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A metric for evaluating novelty and circularity as a whole in conceptual design proposals

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ABSTRACT

Product design is one of the most important factors to introduce the circular economy model. In this discipline, the decisions made influence the whole life cycle of the product, since the raw material obtaining to the end of life of the product. Product engineering uses resources, both technical and material to create products. In this way, among all stages that product design encompasses, most relevant and significant decisions are taken during the conceptual stage, when changes can more easily be introduced. On the other hand, creativity plays an important role in introducing new features in products (as circularity is) in a new way. To implement in a proper manner these new functionalities in the products the concepts have to be evaluated. There are methods for assessing novelty and for assessing circularity, but in the case of circularity they are focused on products that have already been developed. Moreover, these methods do not assess circularity in a holistic way, as they only cover some of the aspects that the circular economy encompasses. This work intends to fill the gap that currently exists in the tools for evaluating product concepts by designing a metric, CN_Con, that measures the circularity and the novelty of conceptual proposals as a whole. The metric works according the product functions and analysing the novelty, the strategies for durability and for extending the useful life of the product that the concepts use. It also assesses the raw material and the end of life of the materials with which the concepts are designed. The development of CN_Con will help to implement the circular economy paradigm while encouraging creative design solutions.

1. Introduction

Product design engineering is based on, among other things, the use of material and technical resources to create products. Therefore, product design plays a very relevant role in the circular economy, a model of use that proposes extending the life of resources to the maximum through a regenerative system by intention and design (Ellen MacArthur Foundation, 2013). Circular economy aims to maximize the ecosystem functioning and human well-being (Murray et al., 2017). This model is starting to become a reality and is beginning to be implemented in different areas of industry and social behaviour. An appropriate approach to future products can promote the efficient use of resources. Sustainable development encompasses three dimensions: economic, environmental and social. Also the more successful systems are based in innovation, among others (Stahel, 2010). That is one of the reasons why creativity plays a very important role in generating new functionalities and ways of developing products (Amabile, 1996), since it is the basis of any innovation or improvement to be made in general and, specifically, in product design. Hence, applying creativity to product design is very important when considering the new model of the circular economy. Sustainability, of which the circular economy is a part, requires creative thinking and new ideas (Mitchell and Walinga, 2017). The sustainability development of a product requires radically new designs to face these environmental changes without affecting the functionality of the product. Creativity and sustainability are significantly connected (Maccioni et al., 2021).

Introducing circularity into the product design process is not without its difficulties. The requirements regarding circularity introduced into the design process can be seen by designers as restrictions, which can affect the creativity of their work (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010; Cucuzzella, 2016; Mohanani et al., 2014). Even though, the circularity and novelty of the design results can be affected by the personal factors of the designers, as their motivation (Ruiz-Pastor et al., 2021a). In contrast to studies that claim that

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circularity requirements can negatively affect creativity, others claim that using eco-design tools and creativity tools could be useful in creative sessions focused on eco-innovation (Tyl et al., 2010) and can help to obtain more creativity and novel ideas (Chang et al., 2016).

The conceptual stage of product design is the right one to introduce this sort of change in design since. As it is one of the earliest stages of product creation and where the most important decisions in the design process are made (Cross, 1999), it is also the most flexible one. Therefore, the conceptual stage is the one in which less effort is needed to implement any change during the product development process.

For an optimal implementation of circularity and novelty in new products, it is interesting to evaluate the conceptual design proposals. This evaluation must be objective, coherent and complete (Mesa et al., 2018). There are methods for assessing novelty as well as others for assessing circularity, but in the case of circularity they are focused on products that have already been developed. Moreover, these methods do not assess circularity in a holistic way, as they only cover some of the aspects that the circular economy encompasses (Linder et al., 2017).

This work intends to fill the gap that currently exists in the tools for evaluating product concepts by designing a metric that jointly measures the circularity and the novelty of conceptual proposals. This will have an impact on product design at both the professional and academic levels and will help to implement the model of the circular economy while encouraging creative design solutions.

2. Literature review

2.1. Circularity

One of the most important elements for the introduction and application of circular economy principles is product design. Through design the different actions that lead the economy towards a circular model can be achieved. Thus, Gilpin (1996) defined sustainable design as “development that considers the needs of today without compromising the resources of future generations”. On the other hand, Ameta (2009) defined it as the design of products that are sustainable in their life cycle, i.e. that do not endanger the natural resources available during the product’s life cycle. It is a concept that arises from the intention to reduce the environmental impact of a product throughout its life cycle and in all its phases (Sekutowski, 1994).

There are, on the other hand, several approaches to the circular economy focused on product design, such as the circularity loops model of the Ellen MacArthur Foundation (2013), the resource efficiency approaches of Bocken et al. (2016) or the models of raw material origin and end-of-life actions (European Commission, 2015; Faria, 2015; Vermeulen et al., 2019). There are also design strategies for the circular economy, such as those proposed by Bocken et al. (2016) or Afonso et al. (2020).

Circularity assessment is a subject that has been addressed in the last years quite extensively. This can be seen in case studies as those conducted by Mesa et al. (2018), Parchomenko et al. (2019), Saidani et al. (2019) or Vinante et al. (2021), among others. Saidani et al. (2019) define ten categories for classifying indicators, for instance the level of application of the metric, the type of the circularity action or the type of user of the metric (designer, company, etc.). On the other hand, Parchomenko et al. (2019) analyse 63 circularity metrics, including several that focus on the product. Lindgreen et al. (2020) provides an overview of circular economy assessment approaches at the micro level. Table 1 shows a study of how different circularity tools and indicators measure circularity. For this analysis, the most relevant tools found in the literature have been considered, starting with those studied in Ruiz-Pastor et al. (2019), to which ten more have been added in an attempt to cover all the possible variants.

The analysis has shown that, for the most part, existing circularity tools are designed to work by evaluating parameters in fully developed products. Only two of the tools analysed were developed to be used with

Table 1
Summary of existing circularity assessment tools.

TOOL	RESOURCE	PARAMETERS FOR MEASURING CIRCULARITY	HOW THE MEASUREMENT IS PERFORMED
Material Circularity Indicator (MCI)	Ellen Macarthur Foundation; Granta Design (2015)	5 parameters related to material reuse, material recycling and efficiency, and lifetime and functional unit.	Index calculation according to the values given for each parameter.
Circularity Calculator (evolution of the MCI)	IDEAL&CO Explore and Ellen MacArthur Foundation (2020)	13 parameters related to material quantity, material and production costs, material usage and maintenance fractions.	Calculation of the percentage of circularity according to the values indicated for each parameter.
Circular Economy Toolkit (CET)	Bocken and Evans (2013)	Parameters distributed in 6 categories concerning design and manufacturing, use, material utilisation and product-service.	The concept being evaluated is ranked between three positions (from most to least circular) for each of the parameters. Improvement potential is indicated.
CE Designer	CE Designer (2019)	Parameters concerning product durability, service design and sustainability of materials and energy.	By comparison with standard product after completing the required information. It indicates potential for improvement.
A metric for quantifying product-level circularity	Linder et al. (2017)	Costs and weights of the “recirculated” components of the product under evaluation.	Index calculation according to the values indicated.
Circular Spider Map	Van der Berg and Bakker (2015)	Product aspects concerning its lifetime, maintenance and recycling.	The concept being designed or evaluated is situated between four positions (from least to most circular). The categories are compared visually.
LiDS Wheel	Brezet and van Hemel (1997)	7 parameters concerning novelty, production and distribution, lifetime and impact of the product.	The product is situated between the different parameter positions. The categories are compared visually.
Ecolizer	Ecolizer (2011)	Different parameters concerning materials, masses, manufacture and use of a product and its components.	Index calculation based on product data. Web platform.
Ecodesign Pilot	TU Wien (2003)	Product information on: raw material, manufacture, transport, use and disposal.	Information sheets are completed indicating possible product improvements.
Indicator for recycling	Di Maio and Rem (2015)	Detailed information on the recyclability of the materials of the components of a product, as well as their economic value.	Calculates a recyclability index based on product information.
Tool to diagnose product recyclability	de Aguiar et al. (2017)	Parameters related to assembly and materials of product components.	A recyclability index is calculated.
Eco Compass			

(continued on next page)

Table 1 (*continued*)

TOOL	RESOURCE	PARAMETERS FOR MEASURING CIRCULARITY	HOW THE MEASUREMENT IS PERFORMED
	Fussler and James (1996)	Parameters related to materials, use, sustainability and product-service.	Two products are compared by scoring each aspect on a spider map.
Ten Golden Rules	Luttropp and Lagerstedt (2006)	Product information on toxicity, energy, materials and lifetime.	Design aid method using 10 design strategies.
Circular Design Tool	Moreno et al. (2017)	Life cycle, resource conservation, user and product development parameters.	A circularity index is calculated according to the fulfilment of the different parameters.

product concepts (Luttropp and Lagerstedt, 2006; Moreno et al., 2017) but some specific information about the development of the product is also needed to be able to use them completely, i.e. production or energy information. In the 14 tools studied, the data required to perform the calculations or to follow the method are also too specific. These required data is not yet established in the conceptual design phase, examples being costs, weights, efficiencies or transport. Although these specific parameters could be estimated so as to be able to apply the tool or to be able to apply it completely, the result obtained would not be accurate as it would be based on interpretations made by the user of the tool. Moreover, for this reason the result could vary between different evaluators. The tools and indicators studied, on the other hand, only cover specific aspects of circular economy. For instance, the metric developed by Linder et al. (2017) only assesses the costs and weights of parts. In the MCI tool (Ellen Macarthur Foundation and Granta Design, 2015), as another example, recycling, reusing and lifetime aspects are evaluated. According to the analysis carried out, there does not seem to be a tool that measures circularity in a complete way and only using information that is already known at this early stage of development.

2.2. *Creativity*

While various definitions of creativity have been established over time, in broad terms, creativity is the ability to approach a problem differently, restructuring it so as to reach new solutions and possibilities that have not previously been reached (Linsey et al., 2008). In the work by Oman et al. (2013) creativity is defined as the process of evaluating a problem in an unexpected or unusual way to generate novel ideas. Thus innovation is creativity that has an impact on society by introducing something new and useful. Creative solutions are needed so as to break away from products that present only their basic features and allow the introduction of features that make users more interested. The creative solutions also need offering a product design that the user finds more delightful. At the same time it adds utility and bridges the gap that arises between function and form.

On the other hand, it could be said that creativity is the response to a problem in a way that is novel and appropriate, as well as useful and correct (Amabile, 1983). It takes place through a process in which a subject uses his or her skills to generate useful and novel solutions and products (Chulvi and González-Cruz, 2016). Shah et al. (2003) defined creativity as the intersection of novelty and utility. Later, in Sarkar and Chakrabarti (2008), a common definition of creativity as the generation of novel and useful ideas was proposed as a conclusion to previous studies.

In order to be able to quantify the creativity of a product, it is necessary to have metrics that evaluate it objectively and take into account all the necessary aspects for a coherent, correct and objective evaluation. Being able to assess creativity is very important and more so for a correct detection of the aspects in which the product is less creative, which will thus facilitate its development (Jordanous, 2012). Measuring creativity at the conceptual design stage presents design engineers with an opportunity to choose the appropriate design proposal effectively (Oman et al., 2013).

There are many methods for assessing creativity in products and over the years several studies by different authors have collected and classified them (Bahill et al., 1998; Chulvi et al., 2012; Higgins, 1994; Jones, 1970; Oman et al., 2013; Ranjan et al., 2018; Shah et al., 2003; VanGundy, 1988).

Some of the most relevant tools, because they are the most widespread and complete in this field, are described below, showing their basic functioning and how they assess creativity. Table 2 offers the information obtained for each of the tools on how they interpret the measurement of circularity, i.e. which parameters they take to measure it and how the different measurements are made.

As can be seen, one of the most common methods of evaluation is by looking for similar solutions in the product space and by comparison. This comparison it is done either between the same design outcomes or between existing products and aspects in the industry, i.e. identifying existing features and products for comparison, which is in line with the study by Ranjan et al. (2018). Furthermore, the compilation by Chulvi et al. (2012) also agreed that the most widely used parameters for measuring creativity in tools are the combination of the levels of

Table 2
Summary of existing creativity assessment tools.

TOOL	RESOURCE	PARAMETERS FOR MEASURING CREATIVITY	HOW THE MEASUREMENT IS PERFORMED
SAPPhIRE Method	Chakrabarti et al. (2005)	Only provides a Novelty result.	Through the product levels of State, Action, Component, Phenomenon, Input, Organ and Effect. Comparison with standard output at each level and establishment of a ranking.
SAPPhIRE Method (extended)	Sarkar and Chakrabarti (2008)	Novelty and Usefulness (usefulness being a relationship between Importance, Frequency of use, Duration of benefit and Popularity ratio).	SAPPhIRE method to obtain novelty. Selection of values on a discrete scale and using mathematical equations. The result obtained is a ranking.
Ranjan et al. Method	Ranjan et al. (2018)	Satisfaction and Novelty.	By weighting requirements and their degree of fulfilment (satisfaction) and by the SAPPhIRE method (novelty).
Creative Products Semantic Scale (CPSS)	O'Quin and Besemer (2006, 1989)	Bipolar pairs of adjectives referring to aspects of Novelty, Resolution and Style.	7-point Likert scale for each pair of adjectives.
Shah Metric	Shah et al. (2003)	Novelty, Variety, Quality and Quantity.	By comparison between ideas and quantitatively.
Moss Scale	Moss (1966)	Utility and Rarity of the product.	Comparison with standard product. Selection of scaled values.
Assessment of innovative potential (EPI)	Justel (2008)	Design Requirements, Novelty, Design Innovation Potential and Business Success Factors.	Select from three options. Completing matrix. Establishing scores. Scoring obtained by weighting and correlations.

usefulness and novelty. Although the terms used may vary from one study to another, they always refer to how new the product is ("novelty" or "rarity", among others) and the degree to which it fulfils a certain function, which has to be present in the product ("usefulness", "resolution" or "degree of compliance", among others). Nevertheless, it is always possible to speak in terms of novelty and usefulness. In addition, in many cases, discrete quantitative value scales are used. In these scales the user must choose one of the values to score the corresponding parameter, according to the extent to which it matches the descriptions given for each of the values to be chosen.

3. Research framework

Studying how the requirements of novelty and circularity affect the creative design process aims to ensure that circularity is not a conditioning factor for creativity. It also ensures that it is possible to obtain more creative and circular conceptual design proposals at the same time. The researchers' consensus on the definition of creativity is that it involves the generation of ideas that are novel and appropriate (Sarkar and Chakrabarti, 2008). Normally, in product design the term "appropriate" is related to feasibility or usefulness. In the case of this work, the requirements of circularity can, in turn, be interpreted as how appropriate the design is. This appropriateness (circularity) plays a very important role in the development of the product along with novelty and, therefore, defining these two terms together, novelty and circularity, the creativity.

The tool to be developed should evaluate conceptual design proposals (results-based, as classified by Nelson et al. (2009)). It must work with product information that is already established at the conceptual design stage, i.e. the basic form and appearance, as well as the functionality of the future product. The materials or manufacturing processes to be used are also commonly indicated.

On the other hand, the metric must be objective when used in the conceptual design stage, both in the input of data and in the output of results. The tool should assess the novelty and the principles of the circular economy (circularity) in the conceptual proposals in a way that covers the whole range of them and should do it as a whole, equally weighting the two aspects. In other words, a well-scored concept will be one that presents both characteristics at the same time. If the concept presents one of them to a large extent, but not the other, the score should be low, as what is sought is that the concepts have these two characteristics at the same time. This favours an optimal introduction of the circular economy in the design of products and results in novel and appropriate products, terms that are in agreement with the general definition of creativity (Sarkar and Chakrabarti, 2008). Finally, the metric designed should be user-friendly.

4. Metric

For a correct evaluation of all the aspects that integrate the circular economy in a product, as well as its novelty, it was considered appropriate to carry out the evaluation by analysing the basic functions and the importance of each of them in the product. This type of analysis is commonly used in creativity tools and can be seen, for example, in the metrics of Shah et al. (2003) or in one of the methods developed by Oman et al. (2013). Sarkar and Chakrabarti (2011), on the other hand, argued that if the functions of a new product are different from those present in existing products of the same type, this product is considered novel. Thus, the importance of working with functions in the evaluation of products in the conceptual phase of development can also be seen here. In such an evaluation, the concept is subdivided into the functions to be fulfilled, which are then assessed separately, making the assessment of the fulfilment of the requirements in the conceptual design proposals more accurate.

4.1. Novelty assessment

To assess the novelty of the concepts in the metric developed, a scale was established that reflects the possibility of finding the way of fulfilling the function being evaluated in an existing product. Specifically, the way of establishing the levels to carry out the evaluation is based on the one proposed by López-Forniés et al. (2017) and was adapted in accordance with the needs of this work. The scale of the scores was changed, multiplying it by 10 to make it simpler, and the possibility that the function being assessed is not fulfilled in this proposal (score 0) has been added. The result is five options from which to rank the novelty of each function of the conceptual design proposal being evaluated (Table 3). The value for scoring the novelty (N) in each of the functions of the concepts was established between 0 and 10, with 10 being the maximum possible novelty and 0 being no novelty. The intermediate scores were set at 1, 3 and 7, this being an equitable scale between the different options and one that has already been used on several occasions in the literature (López-Forniés et al., 2017; Shah et al., 2003).

4.2. Circularity assessment

The assessment of circularity was split into two steps in order to cover the full umbrella that this topic encompasses. First, and again for each function of the concept, scores are given to the design strategies for extending the useful life or its duration that the function follows. With regard to the materials used, an assessment is performed evaluating from where the materials that are used to fulfil each function come from, on the one hand, and the destination of the materials at the end of their life, on the other.

Regarding the first step, the evaluation was based on whether the design strategies of durability and life extension are present in the concepts under evaluation. The strategies considered are a combination of those of the Afonso et al. (2020), Bocken et al. (2016) and Ellen MacArthur Foundation (2013). The list of strategies was set up to be comprehensive but not redundant, and the nomenclature was slightly modified to make it as simple and understandable as possible. The strategies identified in the metric developed (Ne) are the following:

Table 3
Novelty scoring options.

SCORE	DEFINITION	CLARIFICATION
N = 10	The function is solved in a way that does not exist and cannot be compared.	The proposed solution of the function is completely new. It is solved, for example, by using new technologies or materials, which do not yet exist. It is the first time that such a solution has been proposed to solve a function that a product must have.
N = 7	The function is solved in a way that exists, but is not used, not exploited.	The function is solved in a new way that has not yet been implemented, even though it has already been conceived. This could be a new material or manufacturing process, among many other options, the use of which is not yet standardised.
N = 3	The function is solved, in a way that already exists for other applications, but not for the one being evaluated.	The function is solved in a way that is usually implemented to solve another application. Using a feature that solves the function but is commonly used in other types of products.
N = 1	The function is solved, in a way that already exists for that application.	The function is solved in this case in the usual way, i.e. in some way or with some characteristic that is usual for this type of product.
N = 0	The function is not solved in the concept.	This product requirement is not satisfied in any way or by any concept feature.

- Design for attachment
- Design for durability and reliability
- Design for lifetime extension through versatility
- Design for upgradeability/adaptability
- Design for standardisation/compatibility
- Design for assembly/disassembly
- Product-service design
- Service design for life extension
- Design for social innovation
- Use of renewable energy
- No strategy (it may be the case, when carrying out an assessment, that the function does not use any of the above strategies)

To establish an exact score for the number of strategies considered in the concept, a logarithmic distribution was used. This choice has been done because the concept does not improve its circularity in a linear way as it presents more strategies. The increase in circularity when raising the number of strategies beyond a certain point is not as high as it is when going from not using any strategies to using a few. The equation is designed in such a way that the score of the circularity strategies is between 0 and 10, with 0 being the score for a function that does not use any strategy and 10 being the score for a function that uses all 10 strategies. On the other hand, Fig. 1 shows the distribution of the scores given to each number of strategies present in the concept.

$$Ne = 10^{*}\left(\frac{LOG10\ (no.\ strategies + 1)}{LOG10(11)}\right)$$

Eq. (1). Scores for each case of Ne.

In order to carry out the second stage of evaluation, a list of parameters was established covering all the possible actions that can be conducted with the material, both for the manufacture of the product at the time of obtaining the starting material (Mi) and concerning the end of life of the material (Mf). They were selected in such a way that they represent the full range of possibilities and the evaluation covers all the necessary aspects, but with the minimum number of alternatives so as not to be too complex. The selection of the different actions is based in the Rs frameworks of European Commission (2020), Faria (2015) and Vermeulen et al. (2019). In these works a hierarchy is established for classifying the different actions for material optimisation, among the worst option (disposal or new material) and the best option (refuse the use of material).

Table 4 shows the parameters established, as well as the score for each of them and a summary of how they were obtained. The subsequent lines detail how each of the scores for the Mi and Mf parameters were obtained.

a) REFUSE (Mi = 10.00)

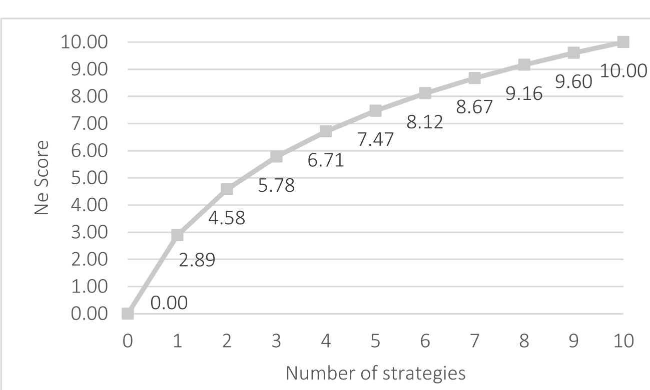

Fig. 1. Distribution of scores for Ne.

Table 4
Scores for Mi and Mf and summary of their definition.

SOURCE OF MANUFACTURING MATERIALS (Mi)	DEFINITION (European Commission, 2020; Vermeulen et al., 2019)	METHOD OF OBTAINING Mi SCORE	SCORE (Mi)
Refuse the use of material	Do not use material, fulfil the function without material, dematerialisation.	a)	10
Reused material	Reuse the material in the same condition as in its previous use, without any processing, with either the same or a different function.	Based on the values provided by the MCI tool (b)	5
Recovered material	Reconditioning the material for use again, extracting part of the material without reprocessing it, by some sort of mechanical process.	c)	4.65
Recycled material	Reprocess the material so that it can be used again.	Based on the values provided by the MCI tool (b)	4.3
Reduce material	Use less material to fulfil the function.	As a halfway point between not using any material and using new material (f)	5
New material	Raw material that has not been used before.	g)	0
DISPOSAL OF MANUFACTURING MATERIALS (Mf)	**DEFINITION (European Commission, 2020; Vermeulen et al., 2019)**	**METHOD OF OBTAINING Mf SCORE**	**SCORE (Mf)**
Reusable material	Material suitable for use again under the same conditions, without any processing, with either the same or a different function.	Based on Reuse values and reprocessing efficiencies (b)	4.6
Repairable material	The design allows the material or component to be repaired.	Based on the % increase in lifetime when a product is repaired and based on the impact of a standard product in the SimaPro® software (d)	2.2
Recoverable material	The material or component is suitable for reconditioning, without reprocessing, by some sort of mechanical process.	c)	4.3
Recyclable material	Material suitable for chemical reprocessing to be used again.	Based on Recycle values and reprocessing efficiencies (b)	4
Incineration of material (energy recovery)	The material can be incinerated with consequent energy recovery.	According to the difference in impact of organic material when landfilled and when incinerated. Based on SimaPro® software results (e)	0.1
Material disposed in landfill	Landfilled material, which cannot be reused.	g)	0

When the function is solved without using any material, it obtains the maximum score (10). This is the action that allows the maximum reduction in material, i.e. not using any material. If the function is given this score, it will have no material end of life (Mf) score, because if no material is used, there is no end of life possible.

b) REUSE (Mi = 5.00), RECYCLED (Mi = 4.30), REUSABLE (Mf = 4.60) and RECYCLABLE (Mf = 4.00)

The Material Circularity Indicator (MCI) tool (Ellen Macarthur Foundation and Granta Design, 2015) was used to establish these scores. Four scores were obtained: a product with 100% reused material at the start (R1) and 100% reused at the end of its life (R2), 91% recycled as starting material (Y1) and 91% recycled at the end of the material's life (Y2), 91% recycled raw material and 100% reused at the end of its life and, finally, 100% reused starting material and 91% recycled at the end of its life. 91% is the maximum recycling value that the tool allows. The values obtained were as follows:

$$R1 + R2 = 0.96$$

$$Y1 + Y2 = 0.88$$

$$Y1 + R2 = 0.90$$

$$R1 + Y2 = 0.94$$

As obtained, a reused and reusable material should add up to 0.96 (R1 + R2 = 0.96) and a material that is only reused at the beginning has a score of 0.55; a material that is only reusable has a score of 0.51, according to the MCI tool. Therefore, the difference between the Reused and Reusable score should be 0.04. Looking for two values (X and X′) that are 0.04 apart and add up to 0.96, the following equation is solved:

$$X - X' = 0.04$$

$$X + X' = 0.96$$

$$X = 0.04 + X'$$

$$0.04 + X' + X' = 0.96$$

$$0.04 + 2X' = 0.96$$

$$X' = \frac{(0.96 - 0.04)}{2} = 0.46$$

$$X = 0.96 - 0.46 = 0.5$$

$$X = 0.5;\ X' = 0.46$$

Once these two values had been obtained and following the criteria of the MCI tool, in which the score for reused material is higher than that of a reusable material, the score for the metric developed was set at 5 for reused material and 4.6 for reusable material. The results obtained were multiplied by a factor of ten as the MCI tool works on a scale of 0–1 and in the metric the values defined for start and end-of-life material must range between 0 and 10.

To calculate the scores for recycled and recyclable materials, the reuse values obtained according to material reprocessing efficiencies were lowered as the impact of reprocessing is greater for a reused material than a recycled one. The average value of the efficiencies shown in Rigamonti et al. (2009) was calculated, since they reflect the most representative materials. The average value of the efficiencies is 86.7%.

86.7% of 0.5 is 0.43, so 4.3 will be the score for the Recycled material parameter.

$$\frac{86.7*0.5}{100} = 0.43$$

86.7% of 0.46 is 0.4, so 4 will be the score for the Recyclable material parameter.

$$\frac{86.7*0.46}{100} = 0.4$$

As can be seen, as in the previous case, the scores were scaled so that the total scores are between 0 and 10.

c) RECOVERED (Mi = 4.65) and RECOVERABLE (Mf = 4.30)

The scores for a material that fulfils a function and is recovered or recoverable were established, by the very definition of the term "recover". This means as an average value between a reused/reusable and a recycled/recyclable material, respectively. As seen above, it can be said that recycling a material is usually given by a chemical processing of the material plus some remanufacturing process. Recovering a material, on the other hand, usually implies an actual remanufacturing process. To reuse the material, is to reuse it again without any processing. Therefore, since reclaiming the material is usually somewhere in between recycling and reusing, the score assigned to a reclaimed material is the average score between these two parameters: 4.65 (Recycled material = 4.30 and Reused material = 5.00). Following the same criteria, the score for a recoverable material is 4.30 (Recyclable material = 4.00 and Reusable material = 4.60).

d) REPAIRABLE (Mf = 2.20)

In this case, the starting point was how much the lifetime of a product increases when it is repaired. According to the literature, a product increases its lifespan by an average of 21.85% when repaired (Bakker et al., 2014; Hennies and Stamminger, 2016).

To proceed with the estimation, the impact of a product deposited in the landfill was calculated using the SimaPro® software (4.22 Pt), specifically, a coffee machine with a variety of materials and manufacturing processes in its components and a useful life of 5 years. It was assumed that, in this case, the product is repairable, so that, of the 5 years of useful life, the last 21.85% of the product's life is after it has been repaired. For 3.91 years of useful life (years of life of the coffee machine before repair), it was calculated by the corresponding linear ratio that the impact is 3.29 Pt.

To obtain the difference in impact of a repaired product versus a product that is not repaired, the impact per year was calculated in each case:

- Product repaired: 3.29 Pt/5 years of useful life → 0.658 Pt per year
- Product not repaired: 3.29 Pt/3.91 years of useful life → 0.841 Pt per year

From these two values and knowing that the unrepaired product would have a score of 0 when evaluated with the metric, the difference in score between the two cases is 0.218. This value was multiplied by ten to make the scale consistent with that of the scores of the other parameters, as in the previous cases. Therefore, the score for a function that is fulfilled with repairable material in the metric was set to 2.2.

e) INCINERATION (energy recovery) (Mf = 0.10)

For the incineration of material, the SimaPro® software package has been used again. The impact of an amount of organic material when deposited in the landfill has been calculated and subsequently the impact of the same amount of organic material when incinerated was calculated. The materials used for this are: 0.2 kg of cardboard offcuts, 0.4 kg of packaging cardboard, 0.82 kg of corrugated cardboard, 150 g of oriented strand board, 0.12 kg of corn grain, 1.64 kg of composite wood, 60 g of corn flour and 105 g of paper. A battery of miscellaneous organic materials was selected as representative of the diverse options that the concepts can exhibit.

- Impact of organic material disposed of in landfills: 16.2 Pt
- Impact of organic material incinerated: 16.1 Pt

Therefore, the ratio obtained between the two parameters is 0.1, so that the scores for incinerate material and landfilled material will be 0.01 apart, calculating the corresponding linear relationship (an impact of 16.2 Pt has a score of 0, so an impact of 16.1 Pt has a score of 0.01).

To fit the score to the scale of the metric, the final score of an incinerated material was multiplied by 10, as in the previous cases, setting it to 0.10.

f) REDUCE (Mi = 5.00)

The score for the action of reducing material when fulfilling a function was set at 5 as a mid-point between rejecting the use of material (10) and using new material (0), which would be considered a 50% reduction in material. The decision was made to reduce the material by half to set the score for this action as an intermediate and moderate option.

In addition, a start material action score together with an end-of-life material score cannot add up to more than 10, due to the way the metric design was set up. However, by setting the reduce score to 5, the maximum score a function can obtain together with an end-of-life action is 9.6 (reject together with reuse), so the premise of not exceeding the score of 10 by adding the two scores together is still met.

g) NEW MATERIAL (Mi = 0) AND MATERIAL DISPOSED IN LANDFILL (Mf = 0)

In these two cases (new raw material and end of life of the material on landfill) the score given to the function when applying the metric is the minimum possible (0) as no material recovery action is carried out, for the manufacture of the future product or at its end of life.

4.2.1. Calculation of the circularity score

Once the three values, Ne, Mi and Mf, have been established, the circularity score for each function (C) is calculated with Eq. (2). The result will be a value between 0 and 10, with 0 being not at all circular and 10 being the maximum circularity score. This scale has been chosen in order to fit with the other scales present in the metric and in order to make the metric more understandable for its users. By adding up the three parameters, all of them are taken into account to the same extent. The logarithmic operations and the other numerical combinations, on the other hand, were added to make it possible for the final score to be between 0 and 10.

$$C = 10 * \frac{\left(log10\left((Ne + Mi + Mf + 2)/2\right)\right)}{(log10(11))}$$

Eq. (2). Circularity calculation for a function (C).

Where
Ne = Score for the number of strategies used
Mi = Score of the raw material
Mf = Score of the end of material

4.3. Method of operation of the metric

The parameters established have been combined in a way that gives equal importance to novelty (N) and circularity (C), since these two aspects are being measured together. Likewise, the three aspects that comprise the measurement of circularity, as mentioned in previous sections, are also evaluated equally.

Based on the fact that both novelty and circularity have a score for each function of between 0 and 10, it was considered that the combination of novelty and circularity should result in a value between 0 and 100. Thus, it was determined that this result should be calculated by adding the product of the results for each function, correcting it by their importance (Eq. (3)). The total score (CN) is a sum weighted according to the importance of each function combining novelty (N) and circularity (C) scores, also for each function. The calculation of the total score (CN) for a concept is therefore defined as follows:

$$CN = [imp_1*(N_1*C_1)] + [imp_2*(N_2*C_2)] + \ldots + [imp_i*(N_i*C_i)]$$

Eq. (3). Calculation of the total score (CN) for a concept.

Where
Imp_i = importance of function i
N_i = novelty of function i
C_i = circularity of function i

The metric designed was given the name "CN_Con" as a combination of circularity (C), novelty (N) and concepts (Con). The steps for applying it can be seen in Fig. 2. Once the product functions and their importance had been established (all importance must add up to 1), the corresponding values were set to obtain a final score of circularity and novelty together for the concept.

4.4. Considerations in the use of the tool

Due to the characteristics of a conceptual product proposal, when applying the metric several situations may arise that give rise to doubt. For solving this, it has been defined how to act in each of these cases. Table 5 shows each of the situations. Fig. 3, on the other hand, shows the procedure to be followed if the end of life of the material is not specified.

5. Metric validation

5.1. Case study

An example of applying the metric to a concept for school furniture is shown below (Fig. 4). First, the functions to be fulfilled by the product and their importance were established. The design problem asked for generating novel solutions that adhere to the principles of the circular economy. Other requirement was following educational trends in which furniture plays a fundamental role. The functions to be evaluated were thus established according to the features that a product of this type needs to fulfil its function correctly.

Hence, the functions established are shown in Table 6, together with the importance considered for each of them. The different values of importance for each function were established by consensus among three of the researchers involved in this study. Once the functions had been established, the component or components of the product that solve each of the functions were defined.

The next step was to score the novelty for each of the functions in the proposal, according with the criterion defined in Table 3 (Table 7).

As for circularity, Table 8 shows the circularity results obtained by the concept according to Fig. 1 and Table 4.

Once the scores for each of the circularity parameters had been established, the total circularity score for each function (C) was calculated using Eq. (2).

$$C_1 = 10 * \frac{\left(log10\left((2.89 + 4.65 + 4.3 + 2)/2\right)\right)}{(log10(11))} = 8.07$$

$$C_2 = 10 * \frac{\left(log10\left((0 + 5 + 4.3 + 2)/2\right)\right)}{(log10(11))} = 7.22$$

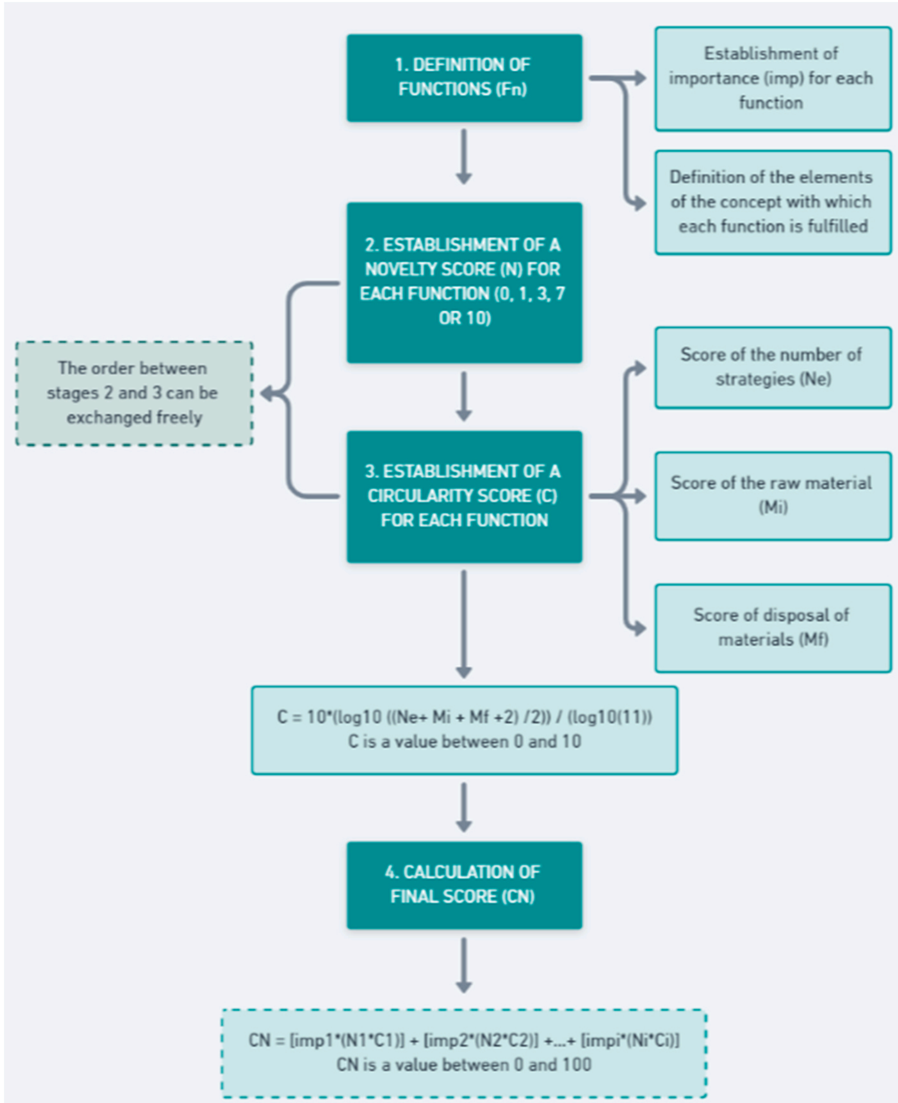

Fig. 2. CN_Con operation stages.

Table 5
How to deal with cases of unclear application.

SITUATION	HOW TO OPERATE
Mi = 10 (Refuse use of material)	Not scored Mf
The origin of the material is not specified	Assumes new material (Mi = 0)
End of life of the material is not specified	Mf is set according to the properties of the material and/or the function being solved
Material with several possibilities of origin and/or end of life in a function	The highest possible score for Mi and/or Mf is taken into account
Function solved with more than one material	Lowest possible score for Mi or Mf is taken into account

$$C_3 = 10 * \frac{\left(log10\left((2.89+5+4.3+2)/2\right)\right)}{(log10(11))} = 8.17$$

$$C_4 = 10 * \frac{\left(log10\left((0+0+0+2)/2\right)\right)}{(log10(11))} = 0$$

To calculate the final score for circularity and novelty together, all partial scores obtained for all functions (importance, novelty and circularity) were combined in accordance with Eq. (3).

CN = [0.25*(3*8.07)] + [0.25*(3*7.22)] + [0.30*(3*8.17)] + [0.20*(0*0)] = 18.82

The result obtained was 18.82 out of a maximum of 100 points. In this case, analysing the scores for each parameter, it can be seen how the concept could be improved by fulfilling the function it does not satisfy in terms of both circularity and novelty, especially with regard to the use of strategies to extend the useful life of the product.

5.2. Validation

5.2.1. Internal validation

For the validation of the metric, the conceptual proposals shown in Ruiz-Pastor et al. (2021b) were used. In Ruiz-Pastor et al. (2021b), an experiment was carried out in which 72 industrial design students with the same training were asked to generate concepts for school furniture for use with new educational trends. The concepts had to be novel and follow the principles of the circular economy. In the cited work, the creativity of the concepts was assessed using an adaptation of the metric of López-Forniés et al. (2017) and circularity was measured by counting circular features. The results of the scores obtained are shown in Table 9.

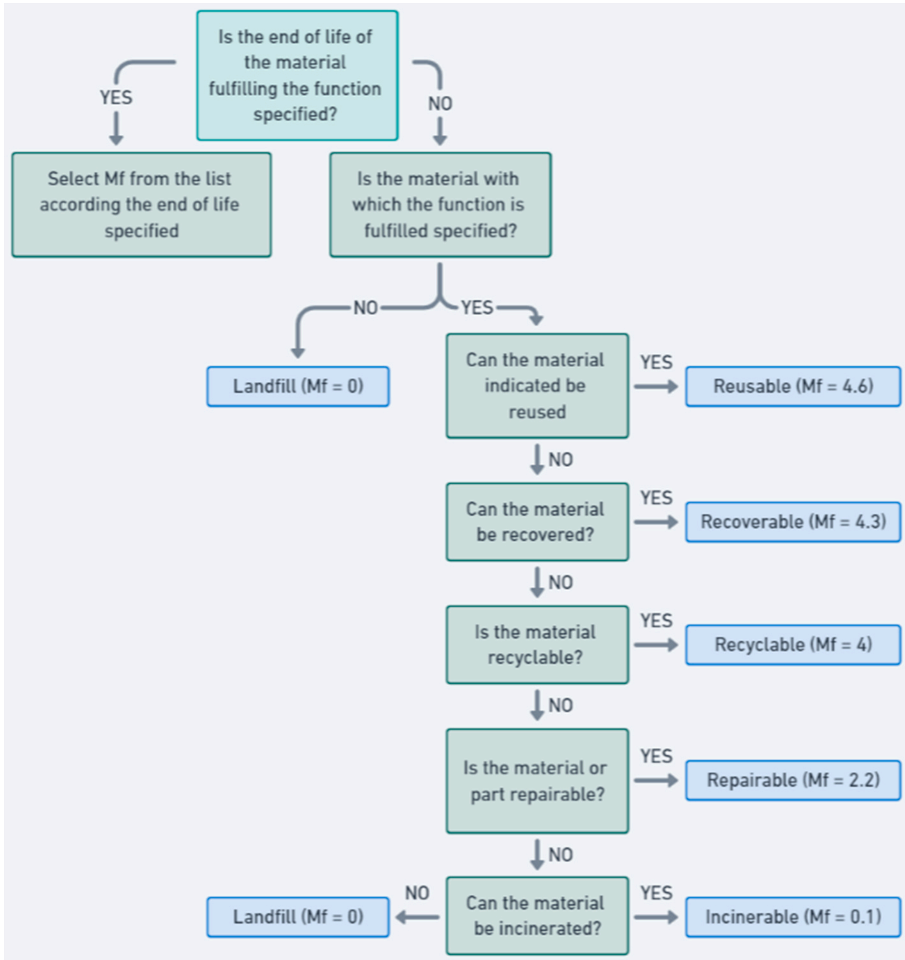

Fig. 3. Mf selection procedure if the end of life of the material is not specified.

For instance, in proposal L71 it has been designed a desk with a rotating table in order to get different inclinations. This table also can be used as a blackboard. The table is also adaptable to different heights and suitable for wheelchair users. The desks are stackable for allowing to have different types of spaces in the classroom and for facilitating the storage. The desk is also designed for disassembly and part of its materials (the wood and the blackboard) are from recycled and remanufactured materials. The design has been thought for long duration and it is available in several colours. As another example, the proposal L53 is a modular desk designed for allowing both individual or group work with multiple combinations possible. The modules are easy to assembly and disassembly and each module has different allocation options, as for example table extension or seat.

In the present work, these same concepts generated in Ruiz-Pastor et al. (2021b) has been evaluated with CN_Con in order to study the level of agreement between the scores obtained with CN_Con and the scores obtained with existing methods in Ruiz-Pastor et al. (2021b). The comparative evaluations are shown in Table 9.

In this case, in the results obtained with the two existing methods, the lowest scores ranged from 0 to 4.3 and the highest scores ranged from 22.4 to 15.3, with a maximum of 100 and a minimum of 0, as they were scaled to allow them to be compared with the values obtained with CN_Con. In terms of the scores generated by the metric, the lowest scores were between 0 and 4.29 and the highest scores were between 16.58 and 13.53. In this experiment, the values between the low scores were the same in both cases and, in the case of the highest scores, they were also very similar.

Once the data had been prepared, the correlation coefficient between them was calculated, to see to what extent they increased and/or decreased in a consistent manner. The result obtained was a correlation coefficient of $r = 0.66$. This means that the data were mostly moderately correlated, but there were some differences between the groups of scores that needed to be analysed. On analysing these differences in scores (Fig. 5), it was concluded that the function-based evaluation was more accurate, i.e. it penalises the overall score if a function is not fulfilled, as well as if a proposal has low circularity or novelty. In the evaluation provided by CN_Con, if an aspect of the concept is not indicated, the final score is penalised. In addition, the circularity parameters are more complete and better adapted to concept proposals in the CN_Con assessment, and thus CN_Con provides a more realistic assessment in terms of both novelty and circular economy together.

5.2.2. *Professional experts validation*

To externally validate the proposed metric, five design engineering experts with professional experience in the field have applied CN_Con to 12 concepts of elements for transporting food away. These concepts have been randomly generated by master students. The experts were among 28 and 45 years old, with 5–23 years of work experience in different fields of design engineering, specifically in furniture, ceramics, product, graphic and automotive areas. The results for each proposal according each expert can be seen in Table 10. As an example, proposal P6 is a lunchbox made with cork with polymeric reinforcement, both recyclable materials. It is made with flexible shapes in order to be adaptable and more comfortable for different users and ways of transport and situations. On the other hand, P8 is a modular lunchbox which allows transport away different typologies of food. The modules are

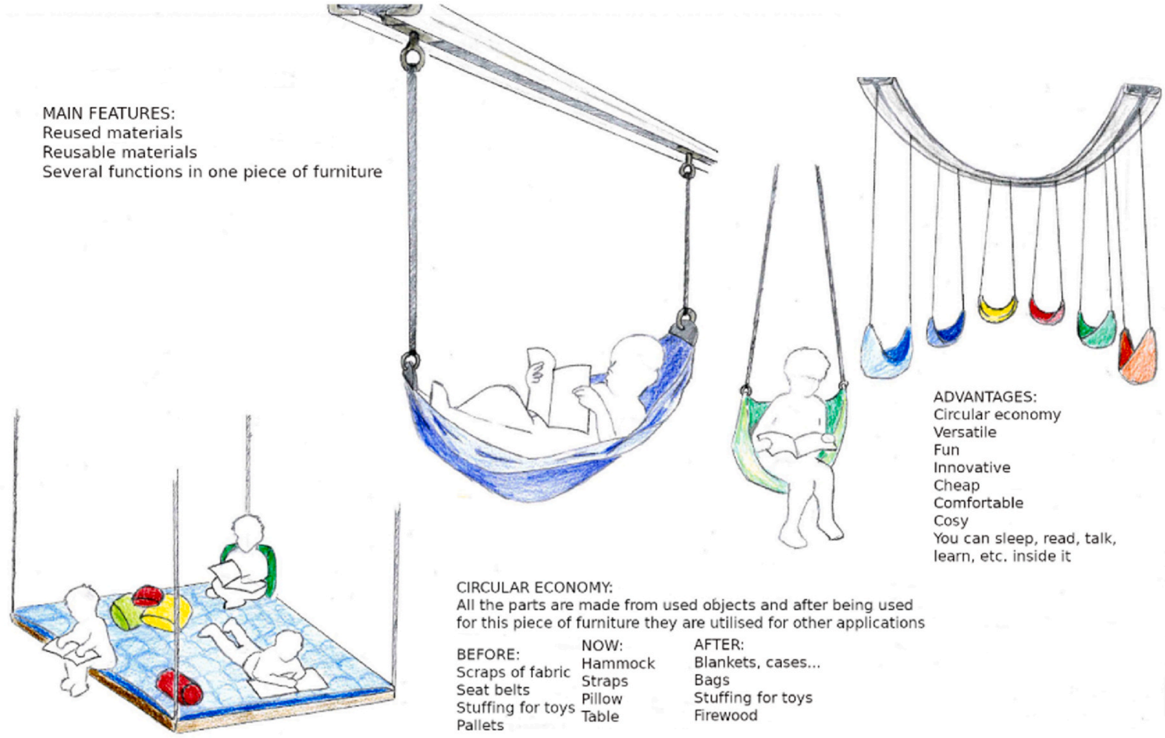

Fig. 4. Concept of school furniture generated in the experiment.

Table 6
Functions and importance for the item of school furniture.

FUNCTIONS	IMPORTANCE	COMPONENTS INVOLVED IN THE FUNCTION
F1: Seat	0.25	Seats and their supports
F2: Standing surface (table)	0.25	Surface blanket and its supports
F3: Following new trends in education	0.30	All product components
F4: Storage	0.20	No components

Table 7
Assessment of novelty for the school furniture concept.

FUNCTIONS	NOVELTY SCORE	JUSTIFICATION
F1: Seat	3	This type of swing seat already exists, but is used for applications other than in schools.
F2: Standing surface (table)	3	There is an existing swing-type support surface in the concept, but it is not used for application in schools.
F3: Following new trends in education	3	The versatility of the components of the concept that make it follow the corresponding educational trends is solved in this way for other applications, but not for schools.
F4: Storage	0	The storage function is not fulfilled.

designed for an easy assembly and disassembly. The lunchbox concept created in this proposal is made with recycled plastic. It also has been established a refill service for incentive the users to bring their own empty recipient for food.

In order to study the concordance of the results the Intra-class Correlation Coefficient has been calculated. The correlation coefficient obtained is $r = 0.856$, which means a high correlation. In Fig. 6 it can be graphically seen the answers given to each concept by all the experts. Despite there are some differences in the values given for the experts, the assessments have a high correlation, what means that this first external validation has proved to be positive.

The experts have also answered a questionnaire with 12 questions regarding the results obtained with the metric, the metric itself and its understandability. The questionnaire has been developed adapting the adjective pairs of the semantic scale (CPSS method) in O'Quin and Besemer (1989). Each expert has evaluated the semantic pairs according a seven points Likert scale (Likert, 1932). In Table 11 de different aspects evaluated as well as the scores given by each expert can be seen.

As it can be seen, most of the aspects evaluated have a good evaluation. The last group of adjectives (understandability) has the lowest scores, however, any median is higher than 5 out of 7. The results obtained in the questionnaire show that CN_Con metric is mostly suitable to fulfill its function according to the point of view of the engineering design experts that have tested it.

6. Conclusion

In this work, a metric has been proposed to measure the degree to which conceptual design proposals are novel and circular as a whole. This metric helps to select circular and novel ideas in a way that is appropriate for an early stage of the process such as the conceptual one. Also, CN_Con helps to compare quantitatively the circularity and novelty potential of different conceptual design alternatives, which is in line with Saidani et al. (2020). The measurement is carried out in a complete way, covering all the necessary aspects of those included in the circular economy in product design terms and through parameters that can be specified in the conceptual design stage. Moreover, its use is reasonably simple for the evaluator. Therefore, the existing gap in the literature has been covered by providing a metric that allows novelty and circularity to be evaluated together in conceptual product designs.

The metric that has been designed is applicable in both academic and professional works. At the same time, besides serving to evaluate conceptual design proposals, it can also be useful as a guide during the

Table 8
Circularity assessment for the concept of school furniture.

FUNCTIONS	Ne	Description of Ne	Mi	Description of Mi	Mf	Description of Mf	C
F1: Seat	2.89	The function uses 1 strategy: extending life through versatility	4.65	The seats are recovered from patches of fabric.	4.3	The seats are recoverable for making blankets, cases, etc.	8.07
F2: Standing surface (table)	0	No strategy is used to fulfil the function	5	The table surface is made of reused pallets.	4.3	Pallets can be recovered for firewood	7.22
F3: Following new trends in education	2.89	New trends in education are addressed by means of 1 strategy: extending life through versatility	5	The components that give the concept versatility are reused	4.3	The components that give versatility to the concept are retrievable	8.17
F4: Storage	0	–	0	–	0	–	0

Table 9
Scores obtained for the concepts with existing methods (Ruiz-Pastor et al., 2021b) and with CN_Con.

Proposal	Ruiz-Pastor et al. (2021b)			CN_Con result
	Novelty (N)	Circularity (C)	N*C	
L11	3	2.3	6.9	7.39
L12	1	0	0	0.00
L13	1	6.6	6.6	16.58
L14	3	3.3	9.9	12.21
L15	1	0	0	3.60
L71	3	4.6	13.8	16.56
L72	7	3.2	22.4	18.82
L73	3	5.2	15.6	13.53
L74	1	2.6	2.6	10.05
L75	1	4.3	4.3	10.80
L76	3	5.1	15.3	9.30
L31	3	4.3	12.9	9.19
L32	3	4.6	13.8	10.18
L33	3	2.3	6.9	4.29
L34	3	2	6	3.92
L51	3	2.7	8.1	8.13
L52	3	3.3	9.9	12.14
L53	7	1	7	11.92
L54	3	4.7	14.1	9.23
L55	3	1.9	5.7	2.56

process of design itself for the redesign of concepts, if the aspects to be evaluated are known in advance. Furthermore, the tool encourages the introduction of the circular economy in a creative and comprehensive way into the design process, thereby filling the gap that has existed so far in terms of evaluating the circular economy in design concepts.

The scores calculated in subsections a) to g) could deviate somewhat from the exact score of the final product designed, but as it is a tool developed for concept evaluation certain aspects used to establish the scores have not yet been defined. This is why the standard reference values and/or averages used are considered enough to determine the score for each of the values. This could cause the circularity and novelty of the final products, which have already been developed, to vary with respect to the score obtained as some of their characteristics may change during development. Nevertheless, this does not diminish the value of the evaluation carried out by CN_Con in the conceptual design stage. The metric designed has been tested through the assessment of design concepts by professionals with experience in design engineering. In this way, it has been observed how CN_Con performs with high level evaluators.

On the other hand, it would be interesting to study how the weights established for each function in the concepts make their final score change. In this line, potential future work would be to perform a sensibility analysis in order to study how the change of importance among

Table 10
Scores obtained with CN_Con for each proposal according the experts.

	EXPERT 1	EXPERT 2	EXPERT 3	EXPERT 4	EXPERT 5
P1	5.911	5.956	1.677	2.424	5.407
P2	5.203	4.811	2.423	6.960	4.848
P3	3.576	4.307	3.914	3.356	4.406
P4	4.910	3.931	4.502	5.926	3.865
P5	4.593	6.221	5.599	4.851	7.034
P6	2.876	2.291	3.169	2.922	2.522
P7	6.153	4.123	2.733	6.458	5.961
P8	14.184	10.227	6.532	15.541	14.876
P9	1.856	1.833	0.000	2.237	1.928
P10	11.144	5.532	2.079	11.353	11.612
P11	9.778	10.227	1.812	10.024	9.421
P12	7.693	6.751	2.544	15.425	9.752

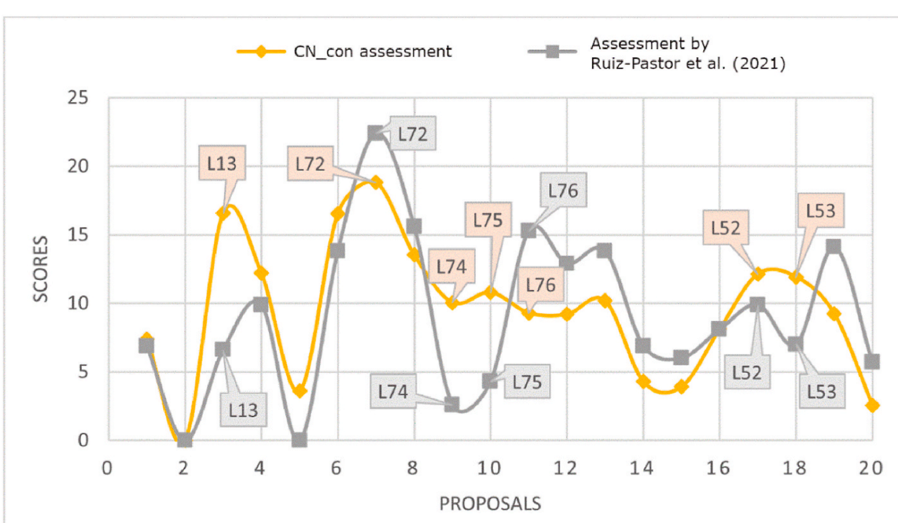

Fig. 5. Proposals with discordant scores for school furniture.

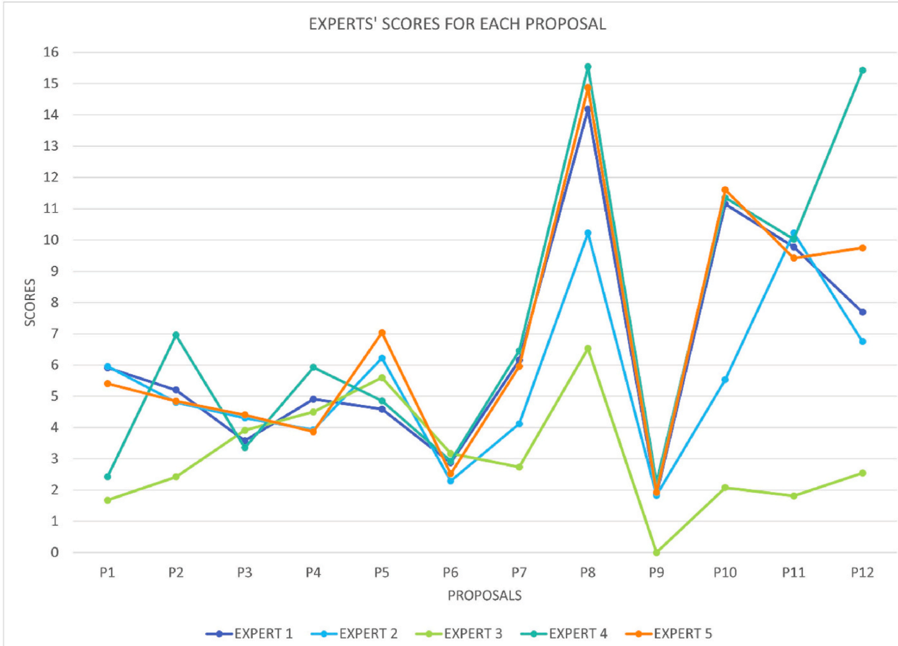

Fig. 6. Scores given by the experts to each proposal.

Table 11
Experts' answers to the questionnaire.

	EXPERT 1	EXPERT 2	EXPERT 3	EXPERT 4	EXPERT 5	MEDIAN
Correct/Incorrect	7	7	5	6	6	**6.0**
Useful/Useless	7	7	6	6	6	**6.0**
Useable/Unusable	7	7	5	7	6	**7.0**
Complete/Incomplete	6	6	5	7	7	**6.0**
Logical/Illogical	7	7	4	7	7	**7.0**
Appropriate/Inappropriate	7	7	5	6	7	**7.0**
Durable/Flimsy	5	6	6	7	7	**6.0**
Substantial/Insubstantial	7	7	4	6	6	**6.0**
Adequate/Inadequate	7	7	3	5	7	**7.0**
Self-explanatory/Unexplained	4	6	4	5	5	**5.0**
Clear/Ambiguous	4	6	4	5	6	**5.0**
Simple/Complex	7	6	4	5	6	**6.0**

functions affects the results. Another aspect that takes this work a step further could be the automation and graphic improvement of the tool, thereby providing the user with a simple and complete concept evaluation experience.

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CRediT author statement

Laura Ruiz-Pastor: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft, Visualization. **Vicente Chulvi:** Conceptualization, Validation, Investigation, Resources, Writing - Review & Editing, Supervision, Project administration. **Elena Mulet:** Investigation, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Marta Royo:** Investigation, Resources, Writing - Review & Editing, Visualization, Funding acquisition.

Declaration of competing interest

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

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