PRODUCT CIRCULARITY INDICATOR USING CUMULATIVE ENERGY DEMAND

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Abstract: This paper presents a tool to measure the circularity of a product and discusses how such a product circularity index can support decision making in early product development and design stage that has conclusive influence on the remainder of the product's life, particularly on possibilities to extend product life and preserve or recover valuable resources. The calculation is constructed on a method presented by Linder (2017); however, the monetary value was replaced by cumulative energy demand (CED) as a basis for measuring product resource value and to establish a connection to environmental and resource use aspects. The circularity indicator calculates the ratio between the amount of CED saved by recirculating products, components or materials, and the total CED of the product produced from virgin and secondary resources. The tool presented has been developed in an action research-based approach and validated through multiple calculations of product circularity for different product concepts. In doing so, circularity indices for product concepts based on different re-strategies (i.e. reduce, reuse, repair, refurbishment, remanufacture and recycle) were investigated and compared to provide a preliminary evaluation of different re-strategies as promoted by the Ellen MacArthur Foundation. Insights are to be used in new product development and design efforts with regards to circular economy. The generic nature of the tool makes it applicable to be used for different products, components and companies.

1. INTRODUCTION

There is no doubt that the way a product is put together and what materials it is made from play an important role in circular economy within the manufacturing industry, where longevity and recirculation are major parts. However, product circularity measurement is still under-researched and a well-established method and tool is lacking [4]. In this context, product circularity is the possibility to repair, reuse, remanufacture or recycle the product, its parts or the materials it is made of. The methods available for calculating circularity mainly aim at analysing companies or fully developed products [4], whereas a method to help early product development decision-making is lacking.

Circular economy aims to close the loop in a way that resources are circulated with help of new product design and development and also new business models. Within recirculation, some strategies are considered better than others, for example reusing a component is better than recycling the materials it is built from, as the former preserves the value put into constructing the component. However, it is difficult to measure and compare circulation strategies (e.g., repair, reuse, remanufacture, recycle, etc.). Hence, a method is needed.

This paper presents a tool that measures the circularity of a product and discusses how such a product circularity index can support decision making in early product development and design stage that has conclusive influence on the remainder of the product's life, particularly on possibilities to extend product life and preserve or recover valuable resources. The tool is based on preliminary evaluation of different re-strategies as promoted by the Ellen MacArthur Foundation [1, 2] i.e., reduce, reuse, repair, refurbishment, remanufacture and recycle. This tool is based on a Life Cycle Assessment (LCA) approach that is easy to understand and use for comparisons of primarily alternative concepts, using cumulative energy demand (CED) as its base for calculations because of its connection to environmental impact.

The goal of this paper is to present a method with which circularity can be measured and by that encourage adaptation of circular economy to a greater extent.

2. METHODOLOGY

Prior to the tool development, a structured literature review on circular economy and sustainable product development was carried out. The literature search incorporated different keywords such as “circular economy”, “product development”, “measurement tool” and combinations thereof. The literature selection focused on papers addressing circular economy and related tools and guidelines for early product development. Furthermore, the tool has been developed in an action research-based approach [2] in two case companies. Case company A is located in Sweden and develops, manufactures and provides service for coffee machines. Case company B is located in Iceland and designs, develops and manufactures mobility solutions for prosthetic, osteoarthritis and injuries.

Action research is an iterative process that foresees researchers and practitioners working together on a practical issue including problem identification, planning, implementing, testing and validating of improvement actions. The method is therefore well suited to our study with iterative cycles to explore, develop, test, improve and validate a tool for circularity index that aims to support the participating companies in decision making in early product development, and structuring their circular economy strategies. In both cases, the researchers were interactively and regularly working with (environmental and operational) management and product design team for several months in order to improve their product design to address circularity issues in the product development processes. All meetings, discussions, plans and actions have been summarized in minutes of meetings with approval of both sides on the content.

3. THEORETICAL BACKGROUND

There is currently a limited number of methods available for measuring circularity, including Material Circularity Indicator [1] where material input, output and the materials effects on the environment is studied on a company or product level, Circular Economy Toolkit [3], an interactive tool calculating circularity by grading a number of statements, Circular Economy Indicator Prototype which is a questionnaire based indicator [6]. Furthermore, Circularity Metric [5] uses the value of all recirculated parts and materials in the product compared to the total value of the product to calculate circularity. The circularity in this tool is calculated with the following formula:

$$c_{tot} = \sum_{i=1}^{n} c_i \frac{v_i}{v_{tot}}$$

$$v_{tot} = \sum_{i=1}^{n} v_i$$

where c stands for circularity and v for monetary value. According to [5], this tool covers certain criteria that the other tools lack, including construct validity, reliability, unambiguous methodological principles, transparency, generality and low dimensionality of result.

Cumulative energy Demand (CED) is an energy use indicator to calculate the embodied energy used to manufacture a product or provide a service through its entire life cycle. However, such a simple metric can provide an oversimplified picture of the environmental impacts, and there are cases where it falls short. An example of this is certain chemicals where the production requires a small amount of energy, but the chemical is highly toxic when emitted into the environment.

According to [5] there is a strong correlation between environmental impact as calculated with the different methods i.e., the larger the environmental impact, the larger the CED. However, none of the studied methods had specific focus on chemicals and toxicity, many resource and energy dominated. Two advantages of using CED in calculation methods is the smaller amount of data needed and lower uncertainty of the data needed.

4. CIRCULARITY INDICATOR TOOL

4.1. Creating the Circularity indicator calculation tool

The Circularity indicator calculation tool (CICT) is constructed on a method presented by [4]. They use monetary values to calculate a comprehensible circularity ranging between 0-1 (0% to 100% recirculated components) for comparing different product concepts. However, in CICT the monetary value was replaced by CED as a basis for measuring product resource value and to establish a stronger connection to environmental and resource use aspects. CED was chosen for the following reasons: (1) it gives a clearer connection to environmental issues [5], (2) to counteract the influence of price volatility on immature markets, resulting in calculations made on a product consistent over time, (3) CED provides an opportunity to expand the tool and develop an evaluation framework for inclusion of use and end-of-life activities and (4) CED has the benefits to include both energy and material use in a single value based on the primary energy demand. This approach is in line with life cycle assessment and management studies where primary energy is used as a common impact category and has been proven to have a good correlation with overall environmental impact and resource use.

CICT was built using Microsoft Excel due to its prevalence in manufacturing industry and familiarity and experience of people working in that environment. To make the operation of the tool intuitive, making a calculation in CICT follows the same steps as building a product in reality: by first preparing materials, putting them together into low level subassemblies, which can then be assembled into higher level subassemblies and finally into the main assembled product. An illustration of the procedure can be seen in figure 1.

4.2. Testing and modifying the CICT

The CICT was regularly tested during the development process, and several examples were calculated to check the tool's functionality and correctness. Several modifications and evaluations were carried out during the tests. The first challenge was how the c of anything recirculated is weighted into the equation. Assume that sub-assembly A consist of part A made from recirculated materials and part 1 made from virgin materials. Part A has $c_A = 1$ and $\mathrm{CED}_A = 10$ and part 1 $c_1 = 0$ and $\mathrm{CED}_1 = 2$. The equation for calculating the total c for the sub-assembly A looks as follows:

$$c_{sub\ A} = c_A \frac{v_A}{v_A + v_1} + c_1 \frac{v_1}{v_A + v_1} = 1 \frac{10}{10+2} + 0 \frac{2}{10+2} = \frac{10}{12} \approx 0{,}83 \quad (1)$$

Sub-assembly B is identical to sub-assembly A, except for the recirculated part B which requires less CED than part A. Part B has a $c_B = 1$ and $\mathrm{CED}_B = 10$ and part 1 $c_1 = 0$ and $\mathrm{CED}_1 = 2$. The equation for calculating the total C for sub-assembly B will then look as follows:

$$c_{sub\ B} = c_B \frac{v_B}{v_B + v_1} + c_1 \frac{v_1}{v_B + v_1} = 1 \frac{4}{4+2} + 0 \frac{2}{4+2} = \frac{2}{3} \approx 0{,}66 \ (2)$$

As can be seen from equations (1) and (2), the better performing alternative get a lower c score. This example shows that given two alternatives of a part, the one with the lower CED (probably lower environmental impact) will receive a circularity indicator that is lower for a part with higher CED. This mean that the better a component is, as in lower CED, the less impact it will have on the final c score of the product.

The second odd behaviour observed is also illustrated with an example: if there are two alternatives of a component, one which requires less processing and thereby less CED compared to the other, the one that needs more processing and by that adding more energy and environmental impact receives a larger c. Consider a new part 1 with $c_1 = 0$ and $\mathrm{CED}_1 = 2$ and a recirculated part A with $c_A = 1$ and $\mathrm{CED}_A = 2$. Adding processing worth 8 and 2 units of work results in the following:

$$c_{much\ processing} = c_A \frac{v_A + v_{much\ processing}}{(v_A + v_{much\ processing}) + v_1} + c_1 \frac{v_1}{(v_A + v_{much\ processing}) + v_1} = 1 \frac{2+8}{(2+8)+2} + 0 \frac{2}{(2+8)+2} = \frac{10}{12} \approx 0{,}83 \ (3)$$

and

$$c_{little\ processing} = c_A \frac{v_A + v_{little\ processing}}{(v_A + v_{little\ processing}) + v_1} + c_1 \frac{v_1}{(v_A + v_{little\ processing}) + v_1} = 1 \frac{2+2}{(2+2)+2} + 0 \frac{2}{(2+2)+2} = \frac{2}{3} \approx 0{,}66 \ (4)$$

This led to several discussions and eventually two modifications for calculating the circularity indicator:

1. The circularity indicator for a product is equal to the amount of CED saved by using a recirculated part instead of a virgin component, divided by the sum of CED from all virgin parts, materials and processes and the energy saved by using recirculated parts instead of virgin equivalent
2. Only recirculated materials and parts contribute to an increased c.

In equation form, the modified method looks as follows:

$$c_{tot} = \sum_{i=1}^{n} c_n \frac{(v_{n_{virgin}} - v_{n_{re}})}{v_{tot}} \ (5),$$

$$v_{tot} = \sum_{i=1}^{n} (n_{n_{virgin}} - v_{n_{re}}) \ (6)$$

$$f(x) = \begin{cases} 0, & \text{if step is addition of a non-recirculated material, component or process} \\ 1, & \text{if step is addition of a non-processed recirculated component or material} \\ 0-1, & \text{if step is addition of someting the algorithm treats as a subassembly} \end{cases}$$

(7)

The implementation of the equations in Excel was made in a sequential manner that adds each new entry in the form of a new row into the total and calculates a total c, see Figure 2 and 3.

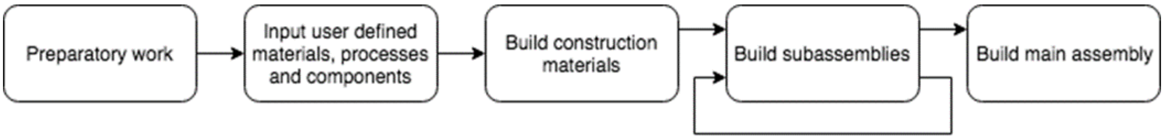


Figure 1 - Flowchart of the steps required to calculate a circularity indicator

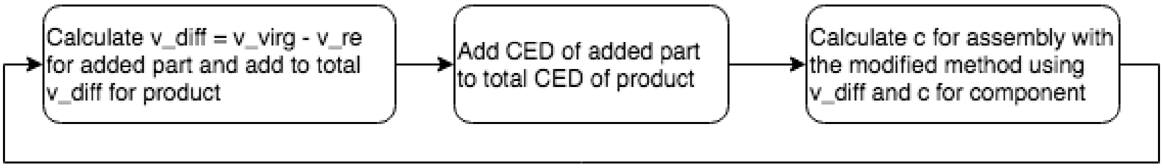
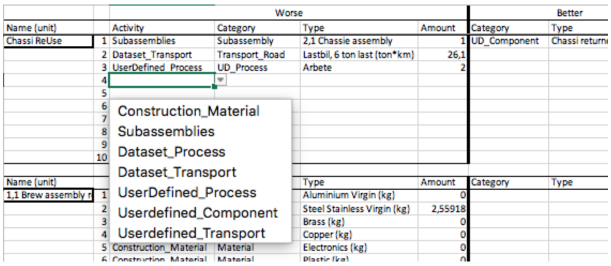


Figure 1 - The calculation algorithm of the tool

These modifications entail that whenever a recirculated component is used, it must be compared against a virgin equivalent (or at least as virgin as is possible, using steel as an example, where most steel available contain some part recycled material), adding a step in the building of the assembly, see figure 3. Having made these modifications, the calculation part of the tool was again tested against the same examples as earlier and was now behaving as desired, and the final validation of the tool could be performed, see section 5.



		Worse				Better	
Name (unit)		Activity	Category	Type	Amount	Category	Type
Chassi ReUse	1	Subassemblies	Subassembly	2,1 Chassie assembly	1	UD_Component	Chassi return
	2	Dataset_Transport	Transport_Road	Lastbil, 6 ton last (ton*km)	26,1		
	3	UserDefined_Process	UD_Process	Arbete	2		
	4						
	5						
	6						
	7						
	8						
	9						
	10						

Name (unit)				Type	Amount	Category	Type
1,1 Brew assembly r	1			Aluminium Virgin (kg)	0		
	2			Steel Stainless Virgin (kg)	2,55918		
	3			Brass (kg)	0		
	4			Copper (kg)	0		
	5	Construction_Material	Material	Electronics (kg)	0		
	6	Construction_Material	Material	Plastic (kg)	0		

Figure 2 - Illustration of data acquisition system and the substitution of a sub-assembly that was the result of the modification of the calculation algorithm in the tool. To the left are the materials, processes and subassemblies for a higher-level subassembly in a product. To the right is the recirculated substitute for the virgin counterpart on the same row on the left. The data acquisition is handled through drop down lists using the structure as the dataset.

4.3. Dataset

To facilitate the application of the tool and make comparison of different products more equitable, the tool contains a general dataset for common materials and processes, to supply generic data for commonly used materials and processes when specific data for a product is unknown. The data for the datasets has been gathered from ecoinvent v3.4, which is a database for LCA calculations, through open LCA 1.7.

The allocation method used is cut-off, which implies CED of 0 for all recirculated components and materials, as all environmental burden is allocated to the previous use cycle. Hence, $c = 1$ due to recirculation. Accordingly, non-circulated materials and components added to the assembly makes c decrease. The main reason to use cut-off is that this method gives no discounts or additions to the previous cycles' CED based of what happens after the product has left the previous user.

5. EMPIRICAL CASES

The CICT was tested in two different cases described below.

5.1. Coffee Machine

A coffee machine design concept with total weight of 26kg was studied. The chassis of the coffee machine is the chassis of the product which all other parts are mounted to that. The coffee machine was estimated to be made of 7,67 kg aluminium (28%), 15,74 kg stainless steel (58%), 0,70 kg brass (3%), 1,09 kg copper (4%), 1,00 kg magnesium (4%), 0,31 plastics (1%) and 0,44 kg electronic components (2%). For CED calculation, each material type was assigned a generic process, while all metals were assigned the same metal working process. The weight of all components of the same material was then summed up for each assembly. The reason this was done, instead of all component weights just summed up for the whole product was to keep the possibility of making changes to specific subassemblies. Transport between the factory in central Europe and Stockholm was included in all scenarios, and for the scenarios where parts or the whole product were reused, transport for the component or product to the factory from Stockholm and back again was also included. Each trip was assumed to be 1670 km long and carried out by truck.

Due to lack of data, surface treatments were excluded from the calculation. The CED for work carried out during refurbishment as deliberately estimated to be very high to be able to include use of energy intensive machines and processes. Most of the coffee machine is constructed from common metals, giving it the property of being highly recyclable, since these metals are infinitely recyclable. It has also been constructed with the intent of being highly suitable for recirculation by choosing resilient materials and making it modular. According to calculations, the total CED of the coffee machine was 2970 MJ and for different materials were 1059 MJ for aluminium (36%), 1166 MJ for stainless steel (39%), 44 MJ for brass (1%), 49 MJ for copper (2%), 281 MJ for magnesium (9%), 48 MJ for plastics (2%) and 321 MJ for electronic components (11%).

To evaluate the product concept and make it more circular, six different scenarios were investigated, where in all cases, transportation contributed with less than 0,1 MJ of CED.

1. Reduce the weight of the chassis by half via decrease in material thickness
2. Reduce the weight of the chassis by 60% via replacing steel parts with aluminium.
3. Replace virgin steel and aluminium with recycled steel and aluminium throughout the product.
4. Reuse the chassis from an old product and use it in a new product.
5. Remanufacture the whole coffee machine, with some worn components exchanged, and a complete refurbishing represented by 20 man-hours of work.
6. Reuse of the whole product, with a few worn components exchanged and small amount of work represented by 1 man-hour of work.

In scenario 1, where chassis parts were assumed to weigh half as much as in the original one, the CED of the chassis was also halved. This means reduction in total CED of the coffee machine from 2977 MJ to 2721 MJ. However, c remained 0 as no recirculated components or materials were used in the assembly.

According to scenario 2, the exchanged aluminium part in chassis weighted about 1⁄3 of the original steel part (5,8 kg steel to 1,9 kg Al), and led to 5% weight reduction for the product. However, the total CED decreased only by 1,5% because although aluminium is less dense than steel, it has twice the CED.

In scenario 3, there was a change in c as recirculated materials and components are introduced into the product. The total CED of the product decreased by around 30%, and c=0,425. Although the virgin metals were replaced by recycled metals, the c is below 0.5. This may seem low as the exchanged metals accounts for almost 90% of the total weight. However, this is not surprising. As materials are the building blocks located furthest from the final product, the raw material itself needs to be processed into a construction material, and then processed into a component, which will need processing before the final product is built. Each of these steps has a CED that all will contribute to lower the total c of the product. Scoring a total c close to 0,5 with a product where only materials have been recirculated is probably a good result though at this stage, far too few products have been analysed for anyone to get a feeling for what is a “good” or a “bad” score.

The fourth scenario, where the chassis is reused, a reduction of total CED of 17% and total c = 0.181 is seen. In this case, the chassis receives a c of 1, and the CED saved by reusing the chassis accounts for 18.1% of the total CED of the product.

In the fifth scenario, in which the whole product is remanufactured the total c = 0.86 and CED = 480. This c was achieved considering the man-hours needed for refurbishment was high and process was energy extensive. This was countered by the sixth scenario where only little time was required for a restoration, and the results instead was a total CED of 100 and c = 0.96.

5.2. Prosthetic foot

A prosthetic foot with size of 27 and total weight around 730 g was studied. The prosthetic foot is made of different components and materials, and for simplicity of study and to avoid complications with small parts, the foot was considered weigh 409 g and made of 15 components. These components are categorized in three main parts including (1) assembled foot plate and heel piece, (2) assembled pyramid and (3) components to unite. The first part weighs 250 g with around 88% cured carbon fiber, 3% stainless steel and 9% combination of plastic, paper, glue and rubber. The assembled pyramid weighs around 132 g with 80% aluminium and 20% stainless steel. The last part weighs 27g with 78% stainless steel and 22% ABS plastic.

According to rough calculations, the total CED of the prosthetic foot was estimated to be 205 MJ whereof 179MJ (87%) stem from the assembled foot plate and heel, 25MJ (12%) from the assembled pyramid and 2MJ (1%) from components to unite. Calculating CED based on materials, 88% of prosthetic foot is made of cured carbon fibre with 175 MJ CED (85% CED of total product), 21.8 MJ aluminium (11%) and 5.1 MJ stainless steel (2.5%) with the rest combination of paper, rubber and plastics.

This prosthetic foot is designed for strength, longevity and low weight to make is as easy to use as possible and is therefore highly optimized. This results in a build without unnecessary amounts of material or components. One way to prolong the lifespan of a product is to overbuild it so that it will never wear out. In this case this is difficult as that often comes with a weight penalty and making the prosthesis heavier is not an option. Another option is to make sure that the wearing parts are easily replaceable, and the rest of the product can be reused. The parts that are likely to wear on the prosthesis is the carbon fibre foot plate and heel. If an easily replaceable rubber sole is attached to the foot the wear to the high CED carbon fibre would be eliminated, giving it a prolonged life, and compensating this extra weight by using materials with higher specific strength such as titanium alloys instead of steel and aluminium. Adding a rubber sole weighing 35 g and exchanging all steel parts for titanium equivalents results in a prosthesis that weigh as much as the original one, but now has a total CED of 215 MJ. Given that all components now have a more or less infinite lifespan, a resole of the prosthesis would only have a CED cost of around 2,7 MJ. The titanium components will be more expensive than their steel counterparts, but as the life of the product is prolonged the cost/time will likely be decreased.

6. Analysis and discussion

This section presents how changes in CED affect circularity indicator and discusses correlation among CED, c and overall environmental effects.

Starting with scenario 1 and 2 in the coffee machine case, decreasing the chassis weight is an environmental improvement, however, there is not circulation improvement involved. This shows that environmental improvements are NOT necessarily circularity improvements. Scenario 3 receives a high circular index, but still has a relatively high CED, which shows that under certain circumstances it is possible to have both high circularity and high energy use. Therefore, the circularity indicator by itself only states how much of a product is recirculated and not how large environmental impact is. Scenarios 4, 5 and 6 deal with recirculating components or the whole product, which in turn efficiently decrease CED and increase circularity index. However, the CED for man-hours doing the remanufacturing or reusing components were estimated to be high and as a result it is likely that that scenarios 5 and 6 have even lower CED and higher circularity index. Looking at this from an eco-design point of view, if a product is designed in such a way that it is infinitely reusable, it would be the perfect product. If scenarios 4 and 5 were realizable, these would not be far from it, as only a small fraction of the CED of producing the product would be required to give the product a very long life. There is of course a trade-off between over-engineering and reusability. Looking at scenario 5, it would take more than 6 remanufacturing cycles to reach the same CED as required for production of one new product. Additionally, steel or aluminIum constitute a large part of the product, which are not easily worn out.

Looking at scenario 5 and 6, the circularity indicators are high with a big contrast to the circularity index of the baseline scenario. Having a product with a long lifespan over multiple life cycles, calculating a circularity index based on only one cycle does not provide a correct picture of the circularity over product’s full life cycle. To solve this issue, an average circularity index over all product’s lifecycles gives a better indication.

From a producers point of view, doing all preparations and building the product in the tool is likely to be as informative as looking at the actual results from any calculation, as the impact on the product of each individual component and process can be followed all the way into the final assembly, and by that giving the user a feel for what parts of the build is responsible for the largest impacts, and could from that knowledge make qualified suggestions to what changes should be analysed through calculations in the future.

It can be clearly seen when working with the coffee brewer case that even though some of the materials in the product account for only a small portion of the total weight, they account for an disproportionally high amount of CED, making them possible good places to start making changes. It should be noted that although lower CED and higher circularity index are usually good indicators of environmental impacts, but our cases showed that CED and circularity values are not the absolute correct indicators for environmental impact

It is important to note that although CICT is an attempt to determine how circular a product is and there is a strong correlation between CED and environmental impact [2], CICT does not show level of compatibility with environmental aspects of a product. To determine this, the circularity indicator needs to be combined with other metrics. For instance, it is plausible that a material or component with a low CED, has a large environmental impact; chemicals can be named as an example. Hence, using a certain material, component or process to produce a product may result in a good circularity indication, while being a worse choice from an environmental perspective than an alternative with a larger CED and lower overall environmental impact.

Another controversial discussion in developing and modifying the tool was the question of whether renewable energy and bio-based materials can be considered circular and how to incorporate that into the tool. One option is to separate the merged CED into different primary energy sources and treat some of them as circular. Another option is to instead use CO_2-equivalent as a base for calculations, which within the tool have much of the same properties as CED and can therefore be directly substituted into the tool. However, a consequential question arose: what data to use? If the product has been made put of recirculated materials, what should those be compared to? How should this be calculated as there is no virgin part to be substituted? Given that this indicator only is going to be used in-house to compare different options, any data for both recirculated and virgin materials and parts can be used. It is of course encouraged that as accurate data as possible is used in all cases as this will result in more accurate comparisons. On the other hand, if the indicator is used to communicate the circularity of a product to any other party than the own company, a high level of transparency of what data is used is very important. For example, if bad (high CED) virgin alternatives are chosen for comparison, most actions toward circularity will result in very high c-values. A solution to this issue is to always use dataset values for comparisons instead of actual values. Thus, comparison will always be based on the same data and comparison would be made on the same premises. Nevertheless, using dataset values instead of actual available values makes the indicator less accurate.

One crucial aspect in circular economy is end-of-life strategies, which should be also addressed. For example, there are Products A and B. Product A is entirely made of recirculated materials (which will receive a good circularity index), but in such a way that at its end-of-life stage, nothing can be circulated, and it has to end up in landfill. On the other hand, product B is entirely made of virgin material (which will receive a circularity index of 0), but in such a way that at its end-of-life stage, the majority of components can be circulated and reused. Product B is better from the circular economy's perspective, even though with a circularity index of 0 i.e. nothing is reflected in the circularity indicator. A proposed solution to this issue was to include several questions in the tool where positive answers with regards to recirculation options and lifespan length at the end-of-life receive a positive score which increases the circularity index. Examples of these question include: is this part designed for easy disassemble, is this product designed for reuse, is this product easily recirculated?

Inclusion of product lifespan into the tool is also a concern expressed in literature [4], for instance what if using recycled material or a recirculated component reduces the lifespan of the product by half, comparing to the same product made from virgin material. Is it fair to give the short-lived product a better circularity index? A feature to mitigate and solve this issue is to create an index that instead of calculating only a circularity indicator, also calculates circularity per functional unit. Consequently, more aspects of circular economy can be taken into consideration when calculating circularity indicator. However, this expansion indicator is not the main purpose of CICT so far and therefore is not going to be discussed in this paper.

7. CONCLUSION AND FUTURE WORK

The idea of using Linder's method as a base for calculation of a circularity indicator in the shape it is presented in the original paper with the modification of using CED instead of monetary value proved not to be a very good one, based on a few characteristics that makes the model unfit for its purpose. For the indicator to more closely represent how circular a product is, several modifications were made to the model:

- Every addition to an assembly that is not recirculated will receive c = 0. This is mainly targeted at processes as it is these that can distort the result.
- Instead of weighting a recirculated addition to the assembly by its own CED, the difference between the recirculated part and a corresponding virgin one is used.

As circular economy in essence is a way of trying to make consumption more environmentally sound, the correlation between environmental impact and CED is considered to give the use of CED as a metric a good connection to the purpose of the tool. Additionally, as CED is based on scientific measurements, it is stable over time, while monetary value varies depending on the market; calculations made at different times might get different results. Based on this, CED is considered a good metric to use for calculating a circularity indicator. The conclusions that can be drawn from the validation cases are that even though the calculations are rough, the process of producing them gives an idea of what actions have the largest effect on the circularity and the environmental impact of the product. What could also be seen is that the tighter the loop can be kept, the higher the circularity becomes and the lower the CED.

8. REFERENCES

[1] Ellen MacArthur Foundation, *Circularity indicators: an approach to measuring circularity-Methodology*, Ellen MacArthur Foundation, UK, 2015.

[2] P. Reason, and H. Bradbury, *The SAGE Handbook of Action Research: Participative Inquiry and Practice*: SAGE Publications, 2007.

[3] Cradle to Cradle Products Innovation Institute, *Impact study: technical report-Pilot study impact study of the cradle to cradle certified products program*, vol. Available at: https://s3.amazonaws.com/c2c-website/resources/impact_study_technical_report.pdf (accessed Feb 2018), 2014.

[4] Marcus Linder, Steven Sarasini, and Patricia Loon, “A Metric for Quantifying Product-Level Circularity,” *Journal of Industrial Ecology*, vol. 21, no. 3, pp. 545-558, 2017.

[5] Mark A. J. Huijbregts, Stefanie Hellweg, Rolf Frischknecht, Harrie W. M. Hendriks, Konrad Hungerbühler, and A. Jan Hendriks, “Cumulative Energy Demand As Predictor for the Environmental Burden of Commodity Production,” *Environmental Science & Technology*, vol. 44, no. 6, pp. 2189-2196, 2010/03/15, 2010.

[6] Steve Cayzer, Percy Griffiths & Valentina Beghetto (2017): Design of indicators for measuring product performance in the circular economy, International Journal of Sustainable Engineering, DOI: 10.1080/19397038.2017.1333543