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Circularity Indicator Calculation Tool

A comprehensive method and metric for measuring the circularity of a product

Master's thesis in Sustainable Energy Systems

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

With the growing interest in circular economy within the industry there is a need for a way to measure the circularity of a product. This circularity metric needs to, for the sake of fair comparison, stay consistent over time and should therefore have a scientific base. The intended area of use of the metric described in this thesis is during the concept stage of product development to assist in making design decisions of what actions to take to make products more circular based on calculations instead of guesses.

Departing from these criteria, a tool was constructed, based on a methodology suggested by Linder et. al. (2017) and modified to work with cumulative energy demand (CED) instead of monetary value. This circularity indicator is calculated as the ratio between the amount of CED saved from using recirculated materials and components and the sum of the CED of all virgin materials, components and processes and the CED saved from using recirculated materials and components of the product.

In addition to the tool a dataset was constructed to supply data for a small number of commonly used materials and processes to use when product specific data for the product is unknown.

The tool was validated against a number of cases for a coffee brewer from 3Temp where a circularity indicator was calculated and compared. The validation showed that making the calculations are as useful by themselves as the actual results are as it gives insight into what parts of a product accounts for the majority of the environmental impact, as well as the realization that the closer to a whole product the recirculation is made i.e. reusing the product instead of reusing components or recycling materials, the better the circularity indicator becomes.

Keywords: circularity indicator, cumulative energy demand, circular economy, industrial ecology.

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Abbreviations and Definitions

Abbreviations

Below is a list of the abbreviations used throughout this thesis:

- BOM — Bill Of Materials
- CE — Circular Economy
- CED — Cumulative Energy Demand
- CICT — Circularity Indicator Calculation Tool
- LCA — Life Cycle Assessment
- LCT — Life Cycle Thinking
- MS — Microsoft
- PV — Photo Voltaic
- WP — Work Package

Definitions

- Re-part — Any material, component etc. that has been recirculated
- Circular, Circularity — will throughout the thesis refer to the ability to be circulated in accordance to circular economy, see section 1.1

1

Introduction

In this chapter an introduction to the background, purpose and objectives of the thesis work are described.

1.1 Background

Circular Economy

The main idea of circular economy (CE) is that the linearity of most of today's systems is causing too much environmental impact, and instead of this ”use-and-discard” system, product design and business models etc. should be made in such a way that as much as possible can have longer lifespans thanks to recirculation. This should be done with a holistic approach based on a life cycle perspective aiming to minimize the overall environmental impact. As an introduction to the general area of circular economy the Ellen MacArthur Foundation has written a thorough report on the subject: Ellen MacArthur Foundation (2013) [7]. It addresses the limits of the current linear consumption and illustrates how circular economy could work by presenting cases of circular products and business models. It also emphasizes the economic potential that a switch to circular economy has and presenting strategies to get there. One figure used in this report is especially illustrative of how circular economy works at a product level, see figure 1.1. What it in essence shows is that recirculation can be made at many different levels, nut the closer to the user it is made, the smaller the losses.

CIRCit & Swerea

This thesis work is conducted as a part of a research project in CIRCit: Circular Economy Integration in the Nordic Industry for Enhanced Sustainability and Competitiveness. For more information, see circitnord.com. CIRCit is a project under Nordic Innovation that strives to integrate circular economy into Nordic industry. One research partner in that project is Swerea, which is a Swedish research group for industrial renewal and sustainable development.

Swerea IVF is one of the institutes that operates under Swerea AB and develops and implements new technologies and new working methods within a range of sectors focusing on product, process and production development. As a part of CIRCits' WP 03: Development of circular products and services, a tool is to be developed with the purpose of quantifying how "circular" a product is.

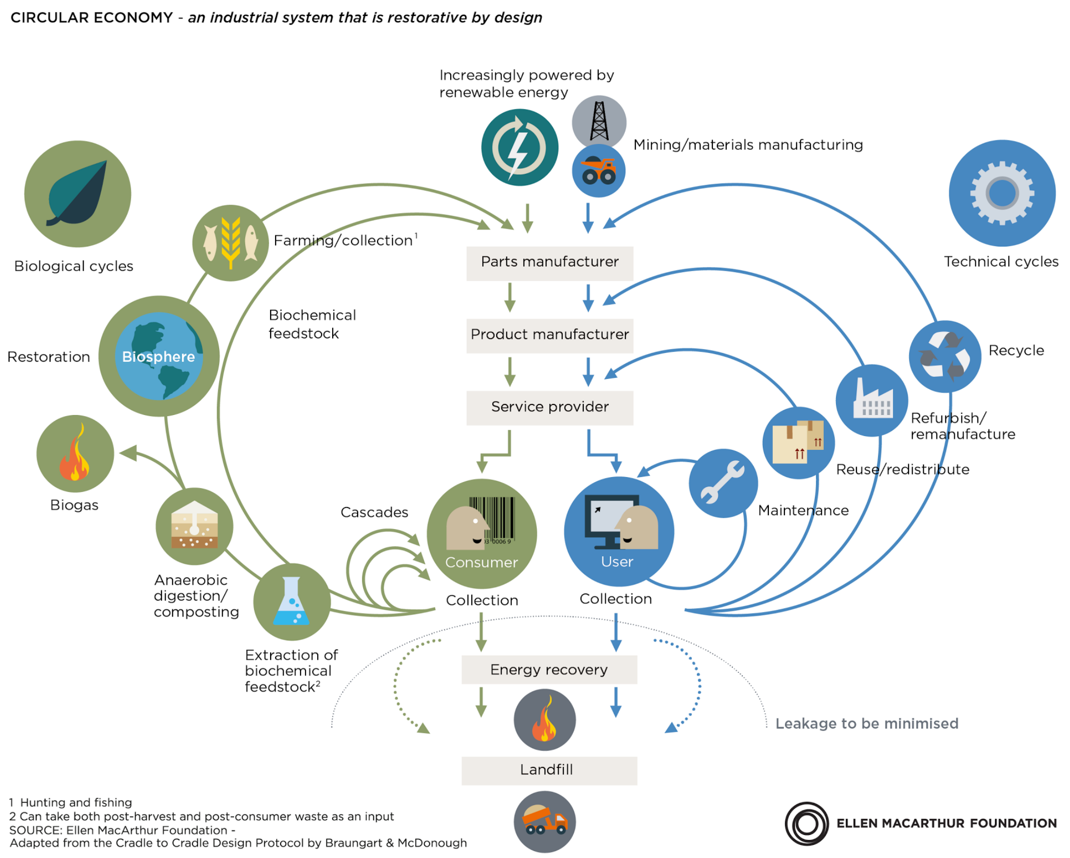


Figure 1.1: This figure illustrates ways to perform recirculation at different levels. The closer the to the user the loop can be made, the less resources are wasted. (Ellen Macarthur foundation)

3Temp AB

3Temp is a company working with development and construction of coffee machines, and is an industrial partner to Swerea. The reason for this is their desire to employ a more circular business model. By contributing to this thesis with a real life case to be evaluated, they in return get insight in what effect different actions have on the circularity of their product.

1.2 Purpose

There are a number of different methods available for calculating circularity, see section 2.4. Most of them are aimed at analyzing companies or products. What is lacking is a method to use as an aid in product development decision-making.

The purpose of this thesis work is to develop and evaluate a method for calculating a circularity indicator, based on how circular a product is from a circular economy point of view and develop a tool that use this method. This tool is intended for use in the early product development and design process, with the goal of calculating a metric for how circular a product concept is. This tool will deliver a simple metric 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 tool should also be easy to operate so that it can be used in industry without expert assistance. The tool will continue to be developed by Swerea after the thesis work is finished.

Questions that are answered in this thesis:

- There is a need for a method of calculating circularity to aid in decision making in the concept stage of product development. Is it possible to create such a method that is comprehensible, based on a scientific metric, and has a connection to environmental impact?

Objectives:

- Create a tool for calculating a circularity indicator together with the CIRCit team at Swerea by:
  - Finding a method of calculating a circularity indicator
  - Constructing an initial dataset to use with the tool when product specific data is unavailable or undesirable
- Validate tool by using it on a product from one of Swereas industrial partners, investigating the what effects a number of different scenarios has on the circularity of the product.

2

Theory

In this section a few theoretical subjects important to the thesis are introduced.

2.1 Life Cycle Assessment & Life Cycle Thinking

Life Cycle Assessment (LCA) is a method where the impact of a product or service is evaluated. It takes all aspects of the products/services stages in consideration, from cradle, i.e. extraction of resources to gate or grave, i.e. out the factory gate or final disposal. It is one way of calculating the total effect a product or service has on the environment (A. M. Tillman 2004) [20].

In Life Cycle Thinking (LCT) the whole life cycle of a product/service is considered when making decisions, with the purpose of having as little impact as possible. This can for example be achieved by designing a component in such a way that it is more resource demanding, but also easy to reuse and therefore has less impact in the long run.

These concepts are important within circular economy as they are tools to evaluate and support.

The connection between LCA, LCT and circular economy is that LCA and LCT are tools used to reach circularity goals. To close the loops, which is advocated in CE, all life cycle stages need to be considered in the development stages of the product/service to make sure that closing the loops will be possible and profitable. LCA is used to evaluate products and services, and from the results, decisions can be on what actions to take to make them more sustainable.

2.2 Cumulative Energy Demand

There are a number of different indicators available for the purpose of evaluating the environmental impact of products and services: Climate Footprint [4], EcoIndicator 99 [18] and Environmental Priority Strategy [19] to name just a few. In a study conducted by Huijbregts et. al. (2010) [11] it is concluded that there is a strong correlation between environmental impact as calculated with the different methods looked at in their study and the Cumulative Energy Demand (CED) for the same product, the larger the environmental impact, the larger the CED. One emphasized aspect that separates CED from the other methods of evaluation is the smaller amount of data needed and compared to other methods the relatively low uncertainty of needed the data. 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.

CED is in essence the total amount of primary energy that goes into a product or service, either directly or indirectly via materials. CED as a concept has been around since the 1970:s. There are a few ways to determine the amount of primary energy going into a system: firstly one can use either upper or lower heating values for fuels meaning either the condensation energy of the water vapour from the combustion is included or not. Secondly, the question of whether all forms of primary energy have the same value has lead to a few different methods of calculating CED (extrapolation can be found below), the simplest one being differentiating between fossil and renewable sources of energy, others treating nuclear energy separate, and even categorizing the primary energy into eight categories for better transparency and enabling more detailed interpretation of the results. [10].

At present, the go to method for calculating CED from different sources is the one referred to as the Energy Harvested approach and is the one used in ecoinvent. As the name suggest, the energy added to the calculations is the energy that is harvested from the energy sources. For fuel based energy, that would be the amount extracted from the well, dug out of the ground or removed from the forest. For fuels, it is the higher heating value of the fuel that is used. The amount of energy used is then calculated by multiplying this with the amount of fuel extracted. Nuclear energy is a bit more difficult to account for as there are many ways of doing this, but following the energy harvested approach, the idea is that the thermal efficiency of a modern light water reactor is used to determine the accessible energy from a certain mass of fuel, and use that as a measure for the energy contents of uranium. For renewable energy sources, the energy from the harvester is the one used, for example the rotational energy of the shaft of a wind turbine before it enters the gearbox, or the electrical energy output of the PV collector before it goes into the converter. [8]

When it comes to materials, all primary energy that goes into making a material usable in construction is added to its CED. This includes the chemical energy in the materials, given that they could be used for production of secondary energy. For metals, it is activities, from mining to initial shaping of the metal before it leaves the gate, that contributes to its CED. As for polymers, where the most common raw material is fossil oil, the energy content of this oil is counted towards the CED as well as the activities that treats it along its way to become plastic.

Ecoinvent delivers its results in eight different categories. Reporting CED for a number of subcategories definitely has a point, it does however make the metrics difficult to use in the setting of this project. Because of this, the different categories are always aggregated into a single, total CED.

2.3 Algorithm for Calculating a Circularity Indicator

In a paper by Linder et. al. [12] they suggest a method for calculating a circularity indicator c based on the ratio of re-circulated economic value to total product value.

The calculation is based on a simple algorithm, where each step in the production adds to the total value of the product:

$$c_{tot} = \sum_{i=1}^{n} c_i \frac{v_i}{v_{tot}} \tag{2.1}$$

$$v_{tot} = \sum_{i=1}^{n} v_i \tag{2.2}$$

where v_i represent the monetary value added for the production step. This method is usually employed in a sequential manner, where every new step added to the sum of the previous ones. Each step contributes with a c_i based on what action is carried out on the assembly:

$$c_n = \begin{cases} 0 & \text{if step is addition of a non-recirculated component or material,} \\ 1 & \text{if step is addition of a non-processed recirculated component} \\ & \text{or material} \\ 0-1 & \text{if step is addition of something the algorithm treats as a} \\ & \text{sub-assembly} \\ - & \text{if step is a process, it gets the same } c \text{ as the current total, thereby} \\ & \text{adding value to the product but have no impact in the circularity} \end{cases} \tag{2.3}$$

All additions that consists of a combination of steps carried out separately from the main assembly, such as materials that has been treated or processed in any way or components that are assembled, are treated as separate assemblies which are calculated separately and whose data can be used in other assemblies.

The reasons this method was chosen as a starting point for this thesis are that it is objective e.g. based on mathematics, and in no way relies on values and opinions. In addition to that, the output metric is easy to understand, as it ranges between 0 and 1, 0 meaning no part of the assembly is recirculated while 1 means that the assembly is perfectly recirculated. It also makes no difference what products are evaluated, making circularity comparable between different product types like for example a skateboard and a bicycle.

2.4 Previous work

There is currently a limited selection of methods available for ”measuring circularity”: Material Circularity Indicator: Ellen MacArthur Foundation (2015) [6], The C2C certification framework: C2C (2014) [2], REPRO: Gehin (2008) [9], Eco-efficient Value Ratio: Scheepens (2016) [13] and Circular economy index: Di Maio (2015) [5] to name a few. According to Linder (2017) [12], There are a number of a properties a circularity indicator should possess in order to be considered a good one:

- Construct validity
  - A metrics ability to measure what it is intended to measure, in this case what amount of a product that is recirculated, and not other things like

    environmental performance, as many other metrics exist that measures other aspects of sustainability.

- Reliability
    - A metric should produce similar results if circularity is calculated for the same product at different times
- Transparency
    - A good circularity indicator might be an advantage for a product, and could encourage opportunistic behavior to try to get as high numbers as possible. It is therefore important to be able to verify the results of the calculations.
- Unambiguous methodological principles
    - A metric should leave as little room as possible for judgments as possible.
- Generality
    - It should be possible to compare products of different types against each other independent of the technology used.
- Low dimensionality of result
    - Having a result presented in a number of different values usually result in difficulties when trying to interpret and use the results. Therefore a result presented in a simple number is preferable.

These criteria are found to be a good evaluation for a good circularity metric.

Each of the existing metrics are lacking one or more of these aspects. Learning from this, Linder proposes a new methodology that they find fulfills the criteria of what according to the paper is important for a circularity indicator.

It was found that according to the fore mentioned properties also this new metric had drawbacks. For example, in basing the calculations on value, prizes can change over time, resulting in low reliability.

This is where this thesis begins, by trying to give this new method an even closer connection to circular economy by using a metric found to have a strong correlation to environmental impact and thus nearing the core values of circular economy: saving the environment.

2.5 Limitations

This thesis work is limited to developing a tool suitable for production of physical products. Only contributions of CED from materials, components and processes will be included and all aspects regarding the use phase excluded. Only end-of-life processes that contribute to putting materials, components or products back into production are included. This is done to narrow the scope to be able to deliver a finished, useful part of a tool of an incomplete one.

3
Methodology

In this chapter the method for finding if the suggested method is suitable as a circularity indicator is described.

3.1 Creating a tool

A Circularity Indicator Calculation tool was created with a twofold purpose: to act as a platform for evaluating the method used for calculations and when a satisfactory method had been found, use the tool to analyze products in Swereas' work.

CED was chosen to be the base instead of using monetary value for estimating circularity values because of the following reasons:

- it gives a clearer connection to environmental issues, as explained in section 2.2
- to counteract the influence of price volatility on immature markets — for novel products it is common that early products are priced high, and as the market matures, the prices go down. Another scenario is if the prize is low for a product/part even if its value is high and the the market have not adapted. This means that a calculation done on the same product, using a component from an immature market will get a result that is different from the same calculation made at a later date when the market has matured. The CED of said component is unlikely to change drastically, as this is independent of the market, and dependent only on the physical process of constructing the component.
- it also gives an opportunity to expand the tool at a later state and develop an evaluation framework for including use/operation and post use activities.

The tool was built using Microsoft Excel due to its prevalence in industry. No additional new software installations will be required and many people have experience working in that environment. To make the operation of the tool as simple as possible, building an assembly in CICT follows the same steps as building one 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 assembly. This will require some preparation; making a list of all steps in the production in the order they are carried out. An illustration of the procedure can be seen in figure 3.1.

The tool was constructed of three modules: one that takes care of the calculations, one that contains the data set and one that delivers the data from the dataset to the calculation part.

Figure 3.1: Flowchart of the steps required to calculate a circularity indicator

The following criteria were set for the different parts to be considered complete:

- Calculation: The calculation part should behave intuitively, and should therefore have the following properties:
  - Using recirculated materials and parts with a lower environmental impact (represented by a lower CED) than a virgin counterpart should increase the circularity indicator for the product, and increase it more the smaller the impact is.
  - Addition of any environmental impact (represented by CED) should lower the circularity indicator
- Dataset: If the dataset is difficult to manage fewer new entries will be made. It should require as little restructuring as possible when alterations are made
  - Additions and subtractions from the dataset should be easy to perform and not affect the function or the structure of the dataset
- Data locating: To save time, locating and using the desired data should be easy.
  - Knowing what you are looking for, prior knowledge about the system should not be needed to find it.

Construction of the tool and gathering of data for the accompanying dataset was made simultaneously.

The tool was given the name CICT which is short for Circularity Indicator Calculation Tool.

3.2 Calculations in CICT

The calculation part of CICT was built upon the method developed by Linder, seen in section 2.3, with CED replacing monetary value.

As development of CICT went on the functionality of it was regularly tested using examples that had been calculated manually to see if the tool functioned as expected. As the method was easy to get to work in the tool it functioned as expected. However, during these tests, interesting behaviours brought on by the change to CED were observed. The first one had to do with how the c of a re-part is weighted into the equation:

Assume that sub-assembly A consist of two parts, the recirculated part A and the new part 1. Part A has $c_A = 1$ and $v_A = 10$ and part 1 a $c_1 = 0$ and $v_1 = 2$. The equation for calculating the total c for the sub-assembly A then looks as follows:

$$c_{subA} = c_A \frac{v_A}{v_A + v_1} + c_1 \frac{v_1}{v_A + v_1} = 1 \frac{10}{10+2} + 0 \frac{2}{10+2} = \frac{10}{12} \approx 0,83 \tag{3.1}$$

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 $v_B = 4$ and part 1 $c_1 = 0$ and $v_1 = 2$. The equation for calculating the total c for sub-assembly B will then look as follows:

$$c_{subB} = c_B \frac{v_B}{v_B + v_1} + c_1 \frac{v_1}{v_B + v_1} = 1 \frac{4}{4+2} + 0 \frac{2}{4+2} = \frac{2}{3} \approx 0,66 \tag{3.2}$$

As can be seen from equations (3.1) and (3.2), the better performing alternative get a lower c score.

What this example shows is that given two alternatives of a part, the one with the lower CED and then probably lower environmental impact will receive a circularity indicator that is lower than for a part with higher CED. What this mean is that the better, as in lower CED, a product is, the less impact it will have on the final c-score of the product.

The second behavior observed to be odd 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 $v_1 = 2$ and a recirculated part A with $c_A = 1$ and $v_A = 2$. Adding processing worth 8 and 2 units of work results in the following:

$$\begin{aligned} c_{muchprocessing} = c_A \frac{v_A + v_{muchprocessing}}{(v_A + v_{muchprocessing}) + v_1} + c_1 \frac{v_1}{(v_A + v_{muchprocessing}) + v_1} = \\ 1 \frac{2+8}{(2+8)+2} + 0 \frac{2}{(2+8)+2} = \frac{10}{12} \approx 0,83 \end{aligned} \tag{3.3}$$

and

$$\begin{aligned} c_{littleprocessing} = c_A \frac{v_A + v_{littleprocessing}}{(v_A + v_{littleprocessing}) + v_1} + c_1 \frac{v_1}{(v_A + v_{littleprocessing}) + v_1} = \\ 1 \frac{2+2}{(2+2)+2} + 0 \frac{2}{(2+2)+2} = \frac{2}{3} \approx 0,66 \end{aligned} \tag{3.4}$$

Both these behaviours are counter intuitive, and thus going against the criteria stating that the results should be intuitive, and being the opposite of what should happen if low environmental impact is the goal. This lead to a number of discussions, and from these came two modifications to the method for calculating the circularity indicator. Expressed in words they are:

- The circularity indicator for a product is equal to the amount of CED saved by using a re-part instead of a virgin counterpart divided by the sum of CED from all virgin parts, materials and processes and the energy saved by using re-parts instead of virgin counterparts.
- Processes no longer contribute to the circularity of a product and is treated as a virgin addition with a $c = 0$.

In equation form the modified method looks as follows:

$$c_{tot} = \sum_{i=1}^{n} c_n \frac{(v_{n_{virgin}} - v_{n_{re}})}{v_{tot}} \tag{3.5}$$

$$v_{tot} = \sum_{i=1}^{n} (v_{n_{virgin}} - v_{n_{re}}) \tag{3.6}$$

$$c_n = \begin{cases} 0 & \text{if step is addition of a non-recirculated material, component} \\ & \text{or process} \\ 1 & \text{if step is addition of a non-processed recirculated component} \\ & \text{or material} \\ 0-1 & \text{if step is addition of something the algorithm treats as a} \\ & \text{sub-assembly} \end{cases} \tag{3.7}$$

What these modifications entail for the tool is that whenever a re-part is used, it must be compared against a virgin equivalent, adding a step in the building of the assembly, see figure 3.3 The implementation of the equations in MS Excel was made in a sequential manner that adds each new entry into the total and calculates a total c, see fig 3.2

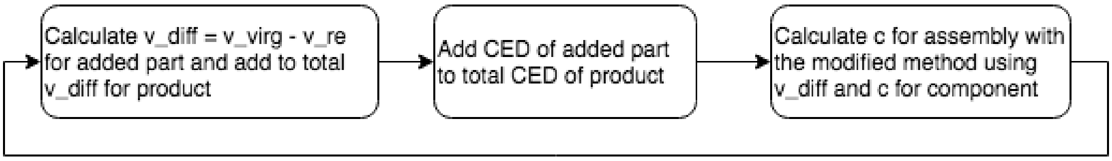


Figure 3.2: The calculation algorithm of the tool.

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 3.5.

3.3 Datasets

Ecoinvent & openLCA

Ecoinvent is a non-profit organization that provides Life Cycle Inventory databases for use in Life Cycle Assessments founded by the Swiss Federal Institute of Technology Zurich (ETH Zurich) and Lausanne (EPF Lausanne), the Paul Scherrer Institute (PSI), the Swiss Federal Laboratories for Materials Science and Technology (Empa), and Agroscope, Institute for Sustainability Sciences.

OpenLCA is a widely used open source software for conducting Life Cycle Assessments.

For the purpose of ease of use and in cases fair comparisons between different products the tool contains a general dataset for common materials and processes for when own data for the used materials and processes are unknown or unwanted (see section 4.3.4 for discussion).

The data for the datasets have been gathered from ecoinvent v3.4 [15] through openLCA 1.7 [16]. The allocation method used is cut-off, which means that the primary production of a material, component or product takes all environmental burden until end of life. This results in that, for example, iron scrap is completely free of any environmental burden. Everything following, such as collection of and treatment of the scrap to convert it to a usable construction material is attributed to the next life cycle. Furthermore, the use of the waste does not give any credit to the primary production, for example reuse in any form or for power production [14]. All but a few of the entries in the dataset base their CED values on a European energy mix. The ones that didn't were chosen to be as geographically close as available in the database.

Using cutoff as the allocation method results in that everything recirculated in any way, be it reuse of a whole product, a reused component or a recycled material, will in its ”raw” form, meaning no processes have been carried out on it, have a CED of 0, as all burden is allocated to the previous use cycle. Logically it will be assigned a $c = 1$, as it is recirculated and have no impact at all. This is why only additions of anything not circulated to the assembly makes c decrease. The reason why cutoff is used 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.

Since the focus of this thesis work is to develop CICT and the method for calculating a circularity indicator, a limited amount of effort went into creation of the dataset. It ended up being composed of a selection of common metals and polymers used in manufacturing and where a few had recycled alternatives. The materials that got alternatives were those that had recycled options in ecoinvent. Concerning processes, all of the material specific ones available from ecoinvent was used, and where no material specific ones were available general processes for each material type were used.

Because of the way that CICT has been built, changing and expanding the dataset is easily done by anyone with a basic understanding of MS Excel, and it is therefore believed that this task can be continued when the thesis is finished.

To enable easy modifications to the dataset it was arranged in a hierarchical manner:

- Activity:
    - Material
    - Process
- Category:
    - Material:
        - Metal
        - Polymer
        - ...
    - Processes:
        - Metal processing
        - Polymer processing
        - ...

- Type:
  - Metal:
    - Aluminium
    - ...
  - ...

Within this hierarchical structure each entry is composed out of four datapoints: Name, CED saved by using re-parts instead of virgin ones, the CED of the entry and its circularity indicator, see table 3.1

Name (unit)	$v_{virg} - v_{re}$	v	c
Example virg (kg)	12	12	0
Example re (pcs)	5	1	0,83

Table 3.1: Format for data in dataset

The idea is that expansion of the dataset can be done little by little over time as need for more data arises. By design, as long as the data follows the format presented in table 3.1,it can easily be incorporated into the dataset. Hopefully, the more the tool is used, the larger and more complete the dataset will become.

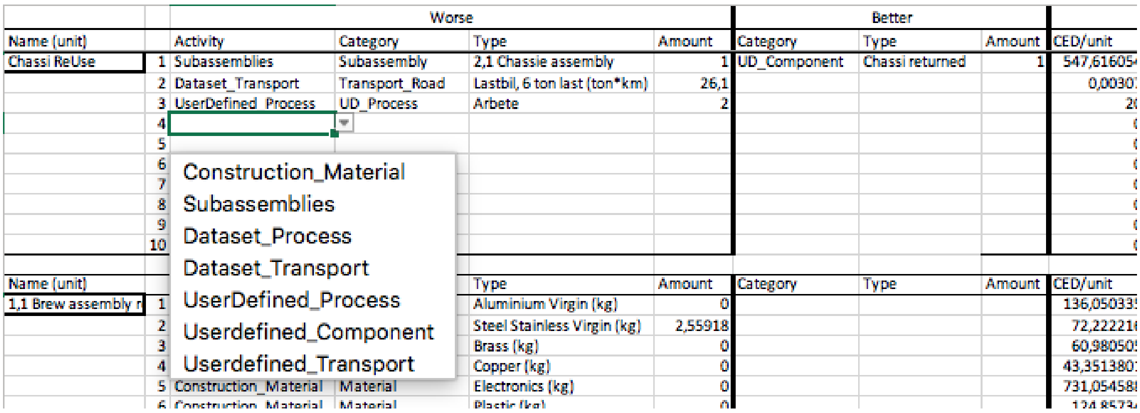
3.4 Data Locating

With a calculation method and a dataset done, the last part needed was a locating system to get the data from the dataset into the calculation. Ideally, a fully searchable dataset would have been preferable, but research showed that such a solution would be very complicated to implement in MS Excel. The second best option was to use the hierarchical structure of the dataset to browse it. It was implemented by using drop down lists to first choose what ”activity”, and based on the choice the second drop down list named ”category” will display the subordinate lists for that activity. In the last drop down list the actual data entry is selected. For example: If the data for ”Aluminium, forging alloy” from the data set is wanted, the procedure would be to first chose ”Dataset Raw Material” as activity, ”Metal” as category and finally ”Aluminium, forging alloy” in type. The corresponding data from the dataset is then put into the calculation. For an image of the acquisition interface, see figure 3.3

3.5 Validation

During the final development of the tool, a validation was made with a twofold purpose, to check if and how the tool works with a complex real life product, and to provide information of the results to the provider of the validation case, one of Swereas industrial partners, 3Temp AB. The product analyzed is their coffee brewer Hipster, see figure 3.4

The Bill of Materials (BOM) received for the case was low in details on materials and weights. It was complemented by an evaluation conducted earlier by Swerea and



		Worse				Better			
Name (unit)		Activity	Category	Type	Amount	Category	Type	Amount	CED/unit
Chassi ReUse	1	Subassemblies	Subassembly	2,1 Chassie assembly	1	UD_Component	Chassi returned	1	547,61605
	2	Dataset_Transport	Transport_Road	Lastbil, 6 ton last (ton*km)	26,1				0,0030
	3	UserDefined_Process	UD_Process	Arbete	2				2
	4								0
	5								0
	6								0
	7								0
	8								0
	9								0
	10								0

Name (unit)				Type	Amount	Category	Type	Amount	CED/unit
1,1 Brew assembly r	1			Aluminium Virgin (kg)	0				136,05033
	2			Steel Stainless Virgin (kg)	2,55918				72,22221
	3			Brass (kg)	0				60,98050
	4			Copper (kg)	0				43,351380
	5	Construction_Material	Material	Electronics (kg)	0				731,05458
	6	Construction_Material	Material	Plastic (kg)	0				124,8573

Figure 3.3: Illustration of data acquisition system and the substitution of a subassembly 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 same structure as the dataset.

they together gave enough information to construct a rough composition in terms of materials and weights.

Given the level of detail, the first task was to assess what materials and their weights the components are constructed from so that the assemblies ended up close to what the the product evaluation stated for individual subassemblies and the complete main assembly.

Due to the uncertainty of the composition, the components were assessed to be constructed from one out of seven different materials. The materials and their composition as well as their CED contributions can be seen in figures 3.5 and 3.6. The total weight of Hipster is 26kg. The chassis of the brewer is the tower into which all other parts are mounted. It is estimated to consist of 2,6 kg aluminium and 2,4 kg stainless steel and thereby representing 19,2% of the weight of the product.

The components were then put into their respective subassembly, where the weights of the different materials were summed up. Each material type was assigned a generic, process, all metals were assigned the same ”metal working” process, to get an estimate of the amount of energy that was used. The weight of all components of the same material was then summed up for that assembly. The reason this was done, and not all component weights just summed up for the whole assembly was to keep the possibility of making changes to specific subassemblies.

Lacking any information regarding transports, it was estimated that the product was transported by truck from Stockholm to the factory in central Europe and back again, 2 times 1666 km.

Many parts in the assembly are surface treated. Due to lack of data this was excluded from the calculation.

For the evaluation five different scenarios were investigated:

1. Reduce the weight of the chassis
   Scenarios 1a and 1b, concerning modification to the chassis, will have no impact on the circularity of the product, but will generate results that is inter-

Figure 3.4: The coffee brewer Hipster (3temp.com, downloaded 20180528)

esting for the company, and are interesting from a CE point of view, which is the base for this thesis.

   (a) Reduce the weight of the chassis components by removing half of the materials in the chassis. This has been tried, but never analyzed in terms of improvements.
   (b) Exchange all steel parts in the chassis for aluminium ones with the same dimensions. This would reduce the weight of the parts by roughly $\frac{2}{3}$ but is not a realistic change to conduct in practice. It is however interesting to see what effects it has on the environmental impacts of the product.

2. Replace virgin steel and aluminium with recycled throughout the product.
   Replacing all virgin materials with recycled ones might be a stretch, but as the reference case for the calculation is rough as it is, is more of a test to see what kind of impact could be anticipated if a large part of the product's materials were exchanged for recycled ones.
3. Treat the chassis assembly as if it were a reused subassembly in an otherwise new product.
   This tests what effect refurbishing a subassembly has on c and CED of the full assembly, in this case the chassis since it is the one the other tests are based on.
4. Remanufacture the whole product, with a few worn components exchanged and a complete refurbishing represented by 20 man-hours of work.
5. Reuse of the whole product, with a few worn components exchanged and a touch up represented by 1 man-hour of work.
   Case 4 and 5 investigates the effects of a potential reuse of the whole product after an extensive refurbish or a lighter restoration. In these cases, the CED for the work put in was deliberately estimated to be very high to be able to include use of energy intensive machines and processes.

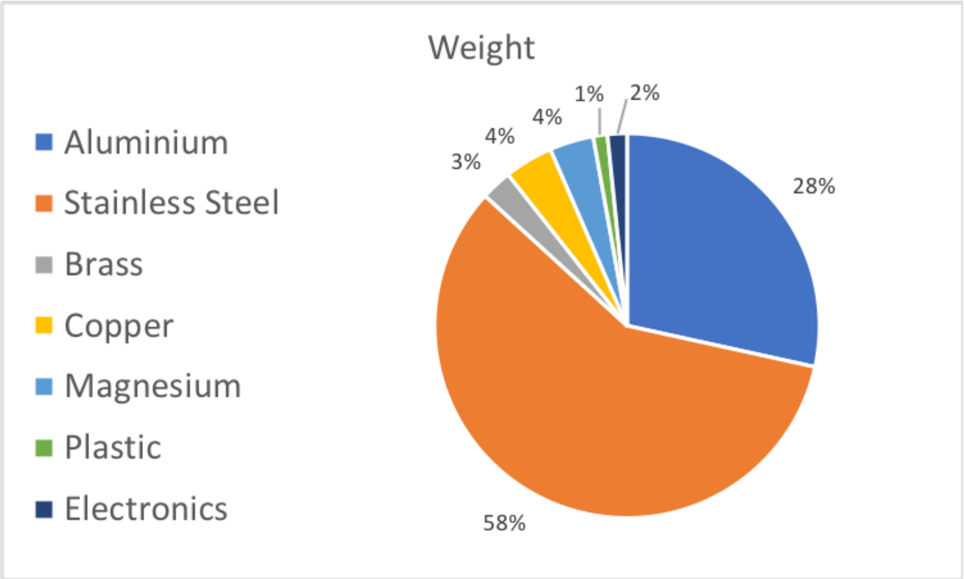


Figure 3.5: The materials Hipster was estimated to be constructed from and their weights

Most of Hipster is constructed from common metals, giving it the property of being highly recyclable, since these metals can be recycled many times with preserved quality. It has also been constructed so that as much of the product as possible can be recirculated by choosing resilient materials and making it modular.

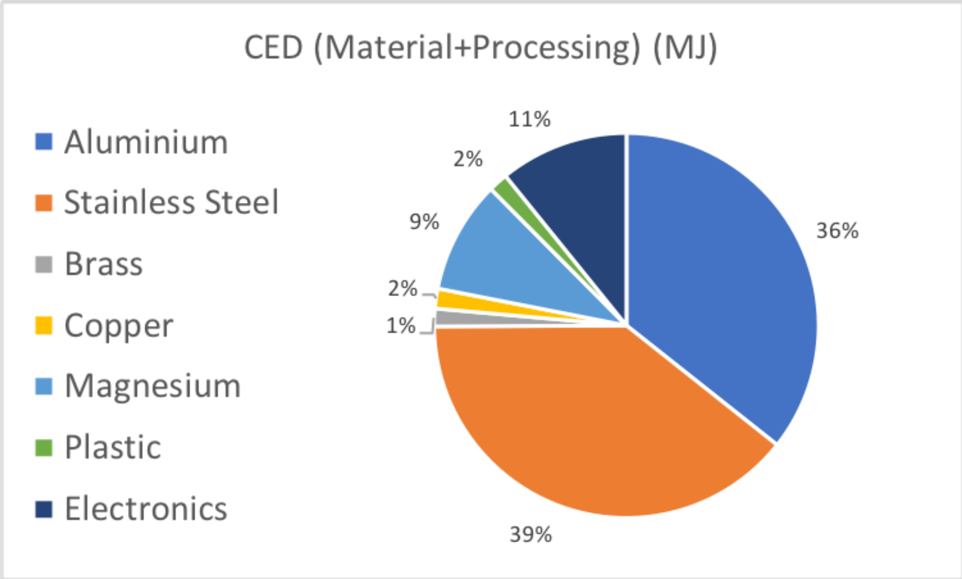


Figure 3.6: The CED contributions from the different materials in Hipster

4

Results & Discussion

In the following section the results from the validations of the tool is presented along with comments and remarks, as well as discussions covering the methodology used for calculating circularity, and the pros and cons of using CED as a metric for the calculations.

4.1 Results

According the tests performed, the tool calculates a circularity indicator correctly using the modified Linder method.

4.2 Results from Validation

The results for the different scenarios are listed in table 4.1.

In scenario 1a, where all chassis parts were assumed to weigh half as much as in the original, the result was exactly what was expected: since half of the material in the chassis was removed, the CED of the chassis was halved. This reduction in CED is what is seen in the total CED for the product: 2721 compared to 2977. c remained 0 as no re-parts were introduced to the assembly.

In scenario 1b, where the idea was that the chassis was lightened by replacing all steel parts with identical ones made from aluminium, gave more interesting results. The parts that were exchanged weighted about $\frac{1}{3}$ of the original steel part, resulting in a relatively small weight reduction, approximately 5% of the total. What is interesting is that although the weight decreased by 5%, the total CED decreased only around 1,5%, from 2977 to 2930 MJ. The explanation is aluminium, although less dense than steel, has twice the CED.

In scenario 2, where aluminium and steel were changed from virgin to recycled, there was a change in c as re-parts now are introduced into the product. The total CED of the product decreased by around 30%, from 2977 to 2048, and $c = 0,425$.

Although a majority of the materials of the product was exchanged for recycled ones, the c is below 0,5. This may seem low as the exchanged material accounts for almost 90% of the total weight. However, this is not at all surprising. As materials are located furthest down in the hierarchy, the raw material itself needs to be processed into a construction material, then processed into a component, which will need processing before the final product is built. Each of these steps have a CED that all will contribute to lower the c. Scoring a 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 analyzed for anyone to get a feeling for what is a ”good” or a ”bad” score.

The third case, where the chassis of the product were recirculated and refurbished gave a reduction of CED down to 2470, which is a reduction of around 17% and $c = 0,181$ In this case, the c behaves as anticipated, as the chassis receives a c of 1, and its $v_{virgin} - v_{re}$ accounts for 18,1 % of v_{tot}

In the fourth case, in which the whole product is refurbished and reused except for a small number of components, $c = 0,86$ and CED = 480. This relatively low c was achieved by a worst case scenario, where the man-hours needed for refurbish were many and CED-wise very expensive. This was countered by the final case were only little time was required for a restoration, and the results instead was a CED of 100 and $c = 0,96$.

Scenario	**CED (MJ)**	**CED decrease (%)**	**Weight decrease (%)**	**c**
0. Reference case	2977	0	0	0
1a. Halve weight of chassis	2721	8,6	9,6	0
1b. Change steel chassis parts for alu	2930	1,6	4,6	0
2. Use only recycled steel and alu	2048	31,2	0	0,425
3. Reuse of refurbished chassis	2470	17,0	0	0,181
4. Remanufacture of product	480	83,9	0	0,86
5. Reuse of product	100	96,6	0	0,96

Table 4.1: Results from validation.

A remark regarding the scenarios concerning decreasing the chassis weight: Even though nothing has been recirculated, the results from both scenarios indicate that, from an environmental point of view, both scenarios are improvements compared to the reference case. In all cases, transports contributed with less than 0,1 MJ of CED. Even though this is a small contribution compared to the CED of the complete product, many products are transported all the time. If all were a little lighter less mass would need transport and therefore less fuel would be required. Even if these changes by themselves don’t make a large difference, it states a position which could make a large difference if employed by all production.

Number 2 is interesting in that it receives a rather high c, but still have a relatively high CED. What this shows is that it under certain circumstances it is possible to have both high circularity and high energy use. This shows that the circularity indicator by itself only states how much of the product is recirculated, not how large environmental impact is has.

3,4 and 5 all deals with recirculating components or the whole product itself, and in these examples it is clear that if recirculation is possible, it is an efficient way of decreasing CED numbers as well as increasing c. As mentioned in section 3.5, the CED of man-hours were estimated to be very high, and due to the fact that it probably is highly excessive, it is likely that scenario 4 and 5 should have even lower CED and higher c.

Looking at this from an ecodesign 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. There is of course a trade-off between over-engineering and reusability. In this case, looking at scenario 4, it would take more than 6 remanufacturing cycles to reach the same CED as required for production of one new product. Also, a large part of the material in the product is either steel or aluminium, used in such a way that it will never be worn out.

Ignoring all practical and economic issues, the best option possible from the cases investigated would be to combine 1a, 2, and 4 or 5, depending on the state of the product. These scenarios decrease the amount of material in the product and using recycled materials, negating the need for extracting new raw materials, and finally, the whole product is reused, preserving the value invested into it.

From seeing improvements in CED and c, it is tempting to draw conclusions like a case that has a higher c value is better, or lower CED is better, and should therefore be implemented. As mentioned in section 2.2, CED values are not perfect indicators for environmental impact, and even if a scenario gets a lower CED than the reference, the processes needed for that change might have impacts not captured by CED and could be environmentally worse. The same argument goes for c. Just because it's recirculated doesn't mean that its better. These are just general indicators. In this case, it is on the contrary believed that all suggested scenarios would have a lesser impact than the reference, based on general knowledge of the materials and associated processes in the product.

From a producer's perspective, the numbers in the table above are alone not worth much. If the changes are too expensive, they won't be implemented. It would be interesting to see how the results compare to each other if they were for example divided by cost of implementation.

Looking at scenario 4 and 5, the c for each of these are high, giving a big contrast to the c of the baseline scenario. Having a product with a long life over multiple use cycles, calculating a c based on only one of those cycles does probably not give a good picture of the circularity of the product over its full life. In such a case, to calculate some kind of average c over all its life cycles might give an interesting result.

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 analyzed through calculations in the future. From figure 3.5 and 3.6 it can be clearly seen that even though some of the materials in the product account for only a small portion of the total weight, they account for an unproportionally large amount of CED, making them possible good places to start making changes.

Looking at the results from the validation, two things among others can be observed: Firstly, recirculating the whole product as in case 4 and 5 results in low CED values and high c, and secondly, the reference case, the current state of the product during its first life cycle, have a high CED and $c = 0$. This might appear a bit skewed, and is a result of using the allocation method cutoff. What this in practice results in is that the life cycle which includes the production of the product takes all the environmental impact while all following only get a fraction of that from the small amount of work needed to refurbish the product. It can be debated whether this is fair or not. A way to make the evaluation fairer could be to in some manner average the c from all life cycles during the products whole life to get results representative for the product instead of just the current life cycle. This would however need a lot of guesswork, trying to estimate the impacts of all life cycles, losing the point of having an objective calculation method combined with the cutoff allocation in the first place. Using another allocation method could possibly resolve this, if each life cycle got allocated a part of production and EoL as well as its own impacts.

4.3 Discussion

Although this tool is an attempt to create a comprehensive way of determining how circular a product is, it is really not a definite method of ensuring that a product is environmentally friendly in any way. To do that, the circularity indicator needs to be combined with other metrics.

4.3.1 Evaluating the modified method using Linders' criteria

In section 2.4 a number of criteria are listed which should be fulfilled for a circularity indicator to be considered good. Using these to evaluate CICT, a number of improvents can be seen if compared to Linders' original method, but also one point that can be seen as a little less desireble:

- Construct validity
  - CICT calculates how much CED is saved by using re-parts compared to virgin ones, and does not calculate the fraction of a product that is recirculated. This modified method is however considered a good indicator of environmental performance as it takes into consideration the actual environmental saving the use of re-parts make, but according to the criteria, CICT fails to fulfill this one.
- Reliability
  - Using CED, which is a more stable metric than monetary value, makes CICT more consistent over time.
- Transparency
  - As CED is scientifically calculated it is therefore relatively easy for an independent party to check the results of a calculation. If a standardization of data for comparison is established in the future, this would be even easier. It would also be possible to check old calculations with current data due to the stability of CED as a metric, whereas price data would need to be collected for the specific time a calculation was first made if value is used.
- Unambiguous methodological principles

  - As CED As CED is scientifically calculated, little room is left for interpretation.
- Generality
  - CED does not discriminate any technology, and can be considered more suitable than value especially where new technologies are used and the market have not yet settled, giving the new technology more weight in the calculation than can be motivated from the environmental impact it has.
- Low dimensionality of result
  - CICT delivers a single figure result ranging from 0 to 1.

Based on these criteria, it is believed that CICT can be considered a good circularity indicator.

4.3.2 CED

As Huijbregts et al. (2010) [11] concludes, there is a strong correlation between CED and environmental impact. However, it is fully possible that a material/component/process requires only small amounts of energy and therefore gets a low CED, but still has a large impact on the environment. Some chemicals can be an example of this. Using such a material/component/process in a product could result in a better c, while being a worse choice from an environmentally point of view than an alternative with larger CED but lower overall environmental impact. Say for example that a re-part can be bought from a country with poor environmental practices, where this re-part is restored to working state using and emitting a chemical that is very cheap to produce and horribly bad for the environment when emitted. This would not be reflected in the c_{tot}, as this only reflects how large a part of the total CED comes from the CED savings from using re-parts. This brings forth the need for using other complementary tools to evaluate the environmental impact of a product.

During a discussion around pros and cons of using the modified method and CED as a base, the question of whether renewable energy and bio-based materials can be considered circular was raised. That question is enough for a thesis of its own, so no effort will be made to supply an answer. However, if that was found to be the case, there are ways in which this can be incorporated into the tool. The first one is that the now merged CED could be separated into its different primary energy sources and then choose to treat some of them as circular. This option would require a fair amount of modification to the tool, but is in no way impossible to implement. It would also require more data for all entries in the dataset, removing some of the simplicity of using a merged CED. Another option is to instead use CO_{2eq} as a base for calculations, which have much of the same properties as CED, and can therefore be directly substituted into the tool.

Then comes the question of what data to use. Say for example that a product is developed to use re-parts from the start, what should these be compared to? There is no virgin part to be substituted. How should this then be calculated? Given that this indicator only is going to be used in-house to compare different options, and data is available for the virgin material that is going to be substituted, all is fine and well, a result will be calculated which can be used for the purpose. If on the other hand, the idea is to use the indicator as a product label, using that same data will not result in a fair comparison. If for example the plan is to get a good score, really bad virgin parts can be chosen as comparison, and what would have been a mediocre improvement with a good virgin part now becomes a fantastic improvement.

One take on this would be to always use dataset values when doing comparisons. That would mean everyone making comparisons to the same data, and comparison between products would be fair(er). However, using dataset values instead of actual ones available makes the indicator less accurate.

It would be possible for a label to dictate what data comparisons must be made against, and such a demand would take away some of the problems of trying to make a product look better by using certain comparisons. This would affect accuracy, but would also work toward transparency. Having the comparison data predetermined and using the scientifically determined CED as a base for the calculations have the possibility of making a label verifiable by a third party. If details concerning the production could be supplied confidentially to for example an institute responsible for the label, the results could be verified and thus resulting in a trustworthy label, given that the data supplied are correct. Such a label could also help in spreading the indicator, by ensuring that that the circularity is in fact verified. Naturally, that kind of verification would need to be financed somehow, and that would likely fall on the users of the label. This makes it difficult to get the label started, since without a reputation that a good score from the label is desirable no one will spend the resources to have their product labeled, and with no labels produced, it will have no spread, and thus no reputation.

Due to the fact that one one the main goals of this thesis work is to produce a method that is easy to grasp, aggregating all sub-categories of primary energy into one metric results in a simple one figure result. Put into the context of concept stage in product development, the loss of accuracy is considered an acceptable trade-off as most of the input data at such a stage probably is rough. It is possible to use all the sub-categories of CED in the tool to a certain extent if desired. The final CED count of the product could be divided into sub-categories for example. The tricky part comes if one would want to use the different sub-categories for the calculations. It would then be possible to calculate different c-values for the different categories. That raises the question of how for example interpret how high circularity for oil-based energy compares to low circularity for nuclear-based energy, which takes away some om the objective qualities of the method.

4.3.3 Linders method

One aspect Linder puts emphasis on in his paper is that his model is intended to be used for calculation of a circularity indicator, and that alone since there are a multitude of other metrics for measuring other aspects of a products performance in areas other than circularity. Even though modifications has been made to Linder's method, the same argument still holds.

One practical effect of this change is that more calculations will be required to reach a result. For example, for every recycled material used, a virgin variant of every part to contain that material need to be created to act as a comparison.

This should not be seen as that much of a downside. When using this method of calculating a circularity indicator, the number of the entries used is likely to be so large that doing it by hand will be out of the question, and with a bit of programming the increased number of steps is a non-issue.

During a meeting with Linder the modified tool was presented along with a number of simple calculated examples of a bicycle: Direct reuse, reuse with exchange of a few components, reuse and refurbish, construction of a new bike out of recycled materials. After looking at the results, Linder said that from calculations done on similar cases using the original method, the results were in the same ballpark. This felt reassuring as very deviating results using two similar method could have suggested that something was awry. If sufficiently detailed information had been available, a comparison between the two methods could have been carried out using the validation case. This would have given an opportunity to study the effects of the modifications in detail and add another layer to the validation, but that will have to be part of future further development.

4.3.3.1 Re-materials Weighed the Same as Re-components

One key aspect of circular economy is that different loop tightnesses are valued differently: reuse of a complete product is valued higher than for example reuse of its components which in turn is valued higher than if the materials it was constructed out of were recycled. In the model, this is indirectly considered. Example:

If a product can be reused with only a small amount of work done to it, the difference $v_{virgin} - v_{reuse}$ will be large, and the work will only sum up to a small fraction of that, giving the product ready for reuse a very high c, close to 1. With reused components a larger amount of work must be added to them before they again will comprise a usable product, resulting in a c that is lower than for the completely reused product, even if it is entirely built of reused components. The same argument holds for recycled materials: these will need much work to be transformed into components before these in turn can make a final assembly, thereby a proportionally larger part of the CED will be made up of processes with $c = 0$, giving it a lower c_{tot}, even if the whole final assembly would be constructed entirely out of recycled materials. If you in the future want to encourage tighter loops, a weighting system could be introduced that somehow rewards tighter loops, giving them larger impact on c_{tot}. This however introduces values into the tool, and opinions may differ on how this should be done and by whom.

4.3.3.2 Other considerations

This section discusses other characteristics of the methods for calculating a circularity indicator. These do fall outside of the scope of the current tool, but are still of interest from a circular economy point of view.

No consideration to End of Life

So far only questions regarding what goes into a product have been addressed, but from a circular economy point of view, the model also has issues with how this is done. An example: A product is made entirely out of recycled material, but in such a way that when the product has reached its end of life, nothing from it can be salvaged, recirculated or recycled. It will receive a perfect c, but end up as landfill. Now instead picture a product constructed from only virgin material, thus getting a c equal to zero. However, it is designed in a way that will let every component be recirculated once its end of life is reached. This would be considered more important from a circular economy point of view, but not be reflected in the circularity indicator.

One idea that has come up during discussions is that together with the calculation of the indicator, there could also be a number of questions added to some part of the build of the product in the tool. These questions could be of the nature: is this part designed for easy disassemble, is this part designed for reuse, is this part easily recirculated etc. To these questions a scalar could be attached, making a part or product score better if the questions are answered positively.

Length of life

Another point when it comes to how products are put together, and this is something Linder brings up in the paper, is that no regard is taken to the lifespan of a product. If a recycled material or a recirculated component reduces the lifespan of the product to half that a product made from virgin material would have, is it fair to give the short-lived product a better c?

A feature that takes care of this issue could most likely be built into the model, and one possible way of mitigating this is to create an index that instead of calculating only a circularity indicator instead/also calculates an indicator showing circularity per functional unit. This way, more aspects of using the re-parts would be taken into consideration when calculating c

This expanded indicator is however not the main purpose of CICT, and is therefore not going to be investigated within this thesis work.

4.3.4 Dataset

In theory, there is no limit to how large assemblies in CICT can be made. In practice though, with too many levels of subassemblies, it will become difficult to work with. The real limiting factor is the dataset that the tool uses. If the user doesn't know all data for every material and process used in an assembly, data from the dataset will need to be relied on. If the set is lacking the needed entries, no calculation can be made.

As with all data of this sort, there will be issues with either the accuracy of the data, or how general it is, as these attributes tend to depend on each other. On one hand, accuracy of the entries in the dataset will grant indicator values more accurate, but for the data to become that much more accurate, the specificity of it also need to increase, and as a result the data will be applicable to a narrower range of users. This does not necessarily cause issues, but will most likely make the correct entry harder to find as the dataset will need to be more extensive to be able to supply the same amount of producers, and will definitely result in additional work to create such an extended dataset.

Depending on what the final goal of the use of CICT is, different guidelines for what data to use might need to be implemented. Take for example the scenario of CICT being used in-house for the sole purpose of comparing different construction options against each other. In this case, using product specific detailed data is obviously best, as this gives the highest amount of accuracy.

If instead the use of CICT is for the purpose of conveying the circularity indicator of a product to others, as for example a labeling on a product, the way of calculating c must be standardized in order to have any validity. This would mean using dataset values for comparisons.

A perhaps cynical example of why this would be necessary is that if the comparisons are made with product specific data, this data can be chosen so that it is the worst data available, compared to which all alternatives generate high circularity indicators, meaning the product can be advertised as well performing although it is not. If the scenario instead is turned the other way around, a company might have put in large resources into finding a really well performing virgin material, and upon transitioning to a recirculated alternative only get a small difference between the two giving a small c, even though the circular performance in absolute terms is very good. Based on this, a fair comparison between the two products is not possible. If the reference remain the same for all, as in using the dataset for calculating the differences, such a comparison between products would be fair.

In using a cut-off approach when calculating CED for the entries in the data set, entering product specific recirculated entries becomes easy as they by definition get designated CED $= 0$, and therefore $c = 1$. If other methods of allocation is chosen, calculating how much CED that should be allocated to that specific entry needs to be done before it can be entered into the tool. A change of allocation method will affect the result, the circularity indicator, for any given product if the procedure of constructing it remains the same, however as long as the properties of the data reflects that the better an entry performs the lower its value, the method for calculating the indicator remain correct. Because of this, data sets that have this property are exchangeable with retained function of the tool. This way, if the need should arise another dataset better fitting the purpose can be chosen without having to make any changes to the tool itself.

The use of data from ecoinvent requires that a method of allocation need to be chosen. For this thesis cutoff was chosen, meaning that every time a re-part is recirculated, its impact is "reset" to 0. This makes the calculations very clean, in the sense that it is only the later added non circulated activities that add to the total CED of the assembly. This also mean that nothing that happens before or after the current life cycle affects the CED of the re-part, which could be very beneficial since a producer won't need any specific information about earlier life cycles or make assumptions about future ones. Another effect is that what happens in the current life cycle won't have an effect on previous ones, meaning that they won't have to be recalculated with new results after re-parts have been used in a later life cycle.

Just because this method of allocation was chosen doesn't mean that it is the only possible one. Any metric that behaves in the same way, i.e. becomes lower the more circular the re-part is can be used with the new modified method. As cutoff results in re-parts having a CED of 0 when recirculated the difference between a virgin counterpart and the re-part will be as large as it possibly can (without a re-part having negative CED numbers, which could be the case when using some allocation methods), which will result in a larger part of v_{tot} consisting of re-parts, and therefore giving higher c numbers than any other metric where some CED remains through a recirculation. The effect of switching to another method of allocation would therefore result in the following, compared to cutoff:

- Total CED for any assembly containing re-parts would be higher
- v_{tot} for any assembly containing re-parts would be lower, and as a direct effect of this
- c_{tot} would be lower.

If the results from using CICT is going to be used for anything other than perhaps comparing concept alternatives among a small group of involved people, it is important to convey what data was used and what limitations and assumptions were made to generate the results. Without such knowledge, the numbers are more or less worthless.

5

Conclusion

The idea of using Linder's [12] method 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 the purpose as mentioned in section 3.2. For the indicator to more closely represent how circular a product is, a number of 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 by giving recirculated parts too much weight in the weighting.
- 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. This way, well performing recirculated additions with low CED will be weighted higher than worse performing ones.

With a method that gives a better representation of circularity, building a tool using this method to calculate a circularity indicator was a small task.

Currently, the limiting factor of the tool is the scope of the thesis. The tool can easily be expanded to handle more aspects of a products life cycle. This will likely be done by Swerea in the future.

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.

5.1 Further development

The next logical step after having developed a working tool for calculating a circularity index for the production stages of a products' life is to expand the tool to also include the use phase and end of life aspects to get a circularity indicator that covers the whole life span of the product. As the tool is aimed at products in the concept stage, it might be a good idea to implement prospective elements into the tool, meaning that it is estimated what technologies will be available when the product reaches production, and the analyses uses the data from these estimations to get a better understanding of the impacts at the actual time for production, see Arvidsson et al. (2017) [1]

Possible future use for this indicator is for example as a product labeling, which could let people make more informed decisions before purchase. This would require rules to make sure that comparisons between different products can be made in a fair manner, but it is considered a real possibility.

For this indicator to become a viable method for comparing different products against each other, an expansion of the dataset will need to be made to make it large and diverse enough for a multitude of products to use it as a source of data.

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