioned in 2.3.2 System Disassembly/Element Assembly (SD), "standardisation of product edge" was used to assess standardisation. Durmisevic (2006) defines three categories for the product edge: pre-made geometry, half-standardised geometry, and in situ geometry. Kamp (2021) explains that a half-standardised geometry could be a project-specific element with non-standard dimensions, as well as an element with standard overall geometry with project-specific reinforcement layout. Based on these descriptions, almost every element would be a non-standardised form due to the manufacturing technique of 3DCP. Therefore, the bounding box of the designed element for standardisation, and the possibility to use it in other scenarios once it is removed from its original context, should be considered. This would determine if an element was half-standardised or pre-made. The assessment sheet for element reusability can be found in Table 6.

Table 6. Grading for element reusability based on two DDFs: logistics and standardisation. Redrawn based on the work of Durmisevic (2006).

DDF	Scenario	Grading
Logistics	Normal transportation	1.0
	Specific transportation	0.8
	No transportation	0.1
Standard-Isolation	Pre-made geometry	1.0
	Half-standard geometry	0.5
	In situ construction	0.1

2.3.4. Element Disassembly/Material Assembly Element disassembly is the step between when the element is obsolete and when the material is recycled or disposed. There is no numerical assessment at this stage. However, this step influences the assessment of material recyclability. For instance, if the element is reinforced with rebar, one must break the concrete to recover the steel. In contrast, if the element was post-tensioned without grout, this would result in an easier separation of materials with significantly lower energy and higher recyclability for the concrete element. Once the operation to separate materials with different EoL processes is determined, the assessment of recyclability can be continued.

2.3.5. Material Recyclability (MR) Material Recyclability is the last step in circularity assessment, where materials used in the design are evaluated for their circularity. Unlike the previous KPIs, Material Recyclability (MR) is a quantitative assessment. The MR value is used to determine an Element Circularity Indicator (ECI) when combined with the element reusability score. For this KPI, the c -indicator for bridges by Coenen et al. (2021) was integrated.

The main aim of MR is to reduce the use of virgin materials (recycled, reused, and renewable) and to encourage the use of recyclable materials. To start, the fraction of virgin materials was calculated using Equation 1, by calculating the fraction of recycled, reused, and renewable materials (Frec, Freu, and Fren, respectively) and subtracting it from the whole, or 1, to obtain the value Linear Flow (LF). All of these fractions are based on the ratio of the mass of each type of material to the total mass of the element. To prioritise reused and renewable over recycled materials, Coenen et al. (2021) add a coefficient of 'k' for the fraction of recycled materials, which is determined to be 0.8.

$$LF = 1 - k * F_{rec} - F_{reu} - F_{ren} \quad (1)$$

The next focus is the circularity potential of the materials. The ratio of the mass of the recyclable material to the total mass of the element, and subtracted from the whole (1), is taken to calculate EF_{rec}. Using Equation 2, the Material Input (MI), indicating the circularity of the materials.

$$MI = \frac{LF + EF_{rec}}{2} \quad (2)$$

Next, Coenen et al. (2021) introduce the concept of robustness. It refers to the overdesigning of bridges based on structural safety calculations. This is a very infrastructure-specific value, as bridges are more utilitarian and expensive than buildings and have longer lifespans. Moreover, it requires well-developed building codes and standards, which 3DCP, being a young technology, lacks. Therefore, it was assumed that 3DCP elements are designed for their intended lifespan, which results in a robustness value of 1. Robustness is converted to corrected robustness (CR) using Equation 3, which is then used in the final calculation.

$$CR = \frac{0.9}{R} \tag{3}$$

Since "robustness (R)" is always assumed to be 1, "corrected robustness (CR)" will always be 0.9 for the recyclability of 3DCP. MI and CR were used in Equation 4, the final stage of MR calculation.

$$MR = 1 - MI * CR \tag{4}$$

The approach of Coenen et al. (2021) was adopted at the material level because of the way MCI is integrated by Khadim et al. (2023) and Verbeke (2013). Verbeke (2013) multiplies the MCI value by the disassembly score to achieve the circularity of the element scale. Similarly, Khadim et al. (2023) multiply MCI by the Material Normalisation Index. This gives the material composition a strong emphasis on the final circularity score, which encourages more circular materials. However, concrete is often used for long lifespans, which elevates the role of reusability and adaptability. For 3DCP-CI, where the main objective is to extend the lifetime through design, the design principles that would extend the lifetime of concrete should be prioritised more. Therefore, for 3DCP-CI, Bridge Circularity Indicator (BrCI) by Coenen et al. (2021), a c-indicator built mainly for concrete structures with longer lifespans, is a more appropriate version of the MCI implementation.

In BrCI, to achieve the final circularity assessment, MR is combined with other KPIs—resource availability, reusability, and adaptability—depending on the lifespan of the bridge design. Shorter lifespans (<50 years) prioritise reusability, middle lifespans (50-110 years) prioritise adaptability over reusability, and long lifespans (>110 years) prioritise recyclability (Coenen et al., 2021). For 3DCP-CI, the importance of these KPIs was kept even, as the lifespan of buildings is not as extensive as that of bridges. However, different lifespans of building layers could have similar considerations, though this is not currently addressed in the literature. Moreover, since BrCI is designed for bridges, it lacks the structure of the building layers and scales. Therefore, the implementation of adaptability, disassembly, and reusability in 3DCP-CI follows a more structured approach that is aligned with the structure proposed in 2.1 Framework Structure. The implementation is further explained in the next chapter.

2.4. Assessment Calculation

The process of applying 3DCP-CI consists of two parts, assessment and calculation. While the assessment should be ordered from the higher to lower scale (system to material) using the methods described in 2.3 Key Performance Indicators (KPIs), the calculation should be in reverse order, as depicted in Figure 7. The calculation aims to combine the different assessment scores obtained on different scales (material, element, system) into a final circularity score between 0 (not circular) and 1 (fully circular), which will determine the circularity of an element (Element Circularity Indicator (ECI)), system (System Circularity Indicator (SCI)) or a collection of systems (Combined Systems Circularity Indicator (CoSCI)).

As explained in 2.3.5 Material Recyclability (MR), to calculate the recyclability and ECI in 3DCP- CI, the method proposed in BrCI by Coenen et al. (2021) was adapted. After calculating Material Recyclability (MR) and assessing Element Reusability (ER) and System Disassembly (SD) of the element, these values were used to calculate ECI, as shown in Equation 5.

$$ECI = \frac{MR + ER + SD}{3} \tag{5}$$

Having established ECI, the SCI is calculated next, similar to the approach of Khadim et al. (2023). This is done by using System Adaptability (SA) as described in Equation 6, where m_i stands for the mass of the element and m_t refers to the total mass of the system.

$$SCI = \frac{\sum ECI_i * m_i}{m_t} * SA \quad (6)$$

When multiple systems are involved, the assessor should combine multiple SCI values into a CoSCI score. Both BCI and WBCI use the concept of Level of Importance (LI) (see Table 7) when calculating the overall circularity score of the building (Khadim et al., 2023; Verberne, J. J. H., 2016). This creates a hierarchy between different layers. The importance of circularity is reduced per layer (Verberne, J. J. H., 2016), as the expected lifespan of the system increases based on its layer.

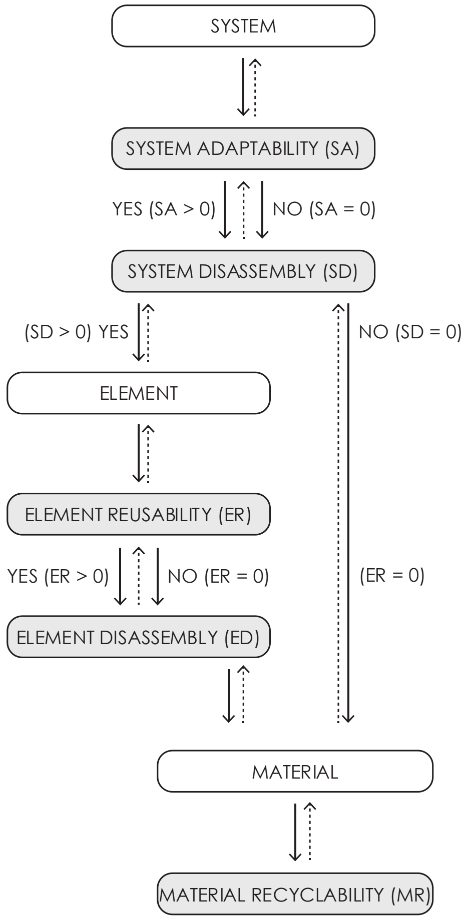

Figure 7. Circularity assessment and calculation direction (continuous and dashed arrow direction, respectively).

When systems are independent of each other per layer, the LI value per SCI is assigned based on the layer to which it belongs. When the system combines more than one layer, the system should take the lower LI value. For instance, a structural wall that also functions as a façade should receive a LI value of 0.2 while the value of LI_t should be 0.9, that is, the total of the layers involved in the design. This aims to discourage layer combining at the system level.

$$CoSCI = \frac{\sum_{k=1}^{n} SCI_k * LI_k}{LI_t} \quad (7)$$

Table 7. Level of importance of the relevant layers based on Khadim et al. (2023) and Verberne, J. J. H. (2016)

Layer	Level of Importance (LI)
Structure	0.2
Skin	0.7
Space Plan	0.9

3. 3DCP-CI Application: Project Milestone

In this chapter, 3DCP-CI is used to assess the Project Milestone for demonstration. Not all data was accurately measured or provided in the project documents. However, the estimates are realistic enough for this assessment to be a viable demonstration. The calculations were intended to be demonstrations of the framework only. The goal is not to accurately measure the real circularity score of Project Milestone.

3.1. Project Description

The first of the five proposed buildings, Project Milestone, is a 3D-printed single-story, single-family house in Eindhoven, the Netherlands. Milestone was built using unreinforced 3D-printed structural wall elements, covering an area of 94 m2 (Wolfs et al., 2023). Only the wall elements were included in the assessment, while other printed components were excluded for simplicity.

The elements were printed off-site. Wolfs et al. (2023) define two wall types: type A elements with a small cantilever (max angle 3°) on the outer edge and type B elements with a larger cantilever (max angle 12°) on the outer edge. While type A elements were printed hollow, type B elements were printed with an inner wall pattern. The negative space inside the wall elements of both types was filled with open-celled polyurethane foam after the concrete hardened. The foam was anchored to the printed concrete using steel anchors that were placed during the printing process (see Figure 8) (Wolfs et al., 2023).

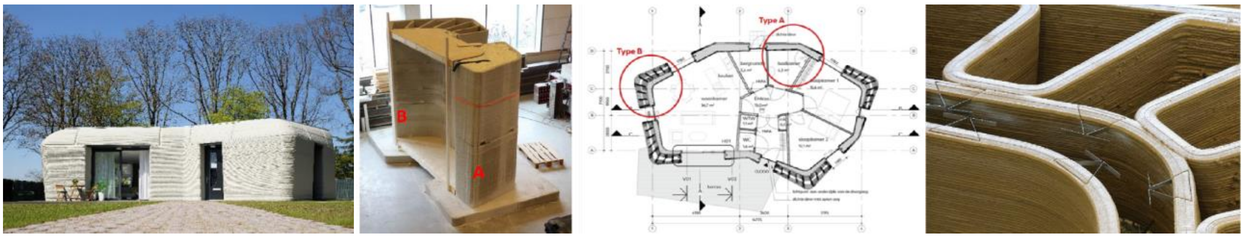

Figure 8. From left to right, Project Milestone (photograph by Bart van Overbeeke), two printed wall types; a plan view showing the wall types; and embedded steel connectors (reproduced from Wolfs et al., 2023).

The estimated numerical data used for the evaluation are documented in Table 8. The wall type, total mass, and inner length were obtained from Snel (2020). The outer length was estimated based on the architectural drawings (Snel, 2020). A single anchor was estimated to weigh 0.15 kg, and the total mass of anchors was calculated based on the estimated number of anchors, determined by the spacing requirements (450 mm) and the number of rows (seven) (Snel, 2020; Wolfs et al., 2023). For type A, each row was calculated based on the sum of the inner and outer lengths of the wall. For type B, the inner length was doubled due to the wall geometry. The insulation volume was calculated from the area measured in the architectural drawings multiplied by the wall height of 2630 mm (Snel, 2020; Wolfs et al., 2023). The insulation density was calculated as 22 kg/m^3 (Technisol, 2023).

Table 8. Approximation of wall data.

	Type	Total Mass(kg)	Inner Length (mm)	Outer Length (mm)	Steel Anchors (count)	Steel Anchors (kg)	Concrete Element (kg)	Insulation (m3)	Insulation (kg)
W1	B	3843	3005	4668	93	14	3776	2.42	53
W2	A	2462	3958	4255	128	19	2331	5.08	112
W3	A	2003	3944	4236	127	19	1906	3.55	78
W4	B	3316	3040	4643	95	14	3259	1.95	43
W5	A	1301	2682	3045	89	13	1225	2.84	62
W6	B	4108	3738	5178	116	17	4038	2.37	52
W7	A	1107	2683	2503	81	12	1040	2.50	55
W8	B	3859	3332	5087	104	16	3791	2.39	53

3.2. KPI Assessment

The initial step of 3DCP-CI is to identify the layers used in the design and determine whether these layers are independent of each other. When the system functions as more than one layer, it should be assessed for all the functions it serves. The elements of Milestone, in their assembled form, function as both skin and structure; hence, the adaptability assessment is conducted for both. The assessment of adaptability, disassembly, and reusability is recorded in Table 9. As the disassembly assessment suggests that disassembly is possible, the reusability of the elements is also assessed.

As recorded in Table 10, each wall element has the same MR, ER, and SD value and also shares the same ECI value of 0.47. ECI combined with the SA score of 0.46 results in a SCI score of 0.22.

Table 9. Combined assessment table for Project Milestone.

Layer	KPI	Assessment Values	Assessment Explanation
Structure	Surplus of building floor	Not oversized [1]	Since it's single-family housing, the building is quite small with no surplus of building floor area.
	Surplus of free floor height	2.60–3.00 (Normal) [2]	The height of the floor is 2.6 m according to the project drawings.
	Positioning obstacles/ columns	No building space is obstructed [4]	Since the façades are load-bearing, there are no structural elements inside the building.
	Surplus of load-bearing capacity	< 3 kN/m^2 [1]	The slab calculations in the project documents show load-bearing capacity below 3 kN/m^2.
	Extendible building/units horizontal	Limited [3]	Because it's a single-story building and the wall elements create openings, there is an opportunity for horizontal expansion.
	Extendible building/units vertical	Very limited [2]	The slab's low load-bearing capacity (despite the walls' high capacity) means vertical expansion is very limited.
Skin	Location/shape daylight	Large open surfaces with different heights [3]	All openings are floor-to-ceiling height, though they are not horizontal or continuous.
	Insulation of façade	Meets demands for housing and care [3]	As this building is designed as a house, the insulation meets residential requirements.

Min score: 8 — **Max score:** 32 — **Score:** 19
System Adaptability Score (SA): 0.46 — **Structure:** 0.39 — **Skin:** 0.67

Disassembly Factors	Scenario	Explanation	Score
Functional Dependence	Total Dependence	The elements are not separable for their different functions.	0.1
Type of Connection	Filled hard chemical connection	The elements are connected using mortar.	0.1
Accessibility to Fixings	Accessible	The seams between the elements are fully accessible.	1.0
Assembly Sequence	Parallel – open assembly	The elements are directly placed next to each other.	1.0
System Disassembly Score (SD)			0.55

Reusability Factor	Scenario	Explanation	Score
Logistics	Normal Transportation	The elements meet the weight and size boundaries for transportation.	1.0
Standardisation	Half standard geometry	Though it is a prefabricated element, it has a non-standard geometry.	0.5
Element Reusability Score (ER)			0.75

Since the system combines the façade and structural layer, calculating the CoSCI value requires identifying two LI values in order to apply Equation 7. As shown in Table 7, LI_k for the structure is 0.2 and for the skin 0.7. When combining two layers, LI_t should be the lowest of the combined layers (in this case, 0.2, the structure), while LI_t should be the sum of all LI_k values, which is 0.9 (0.2 + 0.7). This results in a CoSCI value of 0.05 (see Table 10).

Table 10. Calculation of ECI, SCI, and CoSCI based on data provided in Table 8

MI Parameters	Concrete Element	Steel Connectors	Insulation
Recycled Materials (%)	0.00	0.00	0.00
Reused Materials (%)	0.00	0.00	0.00
Renewable Materials (%)	0.00	0.00	0.00
Recyclable Materials (%)	0.00	0.01	0.00
MR for Individual Wall Element	0.1	Using Equation 4	
ER	0.75	0.75	
SD	0.55		
ECI	0.47	Using Equation 5	

	Wall	Mass	ECI
	W1	3,843	0.47
	W2	2,462	0.47
	W3	2,003	0.47
	W4	3,316	0.47
	W5	1,301	0.47
	W6	4,108	0.47
	W7	1,107	0.47
	W8	3,859	0.47
Total Mass		21,999	
SA		0.46	Using Table 9
SCI		0.22	Using Equation 6
CoSCI		0.05	Using Equation 7

3.3. Discussion

According to the Milestone assessment, some design decisions resulted in a poor circularity score. The greatest impact came from the lack of separation between the skin and structural layers. This reduced SCI from 0.22 to 0.05 in the CoSCI score. Separation would have further increased the disassembly score by the Functional Dependence factor. This practice hinders maintainability, adaptability, and disassembly.

Furthermore, the use of mortar for the connections resulted in a disassembly score of 0.55. This could have been improved to 0.78 by designing reversible joints. Introducing recycled materials into the design noticeably improves MR and ECI scores. Increasing MR from 0.1 to 0.3 could have resulted in an ECI score of 0.54 instead of 0.47. Depending on the intervention, designing the system for future changes would result in greater adaptability and a higher SCI score.

Several hypothetical scenarios were tested to assess the framework's sensitivity, as summarised in Table 11. These scenarios included: the use of reused anchors; anchors made from recycled steel; recyclable insulation for W1 (wall type B) and W2 (wall type A); and concrete mixtures containing recycled aggregates (10% or 15% of the total concrete weight) for W1 and W2. For wall-specific changes, the resulting ECI values were calculated per wall, whereas other changes were assessed at the system level.

Since steel constitutes only a small portion of the total wall mass, its influence on CoSCI was negligible, though its effect on MR was measurable. Similarly, while insulation represents a larger mass fraction than steel, its recyclability produced only a minor but measurable increase in ECI, despite a noticeable improvement in MR. Incorporation of recycled aggregates had a stronger positive effect on ECI compared to insulation or steel elements. In contrast, a design intervention involving reversible joints yielded a substantially greater improvement in ECI.

The application of this framework reveals the essential data required during or after design, manufacturing, and assembly for accurate circularity assessment. Considering the data needed, it is best to conduct the evaluation during the design phase. Additionally, disclosing necessary data in project documentation is beneficial. For each element, the assessor needs to know the mass and bounding box of the element geometry. Furthermore, the inventory of additional materials and products used in the design and their mass is necessary for recyclability calculations. Finally, knowledge of assembly and disassembly plans is crucial for disassembly assessment.

Table 11. Comparison of circularity indicator results under different design scenarios. Fractions for each scenario are shown on the left, with changes from the original state highlighted. The effect on each step of the circularity calculation is shown on the right, with cell shading intensity reflecting improvement relative to the original state.

Scenario	F_{rec}	F_{reu}	F_{able}	EF_{rec}	LF	MI	MR	ER	SD	ECI	SA	SCI	CoSCI
Original state	0.0000	0.0000	0.0100	0.9900	1.0000	0.9950	0.1045	0.7500	0.5500	0.4682	0.4600	0.2154	0.0479
If the connectors were reused	0.0000	0.0100	0.0100	0.9900	0.9900	0.9900	0.1090	0.7500	0.5500	0.4697	0.4600	0.2160	0.0480
If the connectors were made of recycled steel	0.0100	0.0000	0.0100	0.9900	0.9920	0.9910	0.1081	0.7500	0.5500	0.4694	0.4600	0.2159	0.0480
W1 if insulation was recyclable	0.0000	0.0000	0.0200	0.9800	1.0000	0.9900	0.1090	0.7500	0.5500	0.4697			
W2 if insulation was recyclable	0.0000	0.0000	0.0300	0.9468	1.0000	0.9734	0.1239	0.7500	0.5500	0.4746			
W1 if concrete had 10% recycled aggregate	0.1000	0.0000	0.0100	0.9900	0.9214	0.9557	0.1399	0.7500	0.5500	0.4800			
W2 if concrete had 10% recycled aggregate	0.1000	0.0000	0.0100	0.9900	0.9233	0.9567	0.1390	0.7500	0.5500	0.4797			
W1 if concrete had 15% recycled aggregate	0.1500	0.0000	0.0100	0.9900	0.8821	0.9360	0.1576	0.7500	0.5500	0.4859			
W2 if concrete had 15% recycled aggregate	0.1400	0.0000	0.0100	0.9900	0.8850	0.9375	0.1563	0.7500	0.5500	0.4854			
Original state with reversible joints	0.0000	0.0000	0.0100	0.9900	1.0000	0.9950	0.1045	0.7500	0.7800	0.5448	0.4600	0.2506	0.0557

4. Conclusion

In this article, 3DCP-CI was introduced as a new framework to assess the circularity potential of architectural designs using 3DCP for their use and EoL stages. The framework uses four main KPIs—adaptability, disassembly, reusability, and recyclability—to reach a final circularity score. In contrast to existing c-indicators, 3DCP-CI specifically focuses on 3DCP and its applications in building design. It is important to align the development of 3DCP technology and the expansion of its applications with circularity goals. Existing c-indicators were studied and implemented to design the framework. To demonstrate the application of 3DCP-CI, the Project Milestone was evaluated by using the framework.

This is the first attempt to create a c-indicator for 3DCP. The design of 3DCP-CI should evolve as 3DCP continues to develop and the technology's applications expand. The framework was intentionally designed to be modular on different scales, layers, and KPIs for future adaptations.

4.1. Future Research and Limitations

In this study, Project Milestone was evaluated using 3DCP-CI to validate and demonstrate the framework's applicability. The assessment produced a final circularity score and identified key areas for design improvement. As discussed in Section 3.3 Discussion, potential design modifications were shown to enhance the circularity score. However, further assessments of diverse 3DCP projects are needed to strengthen the framework's applicability and generalisability. Moreover, as 3DCP technology and its design applications continue to evolve, refinement of the framework should proceed in parallel with technological advances.

Another important future addition to the framework is the LCA integration for a more comprehensive understanding of the environmental impact of 3DCP designs. This would introduce additional complexity in the material composition of designs. There are studies on the relationship between circularity and LCA, as well as examples of this integration on the level of the building circularity indicator (Brändström & Saidani, 2022; Khadim et al., 2025; Rasmussen et al., 2019; Samani, 2023; van Stijn et al., 2021).

Implementing 3DCP into the building code and creating standards for its use will improve assumptions on the robustness and technical lifetime of elements. As technology matures and these norms are constructed, they should be implemented into the framework, as well. Currently, this framework assumes that the KPIs of adaptability, disassembly, and reusability are of equal importance; however, the relationship between KPIs, building layers, and system lifespan could be refined. The relationship between KPIs and lifespan is established by Coenen et al. (2021), who found that reusability is more relevant for designs with shorter lifespans, whereas adaptability becomes more important as the design lifespan is extended.

The development of the framework highlighted some design principles that require attention in 3DCP designs. Implementing reinforcement strategies that allow dry connections and reusable concrete elements could enhance the circularity of 3DCP designs. Achieving modularity and standardisation of elements and connections remains a challenge, especially when balancing these goals with the advantage of material savings through geometric complexity enabled by 3DCP technology.

The 3DCP-CI framework offers a foundational tool for evaluating circularity in 3DCP designs. The framework provides a valuable tool for the 3DCP community, supporting the integration of circularity into design processes and helping identify gaps in current research and practices.

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Declarations

Competing interests The authors declare no competing interests.

Acronyms

3DCP 3D Concrete Printing.

BCI Building Circularity Indicator.

BrCI Bridge Circularity Indicator.

c-indicator Circularity Indicator.

CoSCI Combined Systems Circularity Indicator.

DDF Design Determining Factor.

ECI Element Circularity Indicator.

EoL End of Life.

ER Element Reusability.

EU European Union.

KPI Key Performance Indicator.

LCA Life Cycle Assessment.

LF Linear Flow.

LI Level of Importance.

MCI Material Circularity Indicator.

MI Material Input.

MR Material Recyclability.

SA System Adaptability.

SCI System Circularity Indicator.

SD System Disassembly.

WBCI Whole Building Circularity Indicator.

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