Design Science

Design issues concerning circular economy assessment methods at the product level: a comparative analysis through a case study of a mobile tiny house

Laura Ruiz-Pastor[1,2], Stefania Altavilla[3] and Yuri Borgianni[2]

[1]*Department of Mechanical Engineering and Construction, Universitat Jaume I, Castelló de la Plana, Spain*
[2]*Faculty of Engineering, Free University of Bozen-Bolzano, Bolzano, Italy*
[3]*Independent researcher, Graz, Austria*

Abstract

Sustainability evaluations are increasingly relevant in the design of products. Within sustainability-related frameworks, circular economy (CE) has gained attention in the last few years, and this has vastly affected design, leading, for example, to design for circularity. This article deals with the wide range of product-level CE assessment tools, out of which some are applied to a case study from the building sector, namely a tiny house made with hemp bricks. Attention was specifically paid to those methods through which a single circularity indicator could be extrapolated. Overall, the objective of this work is to study the convergence of existing CE assessment methods in providing consistent circularity performances. The results show similarities in the overall circularity scores despite differences in the variables used to achieve that final score. Thus, despite the lack of standard methods, the results suggest that many of these tools are sufficiently interchangeable, also in consideration of consistent indications to improve the circularity of the tiny house. This means that consistent inputs are provided to anyone willing to redesign the tiny house with the objective of making it more circular irrespective of the assessment tool used.

Keywords: Circular economy, Eco-design, Product design, Impact assessment, Indicator, Product lifetime

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Corresponding author
Yuri Borgianni
yuri.borgianni@unibz.it

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1. Introduction

The impact of human activities on natural resources is considered a threat to their preservation. The development and manufacturing of products is a primary example of human activities implying the exploitation of natural resources. In this article, the term “product” is intended in a broad sense to mean any physical object and artifact designed to satisfy human needs, that is, including both industrial items and buildings.

As a result of the impact of product development, design is one of the key players in addressing the mentioned sustainability challenges (Buchanan 2001). Through design, the new products have to keep their original aspect and functions as long as possible (den Hollander, Bakker, & Hultink 2017). To this aim, the principles of the circular economy (CE) are gaining traction in the realm of design. According to Bhamra & Hernandez (2021), the focus on CE in design is due to its capability to work as an umbrella concept including the most acknowledged eco-design principles and objectives, from cradle-to-cradle to eco-efficiency. Kim *et al.* (2020) highlight how eco-design is conducive to CE and that the two domains share similar goals. This has led to the proliferation of methods ascribable to "design for CE" and "design for circularity," which have been recently reviewed and classified (Mesa 2023; Stölzle, Roth & Kreimeyer 2023).

The attention to be paid to CE determines new challenges, required knowledge areas and skills for designers (Sumter *et al.* 2020; Dokter, Thuvander & Rahe 2021), who play an important role in the introduction of CE in the industry and the society at large (Golinska *et al.* 2015; Kefayati & Moztarzadeh 2015). As design choices to be made in numerous phases have considerable effects on most CE-oriented acknowledged R strategies (Muñoz, Hosseini & Crawford 2024), the focus on circularity and its measurement are both critical and clearly required. CE assessment is ultimately relevant for the correct implementation of CE principles (Azapagic & Perdan 2000; Bocken *et al.* 2017; Valenzuela-Venegas *et al.* 2016; Vinante *et al.* 2021). Cottafava and Ritzen (2021) stress the need to accurately assess CE performances in the building industry to evaluate how designs have been successful in material recovery. The assessment of product circularity is also critical to companies that attempt to benefit from the opportunities enabled by CE-related policies (Saidani *et al.* 2017a). Contextually, it has to be highlighted that sustainability-oriented assessment methods do not overlap with techniques meant to measure CE. In the literature, some authors have compared results of sustainability and CE assessments for various systems (e.g., Li *et al.* 2023) and have shown complementarity between the two (e.g., Khadim *et al.* 2023). Sustainability and CE concepts have in fact similarities and differences, but ultimately, they both foster peculiar objectives. In this regard, Saidani *et al.* (2022) specifically clarified the difference among CE, life cycle assessment (LCA) and sustainability indicators. In some authors' view, circularity indicators are part of environmental performance systems (Rigamonti & Mancini 2021) and, as such, deserve specific attention.

As materials are a primary concern in CE (e.g., Hallstedt *et al.* 2023), designers have to identify, among the others, the most suitable combination of materials in terms of performance, costs and sustainability (Ruiz-Pastor *et al.* 2023). This optimal combination is still challenging, especially in the building industry. Here, it is exceedingly difficult to anticipate the impact of design choices and strategies on sustainability and compliance with CE principles (Eberhardt, Birkved & Birgisdottir 2022). The correct use and experimentation of new materials are fundamental actions to move towards sustainable development (Arrigoni *et al.* 2017) in consideration of the substantial footprint otherwise caused by traditional construction materials, still in high demand (Hossain *et al.* 2020). These new materials, mostly of natural origin, intrinsically foster the implementation of CE by improving the performance and end-of-life possibilities of the products and buildings they are part of (Barth & Carus 2015). Particularly diffused are natural materials such as hemp or wood, which are supposed to have no negative effect on the performance of the designed products (Galimshina *et al.* 2022). To test the environmental quality of these materials and other innovative building techniques, a common approach is to analyze buildings and houses through LCA (Arrigoni *et al.* 2017;

Cabeza *et al.* 2014; Ruiz-Pastor *et al.* 2023). While the application of LCA follows a nearly standardized procedure, the same cannot be stated for the assessment of the compliance of products with CE principles, as better stressed in the following section. It is also worth highlighting that while the concepts of CE and sustainability share many objectives, differences are likewise acknowledged (Castro *et al.* 2022; Cardoso Chrispim, Mattsson & Ulvenblad 2023), and, consequently, the assessment of both is useful in many instances. This kind of assessments, along with the terms used to assess CE, are particularly important when it comes to design, whether buildings only or products in general are dealt with. On the one hand, the mentioned difficulties of predicting performances, including environmental ones, in the early design stages are known with clear implications on decision-making (Borgianni, Cascini & Rotini 2018; Parolin, McAloone & Pigosso 2023). Markedly, the research aimed to include CE considerations in the early design phases is still immature (Pozo Arcos *et al.* 2018). This calls into question the need to perform accurate assessments once the definition of the product characteristics has moved forward during the design process. On the other hand, CE indicators used for assessment tasks are closely linked to design for circularity (Saidani *et al.* 2020); otherwise said, the acknowledgment and understanding of CE metrics can nurture design practices oriented to cope with CE overall.

This article deals with the variability of the assessment of CE using different established methods, and a case study from the building sector is used to evaluate such variability. In line with the lack of CE assessment standardization, which will be highlighted in Section 2, the objective of this article is to study the convergence of existing CE assessment methods and tools in providing consistent circularity performances. It is worth noting that, while much research agrees on the lack of standardization of CE assessment, its practical consequences for decision-making and design are poorly investigated. This work focuses on the product level of CE by comparing the results obtained with different tools for the same case study. In this way, it is possible to get insights into the practical similarities and differences of the main existing tools.

2. Background about the lack of standardization in circularity assessment

Circularity is a term typically used to denote the overall compliance of systems with the principles and goals of CE (Corona *et al.* 2019; Harris, Martin & Diener 2021; Al-Obaidy, Courard & Attia 2022). Many methods and tools to evaluate circularity exist. The main objective in assessing the circularity of products is to help decision-making by providing some information about them and about their life stages (Bragança, Mateus & Koukkari 2010). Furthermore, the evaluation must be coherent, complete and objective (Mesa, Esparragoza & Maury 2018). There are no standard methods or tools to assess CE in products (European Environment Agency (EEA) 2016), but the need for standardization is strong as witnessed by standardization efforts. In this respect, the standard ISO 59020, intended to assess circularity performances, is under development. It is also worth mentioning that some of the CE objectives are considered in sustainability-related standards too (Ahlstedt & Sundin 2023; EN4555X). Despite commonalities, there are not fully established practices for circularity assessment. However, there are several methods with this purpose, for example, the ones mentioned in Cardoso Chrispim et al. (2023), Ruiz-Pastor *et al.* (2022), Parchomenko *et al.* (2019), Saidani *et al.* (2019), and Bovea and Pérez-Belis (2012). Cardoso Chrispim *et al.* (2023) also define in their work the terms metric, tool and indicator. These definitions are adopted in this work.

CE assessment has been classified in the literature into four main groups based on the level of application of the assessment. According to Yuan, Bi & Moriguichi (2006), these four levels are macro-level (cities and regions), meso-level (industries and industrial symbiosis), micro-level (companies) and nano-level (products). This subdivision is acknowledged in the literature dedicated to CE assessment (e.g., de Oliveira, Dantas & Soares 2021; Khadim *et al.* 2022), and in the mentioned ISO 59020 standard, whose applicability is expected to range "from regional, inter-organizational, organizational to the product level." Because of the attention paid to products and design, this work focuses on the nano-level of CE assessment, which has been recognized as relevant and introduced with this specific terminology also in the design field (Saidani *et al.* 2017b).

To understand the fragmentation, complexity, extent and degree of convergence across different proposals in the field of CE assessment, the authors explored the literature to retrieve two main categories of contributions:

1. works in which a case study is assessed with multiple methods, at any level of circularity and
2. works specifically targeting circularity assessment at the nano-level.

Among the former, it is possible to find different overviews and analyses of CE measurement (Niero & Kalbar 2019; Ruiz-Pastor *et al.* 2019; Saidani *et al.* 2019, 2021). Ruiz-Pastor *et al.* (2019) remark the lack of a standard circularity assessment method and the gaps in this regard. Other works in the same line are Morkunaite *et al.* (2021), Lonca *et al.* (2020) or Bressanelli *et al.* (2019). Several of these works also apply the assessment methods through different case studies (Boer *et al.* 2020; Lonca *et al.* 2020; Minunno *et al.* 2020; Ruiz-Pastor *et al.* 2022). These studies overall converge on the lack of a standard method, which is often cited as one of the most severe limitations for CE assessment.

As for the latter, they mostly show groups of CE indicators or methods (Moraga *et al.* 2019; Niero & Kalbar 2019; Kristensen & Mosgaard 2020; Roos Lindgreen, Salomone & Reyes 2020; Saidani *et al.* 2020; de Oliveira *et al.* 2021; Khadim *et al.* 2022; Kuzma *et al.* 2022). Many of them agree on the lack of standard indicators and robustness in measuring CE. Even if existing methods are a good starting point, as Khadim *et al.* (2022) pointed out, further research is needed (Roos Lindgreen *et al.* 2020).

Two works are ascribable to both categories of analyzed contributions. Jerome *et al.* (2022) study the existing indicators and then test them with seven case studies, stressing that there is a lack of consensus regarding CE indicators. Cayzer, Griffiths & Beghetto (2017) also evaluate the existing indicators while developing a product prototype. Also in this case, the main conclusion is the lack of a common way to measure CE in products.

3. Case study and methodology

This work was developed in the context of the Tiny FOP Mob Project (see details in the Acknowledgments). Within this project, a prototype of a tiny house (Figure 1)

Figure 1. Tiny house prototype.

was developed with the purpose of serving as a real-world laboratory in five locations of the Venosta Valley, Italy (Nezzi *et al.* 2022). One of the purposes of the tiny house was to bring science and society closer with an emphasis on sustainability issues. In this context, the prototype of the tiny house was designed and made with sustainable materials to the largest possible extent. More in details, the used materials were:

- hemp bricks (load-bearing walls) (Figure 2),
- spruce wood (frame, beams and screed),
- larch wood (floor, false ceiling and external cladding),
- natural mortar (bricks assembly),
- hemp fiber and natural hydraulic lime (interior surface finishing) and
- others (galvanized titanium for the roof and vapor barrier made of wood fiber).

The tiny house prototype has a 25 square meters area and a weight of 12 tons.

Despite tiny houses are known to be possible icons of social movements, which largely resonates with the scopes of the mentioned project, the aspects closely concerning CE (and its corresponding assessment methods) are considered here only, that is, the environmental dimension turned to be predominant in the analyses that follow.

All the required data to assess the circularity of the tiny house were collected through semi-structured interviews with the project partners, the manufacturer and material providers of the prototype, as well as from the literature. After data were collected, the most relevant methods to assess CE in literature were selected and applied to the tiny house. The method selection was based on a literature investigation and search for nonacademic, yet established, CE assessment tools.

All the nano-level CE assessment tools identified for the scope of this study were:

- validated or accepted in the literature,

Figure 2. Brick used in the tiny house prototype.

- clearly described or providing online tools for the assessment of circularity so to be straightforwardly applied in the present work and
- the ones providing a specific result for circularity (either with a single variable or with the combination of few variables).

The identification of pertinent tools was supported by the recent overviews of nano-level circularity assessment methods (Ruiz-Pastor *et al.* 2022; Cardoso Chrispim *et al.* 2023). Six tools, which are summarized in Figure 3, complied with the requirements above and they were applied to the tiny house prototype. In the next subsections, the application of the different methods is shown.

3.1 Circularity Calculator

This tool, developed by Ellen MacArthur Foundation and IDEAL&CO (2020), evaluates the circularity of a product or service through several parameters regarding all life stages. It is a web platform with different parameters to be assessed. Specifically, the parameters to introduce in the web tool are shown in Figure 4, which are presented along the data pertaining to the tiny house. The tool is acknowledged in the literature and employed in other works such as de Pascale *et al.* (2021) or Roos Lindgreen *et al.* (2021).

The tool provides three CE-related parameters beyond circularity, namely value capture, recycled content and reuse index. The result obtained with the Circular Economy Calculator shows that the circularity of the tiny house is 40%.

3.2 Circular Economy Toolkit

The Circular Economy Toolkit (Evans & Bocken 2013) is a free web tool, which measures the circularity of a product or service through 33 parameters. These parameters are subdivided into seven categories:

	Variables used									Nº of indicators
METHOD	Product specifications	Costs	Materials optimization	Lifetime	Maintenance	Product-Service	Novelty	System design/Users	**Nº**	
Circularity calculator	X	X	X	X	X				**5**	**15**
Circular Economy Toolkit		X	X	X	X	X			**5**	**33**
CN_Con			X	X	X	X	X		**5**	**3**
Metric for quantifying product-level circularity		X							**1**	**1**
Circular Spidermap			X	X	X				**3**	**5**
Circular Design Tool			X	X	X	X		X	**5**	**46**
Nº	**1**	**3**	**5**	**5**	**5**	**3**	**1**	**1**		

Figure 3. Selected metrics for the assessment of product-level circularity with the indication of variables and number of indicators used by each metric.

Parameter	Tiny house data
Product mass (kg)	12000
Cost of product per Kg	5
% of recycled input in the product	0
Manufacturing costs	60000
Assembly costs	10000
Number of products delivered to the market at the same time	1
Overall sales costs per product	60000
Average amount of period users lease the product	1
% of waste stream downcycled	80
% of collected products recycled in an open loop	40
% of collected products recycled in a closed loop	0
% of collected products remanufactured	0
% of collected products refurbished	0
After how many periods the product needs maintenance	0
% of the product collected after use	75

Figure 4. Tiny house input for the Circularity Calculator tool.

- design, manufacture and distribute,
- usage (by the costumer),
- repair/maintenance of the product,
- reuse/redistribution of the product,
- remanufacturing/refurbishment of product or part,
- product as a service and
- product recycling at the end of life.

Each of the parameters within the categories is evaluated through a slide bar with three different positions. The tool provides as a result a graph, which shows the potential improvement for each category.

In order to achieve a numerical value, the three possible positions of the slide bar have been converted to a three-point Likert scale, quantifying them as a 0, 1 or 2 points and summed up to obtain a final score (Figure 5). For the sake of convenience, ordered variables have been used as continuous ones here and whenever required. The results show that the tiny house has a circularity of 35 out of 66, being 66 the least circular. This means that the tiny house is 47% circular according to the Circular Economy Toolkit.

3.3 Combination of circularity, novelty and concepts

The metric developed to assess the combination of circularity, novelty and concepts was developed by Ruiz-Pastor *et al.* 2022 and designated as CN_Con. It evaluates the circularity and the novelty as a whole in product concepts. The metric covers all the parameters regarding CE that can be considered in the conceptual design stage.

The CE is calculated in two steps: the first one concerns the strategies for durability the product follows. In a second step, the evaluation regards the origin of the raw materials and the destination of the different components and materials in the end of life of the product.

In the case of the tiny house assessed, only one of the 10 strategies proposed by the tool is applied, design for social innovation (2.89 points in the tool). On the other hand, new materials are used to manufacture the prototype (0 points in the tool), but these materials are recoverable (4.3 points in the tool). Accordingly, the circularity score of the tiny house is 6.36 out of 10 points. In order to make the result comparable with the other methods, the final score has been normalized and calculated as a percentage of circularity, namely 63.6%.

3.4 Metric for quantifying product-level circularity

This metric (Linder, Sarasini & van Loon 2017) evaluates the circularity of products only in terms of cost of recirculated parts. In the equation, the scholars propose a numerical value is obtained as the ratio between the economic value of recirculated parts and the economic value of all parts.

In the case of the tiny house studied, there are no recirculated parts in the manufacturing of the product. Therefore, the circularity of the tiny house is 0% in this case.

3.5 Circular Spidermap

This tool (Van den Berg and Bakker, 2015) evaluates circularity according to product aspects regarding its lifetime, the maintenance and the recycling. Specifically, the parameters evaluated are

- future proof,
- disassembly,
- maintenance,
- remake and
- recycle.

The product evaluated is assigned one of four possible values for each parameter. In the case of the tiny house, the parameters have been converted to a four-point Likert scale, quantifying them as 1, 2, 3 or 4 points, being 4 the most circular. The results are shown in Figure 6.

As in the other cases, the circularity score was calculated. In this case, a maximum score in the parameter (4) is equal to 100% circularity and the minimum score (1) is 25% circularity (the score 0 is not foreseen in this method). The final percentage of circularity is the average of all the parameters, which results in 65% for the present case study.

Dematerialization	1
Biodegradability	1
Recycled materials	2
Scarce materials	0
Eco efficiency	0
Toxic materials	0
Waste factory	1
Frequency of failures	1
Lifetime period	0
Using of minimum power	0
Cost of repairing	2
Services for repairing already offered	2
Difficulty to get access to internal workings	2
Simplicity of repairing workings	1
Standardization of components	2
Difficulty of finding fault	1
Second hand market	1
Second hand products already offered	2
Length of lifetime	0
Cost of remanufacturing	1
Cost of return product to factory	0
Remanufacturing currently undertaken	2
Difficulty of disassembly	1
Identification of parts after disassembly	0
Modularity	2
Upgrading of parts	1
Amount of mechanical connections	1
Tools required for disassembly	1
Market for product as a service	1
Product already as a service	2
Combinations of material used	1
Encased materials	1

Figure 5. Data introduced in the Circular Economy Toolkit.

3.6 Circular Design Tool

When applying this tool (Moreno, Ponte & Charnley 2017), parameters about the life cycle, resource conservation and user and product development are assessed. A circularity index is calculated according to different parameters and an importance factor (provided by the tool itself). The score varies between 0 and 787.5, being the largest value the most circular. In the case of the tiny house, the score obtained after assessing all the parameters is 318.2. In Figure 7, the scores for each parameter are reported. The normalized score has been calculated by means of ratio: it is 40.41% of circularity.

4. Comparison results

After applying the methods, a circularity percentage for the tiny house has been obtained for each method. The final normalized scores are summarized in Figure 8 to ease comparisons.

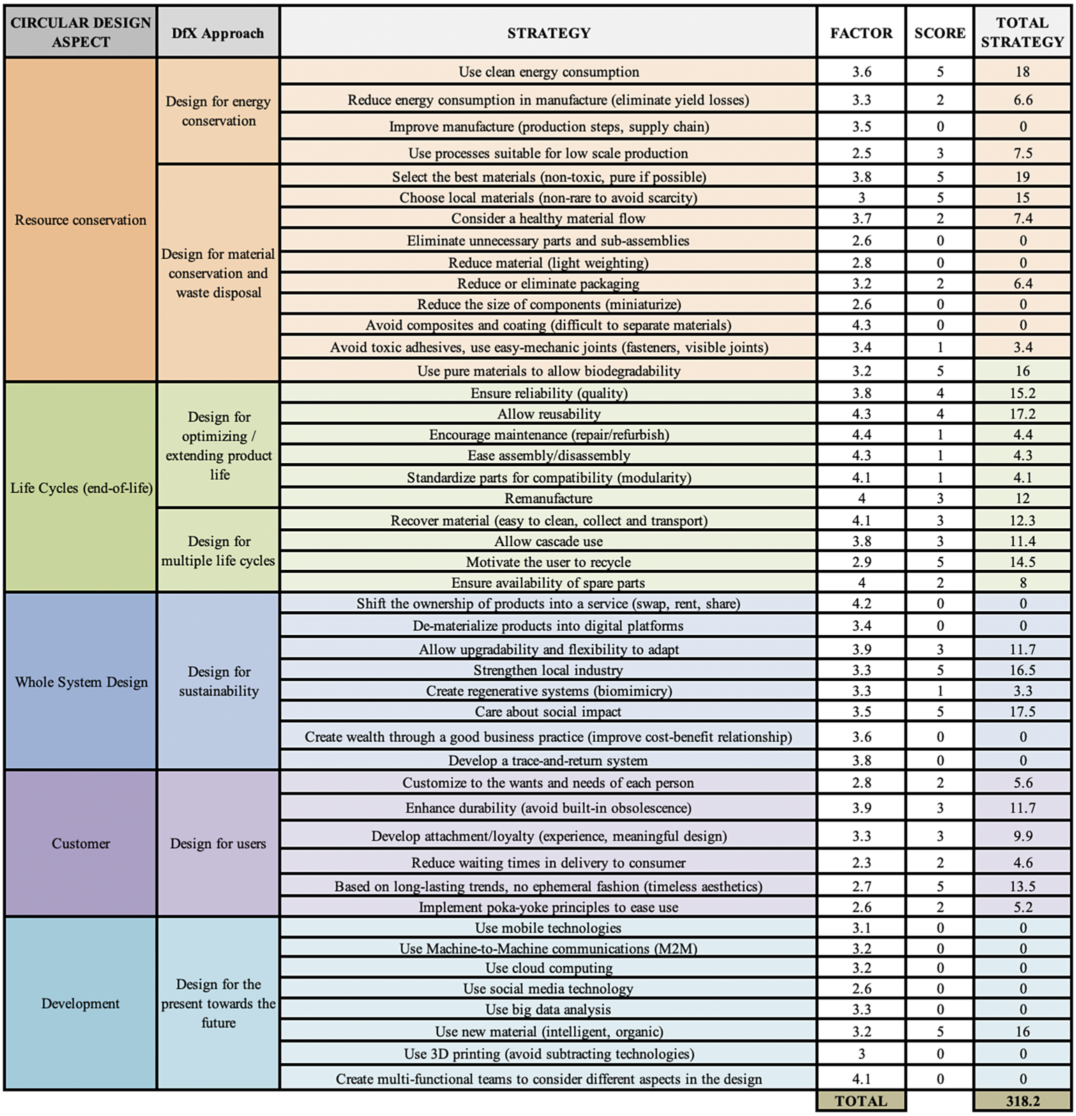
Parameter	1	2	3	4	%
Future proof				x	100
Disassembly	x				25
Maintenance	x				25
Remake				x	100
Recycle			x		75
	Average				**65**

Figure 6. Results of Circular Spidermap tool.

As it is shown, in six out of the seven methods, the circularity scores range between 40 and 65%. In the case of the metric developed by Linder *et al.* (2017), the circularity is clearly affected by the peculiar factors used for the assessment, which differ substantially with respect to the other tools. In Linder *et al.* (2017), only costs are considered, which leads to a result of no circularity, since the other CE-related features of the tiny house prototype are neglected. As the importance of considered variables emerge here, the domains of variables dealt with in each of the employed CE assessment tools is illustrated in Figure 3. According to Figure 3, the most common variables are within materials optimization, lifetime and maintenance, each present in five methods. The least diffused variables are the ones concerning to issues arguably ascribable to CE, such as the product specifications, the novelty and the system design or users; each of these variables are used in one of the methods only. On the other hand, most of the methods consider five variables. The Circularity Calculator (15) and the Circular Economy Toolkit (33) are the methods using the most indicators. As mentioned, the metric for quantifying product-level circularity, instead, uses one indicator only.

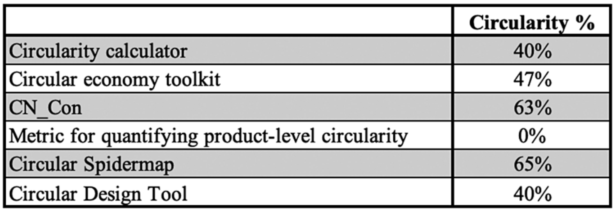
5. Discussion

The results obtained with the assessment tools are consistent according to the main features and materials of the tiny house evaluated, since the house is built with sustainable materials but, for example, end-of-life actions were not focused on in the design of the tiny house. The results underline the need of integrating the CE concepts in all the stages of the design, manufacturing, use and end-of-life of buildings in general, and of the tiny house in particular. Thus, the fair circularity of the prototype is mostly due to its sustainable materials used for its construction, which is obviously one of its strengths. This can be seen from the results obtained in the Circularity Calculator, The Circular Economy Toolkit, the CN_Con, the Circular Spidermap and the Circular Design Tool, since all of them consider variables related to materials. To improve the overall circularity of the tiny house, a possibility would be to manufacture it with recirculated materials; this issue is stressed in the tools considering the starting materials, which are, again, all the tools except the metric for quantifying product-level circularity. In addition, a strong possible improvement would be designing the tiny house for easy disassembly and repair, in line with the CE actions considered in the Circularity Calculator, Circular Economy Toolkit, the CN_Con, the Circular Spidermap and the Circular Design Tool. This evidence supports that not only are circularity scores comparable but also that the priority actions to align with CE are substantially consistent. This can



CIRCULAR DESIGN ASPECT	DfX Approach	STRATEGY	FACTOR	SCORE	TOTAL STRATEGY
Resource conservation	Design for energy conservation	Use clean energy consumption	3.6	5	18
		Reduce energy consumption in manufacture (eliminate yield losses)	3.3	2	6.6
		Improve manufacture (production steps, supply chain)	3.5	0	0
		Use processes suitable for low scale production	2.5	3	7.5
	Design for material conservation and waste disposal	Select the best materials (non-toxic, pure if possible)	3.8	5	19
		Choose local materials (non-rare to avoid scarcity)	3	5	15
		Consider a healthy material flow	3.7	2	7.4
		Eliminate unnecessary parts and sub-assemblies	2.6	0	0
		Reduce material (light weighting)	2.8	0	0
		Reduce or eliminate packaging	3.2	2	6.4
		Reduce the size of components (miniaturize)	2.6	0	0
		Avoid composites and coating (difficult to separate materials)	4.3	0	0
		Avoid toxic adhesives, use easy-mechanic joints (fasteners, visible joints)	3.4	1	3.4
		Use pure materials to allow biodegradability	3.2	5	16
Life Cycles (end-of-life)	Design for optimizing / extending product life	Ensure reliability (quality)	3.8	4	15.2
		Allow reusability	4.3	4	17.2
		Encourage maintenance (repair/refurbish)	4.4	1	4.4
		Ease assembly/disassembly	4.3	1	4.3
		Standardize parts for compatibility (modularity)	4.1	1	4.1
		Remanufacture	4	3	12
	Design for multiple life cycles	Recover material (easy to clean, collect and transport)	4.1	3	12.3
		Allow cascade use	3.8	3	11.4
		Motivate the user to recycle	2.9	5	14.5
		Ensure availability of spare parts	4	2	8
Whole System Design	Design for sustainability	Shift the ownership of products into a service (swap, rent, share)	4.2	0	0
		De-materialize products into digital platforms	3.4	0	0
		Allow upgradability and flexibility to adapt	3.9	3	11.7
		Strengthen local industry	3.3	5	16.5
		Create regenerative systems (biomimicry)	3.3	1	3.3
		Care about social impact	3.5	5	17.5
		Create wealth through a good business practice (improve cost-benefit relationship)	3.6	0	0
		Develop a trace-and-return system	3.8	0	0
Customer	Design for users	Customize to the wants and needs of each person	2.8	2	5.6
		Enhance durability (avoid built-in obsolescence)	3.9	3	11.7
		Develop attachment/loyalty (experience, meaningful design)	3.3	3	9.9
		Reduce waiting times in delivery to consumer	2.3	2	4.6
		Based on long-lasting trends, no ephemeral fashion (timeless aesthetics)	2.7	5	13.5
		Implement poka-yoke principles to ease use	2.6	2	5.2
Development	Design for the present towards the future	Use mobile technologies	3.1	0	0
		Use Machine-to-Machine communications (M2M)	3.2	0	0
		Use cloud computing	3.2	0	0
		Use social media technology	2.6	0	0
		Use big data analysis	3.3	0	0
		Use new material (intelligent, organic)	3.2	5	16
		Use 3D printing (avoid subtracting technologies)	3	0	0
		Create multi-functional teams to consider different aspects in the design	4.1	0	0
			TOTAL		318.2

Figure 7. Tiny house assessment with the Circular Design Tool.



	Circularity %
Circularity calculator	40%
Circular economy toolkit	47%
CN_Con	63%
Metric for quantifying product-level circularity	0%
Circular Spidermap	65%
Circular Design Tool	40%

Figure 8. Normalized circularity results.

be justified by the similarity of the set of variables used to calculate circularity, as made more apparent below.

The tools applied mostly focus on the usage and maintenance of products, followed by the material quantity and the lifetime. Other variables considered are the design and manufacturing of the products, the costs, the recycling of materials or the general environmental impact. The possibility of implementing product–service features in the products is considered in two assessment methods (Evans & Bocken 2013; Ruiz-Pastor *et al.* 2022). Also, other aspects are considered, such as the novelty of the products (Brezet & van Hemel 1997; Ruiz-Pastor *et al.* 2022). This can contribute to evaluate in a more comprehensive way products and concepts, since novelty and creativity are crucial to fulfill CE-related requirements (Golinska *et al.* 2015).

Furthermore, the sustainability of the materials must be matched with the right behavior at the end of life of the buildings. There could be the need of incentivizing the users and/or dismantling companies to ensure the most sustainable products' end of life. This issue is not only a matter of design, but it also involves educating the users and manufacturers in a sustainable use of products and materials.

6. Conclusions

In this work, six methods to assess CE were applied to a tiny house prototype. The prototype was built with sustainable materials, such as lime-based hemp bricks and wood, and with the purpose to serve as a real-world laboratory. According to the analysis, the tools exhibit differences in the way CE is assessed, but, despite that, the circularity results are quite close in most of the cases (40–65%), as they show an intermediate score for the case study. The number of variables studied by the tools varies between 1 and 5. On the other hand, the number of indicators ranges between 3 and 46. As all the tools have different features, the results achieved can be considered fairly close.

This similarity shows how the results obtained when applying the considered tools and methods can be a good indicator of product circularity performance. This type of tools can help to design more circular products from the beginning of the design process; benefits can be especially in terms of resources saving and optimization.

A limitation of the present study is that the similarity of circularity scores is observed through a case study only, and other examples could help corroborate the results. The case study was taken from the building sector, and it is therefore worth testing the convergence of CE assessment tools in more traditional product design fields. In addition, for practical reasons, the study focused on nano-level CE assessment tools that provide a well-defined circularity score or where this score can be easily extrapolated. Hence, complex nano-level assessment systems providing a large and non-independent number of variables associated with CE were not considered in this comparative study. The convergence of indications to redesign the tiny house while further aligning it with CE principles can be tested also with other assessment tools.

While the issue concerning the lack of standardization has not been overcome through the presented results, it is possible to claim that the existing CE assessment methods can be considered sufficiently reliable thanks to their convergence. Hence, users can consider the results obtained through most of the studied methods as a good proxy of the circular performance of what is being designed and developed. In practical terms, this alleviates the problem of choosing the “right” or “best” nano-level CE assessment tool. In turn, as the closeness between CE indicators and rules for eco-design has been highlighted in the first section, it can be inferred that the consideration of any of the examined CE assessment tools can be useful for the generation of better designs. However, the claimed methodological shortcomings concerning the introduction of CE principles in early design stages remain an open issue. The results of this work suggest that the understanding of nano-level CE assessment methods can be a starting point here. A point to be evaluated is the applicability of CE assessment tools to different products, whose investigation is part of the authors’ planned future work. In addition, the authors intend to systematically review CE indicators at the nano-level, so to develop a checklist of CE aspects to be considered in product design. This work can benefit from the results recently presented by de Oliveira and Oliveira (2023) and, methodologically, from past experiences where indicators at different CE levels have been selected and aggregated (e.g., Sacco *et al.* 2021). While designers aim for comprehensiveness when they operate, a clear, inclusive, and context-dependent taxonomy of product-level CE indicators can represent a major step forward in designing for the CE. This is to be favorably integrated, nevertheless, by tools supporting designers in the consideration of sustainability aspects that are not included in the concept of CE. It has to be remarked that CE and sustainability show substantial differences beyond the many affinities (Delaney *et al.* 2022), notably when it comes to approaching design (Cao *et al.* 2024). By building upon (e.g., Saidani *et al.* 2022), complementary indicators originating from the fields of sustainable development and design could be used here to ensure that an enhanced circularity leads to sustainable benefits.

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