Reduced Transport Volume: Creating a CO_2 Optimisation Model for Reusable Packaging

Lucas Roos zich noemende en schrijvende Lindgreen
S2399431 - 4456025

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Universiteit Leiden

Abstract

In current LCA studies, the environmental footprint of transport processes is calculated using the weight of the product and the distance travelled. This cannot be considered accurate for returnable packagings that reduce in volume when empty. The weight of the freight as well as the number of trips needed varies and is not taken into account in that calculation. In this research an Excel tool is developed based on an existing CO_2 calculation tool created by Partners for Innovation where reduction in volume is taken into account for the environmental calculation of the transportation processes. A factor of reduction of volume is created, which describes to what extent the packaging nests or folds when empty. Next, a calculation is performed that states whether and how many extra trips are needed because of inefficient stacking, or how many trips are saved because of efficient stacking. All of the aforementioned data is used to create a final factor which is in turn multiplied by the amount of ton kilometre in the original calculation. Applying data of fictitious scenarios to the tool shows that the new calculation gives a more precise result regarding CO_2 emissions. Furthermore, it shows that nesting of packagings makes a significant positive impact on the CO_2 emission as it reduces the number of trips needed to transport the packagings. Lastly, a real-life scenario validates the applicability of the tool in a real situation.

Summary

Introduction

Transportation of goods is a large contributor to the global environmental pollution problem. The popularity of product-service systems is growing, further increasing the need for logistics and transportation. An interesting solution to this problem lies with the concept of *reusability*. If reusability is incorporated into a large-scale system, its results to the environment can be of great proportion. Incorporating smarter logistical systems will reduce the total greenhouse gas emissions, especially when optimised.
Several parts of the supply chain of reusable packaging have the potential to be optimised regarding *volume*: when empty, it would be ideal if the packaging could become more compact, for example by folding it into a smaller size or to nest multiple packagings. That way, fewer trips are needed and more time and CO_2 emissions are saved.
In this study, a model is created that simplifies the calculation and makes it easy to adjust the volume to get the accompanying results on the environmental sustainability of the product.

The CO_2 calculation tool by Partners for Innovation is used as an example to optimise volume within the transport phase for reusable packaging that becomes more compact when empty. The research described in this thesis will be performed in collaboration with Cabka, a secondary and tertiary packaging company based in Berlin, Germany.

In this report, the following research question is answered:

> *How can physical volume be optimally included in the environmental calculation of a returnable packaging that becomes more compact when empty?*

Literature study

Background reports in Ecoinvent processes show that tonkm (ton multiplied by kilometre) is the standard unit used to measure transportation in an LCA. More noteworthy is the GVW (gross vehicle weight) which describes the total weight of the truck including everything that the truck carries. Furthermore, the AFL (average freight load) is used to make an estimation on the weight of the freight that is averagely carried. The ACUF (average capacity utilization factor) of ALF (average load factor) describes to what extent the truck is filled on average. This includes empty trips.

The transport process in LCA studies is virtually always quantified in tonkm or a variation that also describes weight multiplied by distance. This is unsurprising for LCA studies, as it is also the parameter used in the most common LCA databases. Furthermore, logically the level of detail varies per study. In some cases the environmental impact of the transport process is so small compared to the other processes that it is decided not to focus on it. However, in the case of returnable or reusable products a more in-depth analysis of the transport process is usually performed. In such cases, weight is used as a parameter to quantify the environmental footprint of the transportation processes.

Analysis of the original CO_2 calculation tool

The Partners for Innovation (PfI) CO_2 calculation tool is most suitable to be used as a rough indicator on the environmental sustainability of a reusable packaging compared to a single-use alternative. The inputs that are shown in a structured way, as well as the outputs that clearly show the result in a table and graph, make the tool appropriate for a quick sustainability indicator. However, the tool cannot be used as a substitute for a full LCA. The tool does give a clear result of the CO_2 emissions, but no impact assessment is performed. Moreover, *only* CO_2 and cost are given as a result, and a significant number of assumptions are made from the beginning, meaning that the final result cannot be as accurate as a full LCA.

The input parameters are listed in a clear way, categorized per life-cycle step and clearly explained so that the user knows what they are. The output parameters are clear as well, and are shown in numbers as well as graphs, making the result of the analysis performed in this tool clear for the user.
All of the calculations in the tool are done within Excel, using a relatively simple method of calculating. Usability and clarity are key aspects of the tool and make it usable for clients relatively unfamiliar with the extensive LCA process.

A tool for change in volume

The new CO_2 calculation tool that is created functions as an extension on the original tool by Partners for Innovation. It has the same function as the original tool: give a quick overview of the carbon footprint of a reusable packaging and make a comparison with a single-use alternative. The new tool is designed to make the input- and output parameters as clear as possible, and to fit the aesthetic of the original tool.
An additional calculation is set up so that takes into account the reduction of volume of a primary packaging and converts it to mass to fit the original calculation as well as any data taken from LCI databases. To do so, V_1 is set up. V_1 describes the surrounding volume of a primary packaging, and is calculated by multiplying the largest value in all three dimensions.
Efficiency factors are used to calculate to what extent the packagings reduce in volume when transported. Two efficiency factors are used; one to calculate the efficiency of the primary packagings within the secondary packaging, and one to calculate the efficiency of the secondary packagings within the truck. Using this information, a number of trips saved or extra trips needed is given. A weight factor describing how heavy the load is compared to the weight of the truck is given to determine how impactful an extra trip is.
Two final factors are set up to connect the volume calculation with the original calculation that uses tonkm:

When trips are saved:

$$\varphi f1 = \frac{\varphi t}{(ts + 1) * wf}$$

When extra trips are needed:

$$\varphi f2 = \varphi t * (tn + 1) * wf$$

φ_{f1} or φ_{f2} = the final factor used in the calculation
φ_t = the two efficiency factors multiplied
ts = the amount of trips saved
tn = the amount of extra trips needed
wf = the weight factor.

Simplicity and usability are key properties of the new tool. To enhance these aspects, the layout of the new tool as well as its explanation of every parameter are made as clearly as possible.

Several examples of logistical systems show that optimisation of volume reduction would make a significant impact on a logistical system. There is usually one or more transportation steps in which the products are nested and therefore in that case the new CO_2 calculation tool will give a more precise result.

Applying case studies using real and fictitious scenarios

When applying several scenarios to both the original CO_2 calculation tool and the new CO_2 calculation tool, it can be seen that the new tool gives a more precise result regarding CO_2 emissions. By also taking into account the level of efficiency in which the packagings are stacked, the number of trips that are either saved or needed in the transport step, and the importance of the weight of the freight compared to the weight of the truck, it is found that the transportation of products that are nested emit significantly less CO_2 than when they are not nested.

By constantly adjusting the value for 'number of units within a box' in the tool, it is found that several tipping points appear for the final factor. It is, however, unlikely that the suboptimal point will occur in a real life situation, because the client or logistical company will have already optimised this step.
When a trip is considered inefficient, meaning that one or more extra trips are needed, the exact number of units within a box becomes irrelevant. The reason for this is that it appears in two parts of the calculation of the final factor; once in the numerator of a division and once in the numerator of the division. Because the divisions are multiplied in this calculation, the parameter for 'number of units' is cancelled out.
Applying an existing scenario to the tool shows that the tool can be used in practice and will show a realistic result in the CO_2 calculation. It is found that the tool states that some of the transport steps could be optimised. However, the existing scenario showed that optimisation is not possible for reasons that fall outside of the scope of this research.

Conclusion

Physical volume can be incorporated in the environmental calculation of a reusable product by defining a factor that describes its reduction in volume when empty. This factor can be multiplied with the already existing calculation for tonkm. The new calculation is considered more accurate as more parameters are taken into account.
The newly developed CO_2 calculation tool shows a new way of incorporating volume in an environmental calculation of a packaging. Although the study is not a substitute for a full LCA, the calculations used in this study can be used as a building block for future studies in the same field.

Glossary

Allocation – a method of deciding how to assign the value of flows within an MFP (see 'MFP').

Average capacity utilization factor (ACUF) – the amount of space that is used on average in the total process of transportation.

Average freight load (AFL) – the average weight of a load of a truck or any other means of transportation.

Break-even point –the point on the x-axis in a graph where two plots have the same value on the y-axis.

Change in Volume (∂V) – the amount that a packaging reduces in volume when empty.

Efficient – In this report, efficient refers to volume; to what extent a packaging reduces in volume when empty.

Efficiency factor (Fi or φ) – the degree of efficiency of volume at which a product is stored within a box during transport or storage.

GVW (Gross vehicle weight) - the total weight of a transporting truck including the weight of the truck itself, the freight, the gasoline, and every other factor with the exclusion of trailers.

KIDV Calculation tool for CO2 impact of reusable packaging – a CO_2 calculation tool developed by PfI (see 'PfI') used to estimate the environmental sustainability of a reusable product.

LCA (life-cycle assessment) – A method of calculating the environmental footprint of a product or service by looking at its entire life-cycle.

LCI (life-cycle inventory) – The stage in the LCA (see 'LCA') process where an inventory of the input- and output flows is created.

MFP (multifunctional process)– A process in the life-cycle of a product with either:
- Multiple good outflows
- Multiple waste inflows
- A waste inflow and a good outflow

For an MFP, allocation is needed (see 'allocation')

Nesting – For a product to fit into other products of the same shape so that they don't use up as much space during transportation or storage.

PEF (product environmental footprint) – a database that simplifies calculations needed to perform an allocation (see 'allocation').

PfI (Partners for Innovation)– An independent sustainability-oriented consultancy firm.

Primary packaging – a packaging containing a product or food item.

PSS (product-service system) – A system in which a product is combined with a service to satisfy the customers' needs.

Return rate – the amount of times that a reusable product is returned to from the user back to the supplier.

Secondary packaging – a packaging that contains one or more primary packagings, for example a box or a crate.

Tertiary packaging – A packaging that contains one or more secondary packagings, for example a pallet.

Tolerance – Range of measurements of a product in between which it functions properly.

Tonkm (ton kilometre) - a unit used to quantify the transport phase of a life cycle assessment (LCA) (see 'LCA'). It is defined by the distance travelled multiplied by the weight of the product.

Overview of parameters used in calculations created in this report

V_1 – the smallest rectangular volume surrounding a packaging with a non-rectangular shape.

V_2 – The inner volume of the secondary packaging in which the primary packagings are carried

V_t – The inter volume of the truck in which the secondary packagings are carried.

Units – The number of primary packagings that is carried during a transport step.

U_{box} – The amount of secondary packagings that is carried during a transport step.

φ_1 – The first efficiency factor, describing to what extent the primary packagings reduce in volume when empty.

φ_2 – The second efficiency factor, describing to what extent the secondary packagings fit in the truck or any other means of transportation.

φ_t – the total efficiency factor, describing to what extent the primary packagings fit in the truck or any other means of transportation.

Extra trips needed (tn) – The number of extra trips needed because the primary packagings are not stacked efficiently.

Trips saved (ts) – The number of trips that is saved because the products are stacked efficiently.

Final factor (φ_f) – The factor that is used to multiply the volume calculation with the weight calculation. It describes to what extent the CO_2 level is reduced or increased because of the change in volume.

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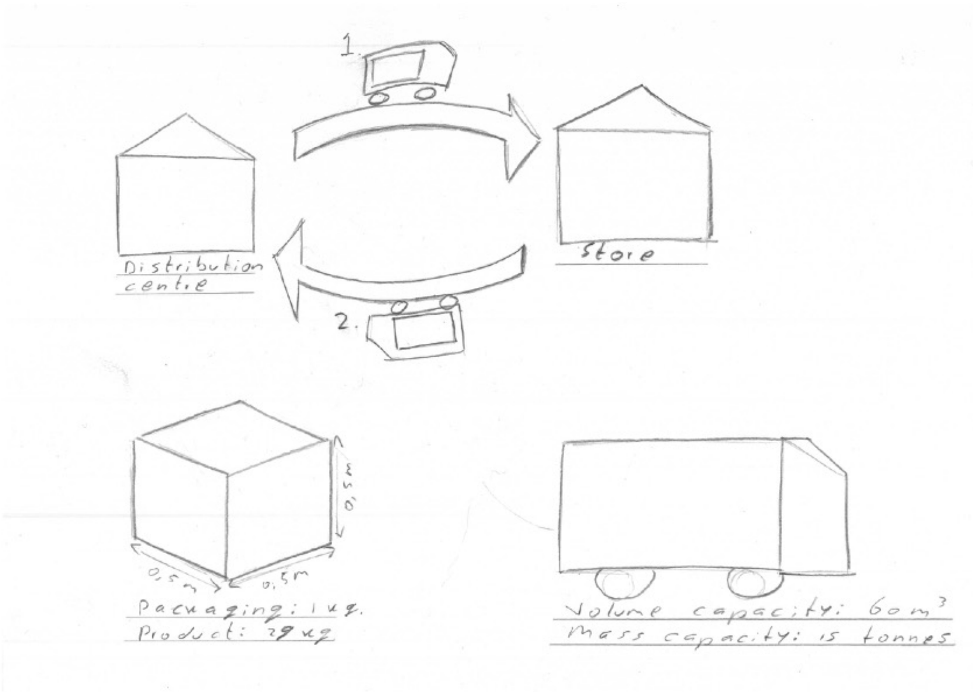
1. Introduction

1.1. Problem description

The concept of transportation is of high importance regarding sustainability. Transportation of goods is a large contributor to the global environmental pollution problem and there are no signs that this will be slowing down any time soon; according to the Environmental protection agency (EPA) (2022) in 2019, transportation alone took up 29% of the total global greenhouse emissions, and Statista (2022) shows that 33% of this comes from shipping and trucks. The ever-growing demand for delivery, mostly of single-use products and food, is a large contributor to this (Alfonso et al., 2021). According to Alfonso et al., the E-commerce sector has grown since the corona pandemic of 2020, -21, and -22, and will continue to grow. Furthermore, according to Lee et al. (2018) the popularity of product-service systems is growing, further increasing the need for logistics and transportation.

The aforementioned examples show that transportation is detrimental to the environment, and needs to be optimised in order to stop it from growing into a global disaster. An interesting solution to mitigate environmental problems lies with the concept of *reusability*. If reusability is incorporated into a large-scale system, its results to the environment can be of great proportion (Coelho, 2020). Furthermore, if consumers are more likely to reuse the packaging that they bought, this will extend its lifespan and therefore result in less packaging waste (Coelho et al., 2020) (Zimmermann, 2020).
However, reuse of packaging usually requires a more complex system including a reverse supply chain, additional transport, and usually a cleaning process (Dekker, van der Laan, 2003). If that is the case, it becomes increasingly more difficult to claim that the reuse system is indeed more sustainable. However, incorporating smarter logistical systems can still reduce the total greenhouse gas emissions, especially when optimised.
Several parts of the supply chain of reusable packaging have the potential to be optimised regarding *volume*: when empty, it would be ideal if the packaging could become more compact, for example by folding it into a smaller size or to nest multiple packagings (Antala, 2020). That way, fewer trips are needed and more time and CO_2 emissions are saved.

A prominent method to assess the environmental sustainability of such a product is life-cycle assessment (LCA) (Guinée et al., 2002). However, LCA does not take into account *volume* within the transport phase, but only the weight of the product and distance travelled (Valsasina et al., 2016). In some cases, the volume of a packaging changes when it is empty, and therefore the data in different transport processes should be altered to get the most realistic result.
An example of this is shown in figure 1.



Packagings:	
Weight when filled:	30 kg.
Weight when empty:	1 kg.
Measurements:	0,5 x 0,5 x 0,5m (0,125 m^3).

Truck:	
Mass capacity:	15.000 kg.
Volume capacity:	60 m^3

Figure 1: example of a logistical system that shows how reduction in volume saves trips.

In figure 1 a simplified example is shown. Here, 30.000 packagings filled with a product must be transported from the distribution centre to the store. The mass capacity of the truck is reached at 500 packagings. However, 480 packagings fit in the truck. Therefore, this is the amount that is transported each trip for step 1. This takes 21 trips (10.000/480, rounded up). On the way back, however, the packagings are empty and many more packagings can fit in the truck before the mass capacity is reached: 15.000/1 = 15.000 packagings. However, this is not possible because the volume capacity is already reached at 480 packagings. This can be solved by folding the packagings:

Packagings:	
Measurements when folded:	0,5 x 0,5 x 0,1m (0,025 m^3).

Now, the volume capacity is reached at 2.400 packagings (600/0,025). This time the truck in transport step 2 only needs to drive 5 times instead of 21.
By reducing volume the logistical system is optimised and CO_2 emissions are reduced.

Although possible, adjusting the volume of the product within one LCA will make the calculation significantly more complicated.
The main objective of this study is to create a *model* that simplifies the calculation and makes it easy to adjust the volume to get the accompanying results on the environmental sustainability of the product.

Currently, a simplified LCA tool specifically for reusable products is developed by Partners for Innovation (PfI) (Nelissen, personal interview, 2021). With this tool, the parameters with regard to reusability (for example the life span or trip rate) can be easily adjusted, and the effect it has on the total CO_2 footprint can be viewed. This tool is used as an example to optimise volume within the transport phase for reusable packaging that becomes more compact when empty.

The research described in this thesis will be performed in collaboration with Cabka (Cabka, 2022), a secondary and tertiary packaging company based in Berlin, Germany. They produce and rent out pallets and containers, most of which can be reduced in volume during empty transport and storage; the pallets are nestable, and the containers can be taken apart and folded into itself (figure 2). Cabka is a company that strongly believes that reusability plays a big role in improving the environment. They want to show the world that circularity is key to a more sustainable future (Cabka, 2022).

Figure 2: two products produced by Cabka: a nestable pallet (left) and a foldable container (right).

1.2. Research questions

In this research, the following research questions will be answered:

> *How can physical volume be included in the environmental calculation of a returnable packaging that becomes more compact when empty?*

To answer this research questions, 6 sub-questions are set up:

1.1 How is transport modelled and quantified in Ecoinvent?
1.2 How is transport currently modelled in LCA studies?

2.1 How does the CO_2 calculation tool by Partners for Innovation measure and show the environmental footprint of a product?
2.2 What are the limits of this tool?

3.1 How can the calculation of volume within the transport phase be optimised for reusable products that become more compact when empty?

4.1 When applying different scenarios to the new CO_2 calculation tool, what does the difference in outcome with the original tool signify?

In the following paragraph it is explained how the research questions are answered to draw a definitive conclusion.

1.3. Methodology

In order to answer the aforementioned research questions, the following setup is used. First, several background processes of the Ecoinvent LCI database are analysed to determine the way of quantifying the environmental footprint of transportation processes. Furthermore, a qualitative desk research is conducted to understand current LCA methods, and if/how change in volume is incorporated in the transport process. The found articles are then ranked in relevance, and a conclusion is drawn. This step will serve as a way to better understand the current way of calculating the environmental footprint of transportation, and will serve as a building block for the following research questions.
Next, the original tool developed by Partners for Innovation is analysed. All of the inputs that the user can add in the tool, the calculations that will then occur, and the outputs that the tool will give as a result are listed and explained. All of the processes that are listed in the tool are substantiated with flowcharts. Next, the main purpose of the tool is clearly defined. This helps give a better understanding of the thought process behind it, as well as the main reason why the user would use this tool. Finally, the limitations and assumptions of the original tool are listed which will give a clear view on where the tool could still be improved.
Next, a new tool is developed in addition to the aforementioned original one. The purpose of this new tool is to incorporate possible reduction in volume during transportation in the environmental calculation. A calculation is set up to achieve this, and the original tool is looked at as an example for both the calculations and the layout. The calculation is created by analysing the original tool and calculations, and theorizing how volume could be included. This is an iterative process of trial and error.
Finally, the tool that was created in the previous chapter is applied to several scenarios. First, several different fictitious scenarios are set up and applied to the tool in order to validate if the calculations are correct. Furthermore, in this step the calculations are closely analysed and checked if any irregularities occur. In doing so, the validity of the calculations of the new tool is more certified and the chances of errors and mistakes are minimized. Using the data from these scenarios, a sensitivity analysis is performed. This will highlight which input parameters are most important for the final CO_2 emissions.
Next, the scenario of a product of Cabka is applied to the new tool. This step has the same goal as the previous one, with the additional purpose of showing how the tool will be used in an existing scenario; by including this step, a more realistic view of the tool is obtained.
Finally, in collaboration with Cabka a user test is conducted, and the usability of the new tool is analysed. In this step, the layout, the clarity of the parameters, and the clarity of the calculation are focused on.

1.4. Knowledge gap

A knowledge gap within the field is found by performing a literature study of articles with similar topics. In doing so, it is proven that the subject discussed in this report is indeed unexplored to an extent where the report will contribute an original research that will add newly found results to the general academia of the field.

It is already clear that reusability has potential to improve the environment. According to Coelho et al. (2020) reusing products reduces the environmental footprint of said product significantly, as it lowers the need for virgin material. Coelho et al. show the potential of reusing packaging and discuss multiple aspects, such as the supply chain (including reverse logistics), marketing, and consumer behaviour. Reusability of packaging as described by Coelho et al. is possibly an important part of the solution to the global plastic waste problem (Chow et al., 2017) (Coelho et al., 2020). Furthermore, Hekkert et al. (1999) state that a large-scale adaptation of reusability with regard to plastic packaging would, although difficult, significantly lower the amount of carbon dioxide that is emitted into the atmosphere.
Despite reducing plastic production and waste, reusable packaging also comes with a downside. Katephap et al. (2017) state that reusable packaging requires a more complex logistical model. Furthermore, Liu et al. (2020) state that the additional impact that reverse logistics brings is still significant. As a solution, Liu et al. suggest combining reusable and disposable (secondary) packaging to balance out the extra impact.
A possible solution lies in compactly storing empty containers during transport. According to Mahmoudi et al. (2020) the amount of packagings that can be transported at once, as well as the storage for empty containers can greatly affect the environmental sustainability and cost of the packaging. This shows that the reduction of volume for empty packaging does have the potential to reduce environmental harm for reusable packaging.

These examples show that volume can make a significant difference during transportation, it is important to quantify it using LCA. Kočí (2019) mentions that the distinction between weight and volume is an important one within the transport process in an LCA. They state that if volume is used as a functional unit, the outcome may differ significantly relative to using weight. Kočí (2019) does not mention reusable packaging. However, Mahmoudi et al. (2020) made clear that transporting empty packaging is a big part of the logistical system of returnable packaging. These two studies (Koči, 2019) (Mahmoudi, 2020) show that incorporating *volume* in the transport process of an LCA of reusable packaging is of great importance. However, within the currently existing literature, it is not yet clearly stated how this variable can be optimised within the LCA process.

Within the aforementioned papers, no documentation on change of volume during the transport phase within an LCA of reusable packaging was found. Several existing LCA studies were found that touch upon the issue, but do not use a change of volume in their calculation, meaning that this is indeed a relevant knowledge gap within the field of LCA.
When performing this literature study, no articles that state a solution to the knowledge gap are found. The only relevant articles in this case address the situation, but either skim over the problem or mention that this is indeed a knowledge gap.

1.5. Goal and scope definition

Goal of this research

The general goal of this research is to contribute to the academic research concerning LCA. This way, more knowledge is shared among experts and the academic field of LCA grows. Furthermore, this thesis can be used as a reference in future studies and be used as a building block in later expansions of the academic field. This thesis provides original calculations that can be used to make the process of an LCA more precise.

In a more specific sense, the goal of this thesis is to find and elaborate the answer to the problem described in the research question; how can difference in volume be taken into account within the transport process of a CO_2 calculation? It is possible that the solution to this question will make a significant difference. If it does not, however, this is still a valid answer to the research question, and a valid conclusion can be drawn.

Scope of this research

The definition of industrial ecology (IE) has shifted over the years and is somewhat open for interpretation. Generally, IE can be described as the 'science of sustainability' (Ehrenfeld, 2004).

Within the master's course of IE taught at Leiden University and TU Delft, the science of sustainability is divided into three subjects: engineering, natural science, and social science.

LCA is a method that provides a highly quantitative result. By giving the result of the study in specific units such as CO_2 equivalent it is one of the few ways to measure the sustainability of a product or system. This makes it highly relevant in the *engineering* section of IE. Within this thesis, LCA will be the main focus as the specific aspect of volume within the transport phase of LCA will be optimised. A visualization of the scope of this thesis within the field of IE is shown in figure 3.

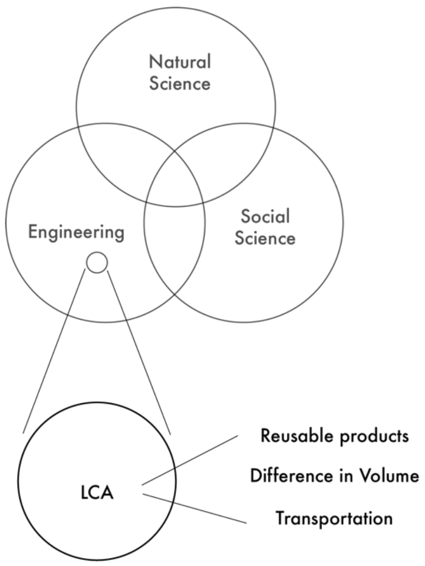


Figure 3: the scope of this thesis within the field of IE.

This specific scope determines the level of detail that is analysed in this thesis. Issues that arise outside of the scope and are seen as important to this research are addressed in the discussion in the final chapter.

In the case study, the distribution, use, and reuse of pallets and containers *in Germany* are analysed. Cabka is a company based in Berlin that mostly distributes their product within Germany (Cabka, 2022). It is possible that the products will be shipped to a different country. In that case, it is specifically mentioned and the distance is adjusted accordingly in the calculation.

The carbon emissions for a product are analysed in the tool that is created in this report. According to Van Maren (personal interview, 2022) the current LCAs performed by Cabka analyse the carbon footprint of their product over the course of *one year*. Therefore, this temporal boundary will not be exceeded in the new calculation.

2. Literature study

2.1. Introduction

A literature study is conducted to analyse the current status quo of transportation in LCA processes. Although it is still a niche concept, reusability is not something entirely new in the field of LCA. Many examples can be found online of studies that analyse the environmental sustainability of reusable products. Moreover, background information used in LCI databases is publicly available. For the study described in this thesis, the transportation processes of said studies will be analysed. In this chapter, these informational sources are used to conduct a literature study and the following research questions are answered:

- *How is transport modelled and quantified in Ecoinvent?*
- *How is transport currently modelled in LCA studies?*

The first question is answered by analysing the background reports (Valsasina et al., 2016) (Motta, 2021) of the transport processes found in Ecoinvent. In these background reports a (often) detailed description of the process is given, which gives a clear overview needed in this chapter.

During this study, several things are looked at specifically. Firstly, the unit that is used to quantify the transport phase (ton kilometre) is determined. This unit will be used in later calculations in this report. Secondly, every important aspect of the aforementioned background reports (for example gross vehicle weight and average freight load) will be analysed and listed.

The second question is answered by conducting a desk research-based literature study. Articles are found using relevant search terms. The search terms are found and optimised through trial and error. Furthermore, more articles are found by searching the reference list of articles that are proven especially relevant.

Next, the articles are ranked according to several categories, for example: 'does the article mention the reverse supply chain?'. The categories are found using the main research question, as well as the first few articles that were found as an example. Using these categories, the articles found in the literature study are listed and their individual scores in these categories are highlighted. In doing so, the relevance and adequacy of each article is shown in a clear way.

By structuring and performing a literature study this way, a clear answer to the research questions is given and a clear path towards the rest of the study is paved.

2.2. A literature study regarding parameters in Ecoinvent

Ecoinvent is a database that contains background processes that can be used in LCA studies. Each process has emissions and inputs linked to them. For example, a transport process has a 'market for diesel' input, meaning that a certain amount of diesel fuel is needed. A long list of inputs and emissions is given for every process that Ecoinvent has (Valsasina et al., 2016).

The output of the Ecoinvent process is given in the same unit as the process it is linked to. In the case of a transport process, this unit is ton kilometre (tonkm)(Valsasina et al., 2016)(Motta, 2021). This describes the weight of the freight times the distance travelled.

By using tonkm as an output, each input value and emission is quantified by that unit. For example, if a transport process uses 0,01 kg diesel *per tonkm*, the actual amount of diesel is found by applying the correct amount of tonkm for that process. An example of how such a background process works is shown in figure 4.

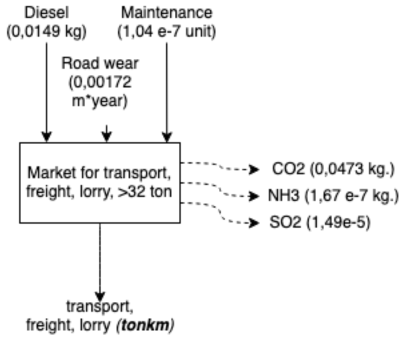


Figure 4: example of an Ecoinvent background process. The values are based on an existing background process (Motta, 2021). However, not all inputs and emissions are shown, as this image only serves as an example.

The aforementioned background reports (Valsasina et al., 2016) (Motta, 2021) mention gross vehicle weight (GVW) which describes the total weight of the truck including cargo, gasoline, and anything else that is carried on the truck itself. The average freight load (AFL) (Motta, 2021) describes the weight of the load that is averagely carried in this transport step.
The AFL is included in the GVW. If the AFL is subtracted from the GVW, the weight of the truck (still including gasoline, tires, etc.) is found. This is visualized in figure 5.

Figure 5: GVW, AFL, and ACUF visualized.

This same document (Motta, 2021) states that empty trips are included in the *average capacity utilization factor (ACUF)*. This factor describes how much space of the total load space is used on average in the *total* process of transportation. The ACUF is calculated by dividing the AFL by the average payload capacity, a value that is also given in the background report (Motta, 2021). Most case studies do not mention this return trip. It is usually left out, or it is included within the background process that is used with a database such as Ecoinvent.
It is important to note that some of the aforementioned parameters are not mentioned in every background process, which means that an assumption must be made in some cases. However, in this literature study the main goal is to analyse which parameters exist, and which ones are important for a calculation regarding volume. When necessary, an assumption can be made for these parameters under the condition that the assumption comes from an educated reasoning.

2.3. A literature study on current LCA studies

In order to accurately determine to what level of detail transport is modelled in current LCA studies, several search terms were used. The search terms are listed in order of when they are used, and become more specific based on the information found in the previous ones. This way, the final search terms will cover exactly the topic that must be analysed, and a precise conclusion can be drawn.
In this paragraph, the articles found are listed based on the search terms that were used. Google scholar, Scopus, and Web of Science are used to retrieve articles.

Several articles are found using search terms related to LCA, reuse, and packaging. The following search terms are used: 'LCA transport', 'LCA packaging', LCA case study', and 'LCA case study reuse'. Furthermore, articles are found using the Dutch knowledge institute for sustainable packaging (Kennisinstituut Duurzame Verpakkingen) (KIDV) website. The full process of the literature study can be found in appendix A.

The articles written by Cleary (2013) and Ferrara et al. (2021) are the closest to an analysis on change in volume during transportation. In their study it was a part of the sensitivity analysis. Unfortunately, even in the background reports, there is no in-depth analysis on this matter.
Ferrara et al. (2021) describe a study in which PET single use drinking bottles are compared with glass reusable ones. Cleary (2013) shows a study where glass *single use* wine and spirit bottles are compared to plastic and cardboard *reusable* cases.

2.4. Setup of criteria to rank the articles on relevance

In order to answer the research question mentioned in the previous paragraph, several categories were set up to define the relevance of each article. Using these categories, the articles found in the literature study are listed and their individual scores in these categories are highlighted. In doing so, the relevance and adequacy of each article is shown in a clear way. The categories are found by taking the main research question as a starting point and determining what categories would best answer it. Furthermore, the first few articles that were found are used as a starting point.

Is transport taken into account?
With this first criterion, it is checked if the article is relevant enough to be used in this literature study. Transport is the main aspect that is discussed in this research, and therefore it is essential to appear in a study for it to be relevant.

Does the case study use a background process?
With this requirement, it is checked if the study in question uses a process taken from a database such as Ecoinvent (Ecoinvent, 2021). Databases like this have a specific way of calculating the emissions from the transport process (this is analysed further in-debt in a later paragraph) and therefore it is necessary to know immediately if such a database is used. If that is the case, oftentimes that background process is the only calculation that is used to measure the impact of transportation. However, this is not necessarily always the case.
In some cases, additional calculations are performed. This is illustrated with the following category:

Is the reverse supply chain addressed?
When analysing product-service systems and reusable products, the reverse supply chain is also highly relevant, especially when analysing the transportation impact. With this requirement, that aspect of relevance is checked. It is expected that this will be the case for articles that describe a reusable product. Essentially, a reverse supply chain is one of the core aspects of such a product, and therefore it would be logical that it is addressed in the study at hand.

Is volume during transport mentioned?
This is a relevant question for this study, as volume during transport will be the centre of the research performed.

What input parameters to quantify the transport process are used?
With this open question, it is easily checked what the input parameters of the transport process are. It is expected that most articles will use a combination of weight and distance, such as ton kilometre (tonkm). However, listing all of the parameters with this requirement will give a clear overview of that.
Using these requirements, the level of detail as well as the specific focus of the studies are assessed. This will give the literature study a coherent view, and will make it easier to definitively answer the research question.

2.5. Results of ranking the found literature

	Is transport taken into account?	Does it use a back-ground process?	Does it mention the reverse supply chain?	Is volume during transport mentioned?	What parameters are used?
Spielmann et al. (2005)					N/A
Zampori & Dotelli (2014)					N/A
Campbell et al. (2020)					tonkm
Cottafava et al. (2021)					tonkm
Tan et al. (2005)					tonkm
Shen et al. (2010)					tonkm
Ferrara et al. (2021)					kgkm
Cleary (2013)					tonkm

Table 1: all of the articles found in the literature study ranked among the listed categories.

In table 1, an overview is provided showing which of the articles mention which aspects relevant to this study. It can be clearly seen that the more specific the categories get, the fewer articles mention said category. In the end, volume during transportation is mentioned in one study. However, it does not mention optimisation, further solidifying the knowledge gap found in chapter 1. When transportation and reverse supply chain are mentioned tonkm is used as a parameter, meaning that the calculation is based on weight and not volume.

2.6. Conclusion of the literature study

Background reports in Ecoinvent processes show that tonkm is used to measure transportation in an LCA. It is apparent that this unit is standardly used in LCA.
More noteworthy is the GVW (gross vehicle weight) which describes the total weight of the truck including everything that the truck carries. Furthermore, the AFL (average freight load) is used to make an estimation on the weight of the freight that is averagely carried. The AFL is included in the GVW. ACUF (average capacity utilization factor) describes to what extent the truck is filled on average. The ACUF as well as the AFL include empty trips.

The transport process is virtually always quantified in tonkm or a variation that also describes weight multiplied by distance. This is unsurprising for LCA studies, as it is also the parameter used in the most common LCA databases. Furthermore, logically the level of detail varies per study. In some cases the environmental impact of the transport process is so small compared to the other processes that it is decided not to focus on it. However, usually in the case of returnable or reusable products a more in-depth analysis of the transport process is performed. In such cases, weight is used as a parameter to quantify the environmental footprint of the transportation processes.

3. Analysis of the original CO_2 calculation tool

3.1. Introduction

LCA is growing in popularity among companies and consumers, and because of this the LCA process is becoming more and more streamlined (Beemsterboer et al., 2020). However, as shown in the previous chapter, there are still specific cases in which LCA is not yet optimised; reusable packaging is one of the types of product that are still difficult to analyse with LCA. In order to make this process easier for the consumer, a CO_2 calculation tool was developed by Partners for Innovation (PfI) (Keuenhof, 2020). The purpose of the CO_2 calculation tool is to give the user (usually the company that develops a reusable product or a product within a product-service system) a clear view on the environmental sustainability of their product or service. This calculation tool will be analysed and used as an example for the tool that will be developed in this report.
This will be done by answering the following research questions:

- *How does the CO_2 calculation tool by Partners for Innovation measure and show the environmental footprint of a product?*
- *What are the limits of this tool?*

First, every input- and output parameter of the tool is determined and analysed. This is one of the key aspects of the tool; everything that the user fills in and every result that follows is of high importance to the main function of the tool. Furthermore, the calculations that take place are analysed. In doing so, a full understanding of what happens in the tool is gained, giving a better overall understanding of the tool itself. Similar calculations are needed in chapter 4, and therefore it is good to know what they entail, as well as how they are performed in Excel. Next, every process listed in the tool is shown in two flowcharts, for the reusable product as well as for the single-use product, and the allocations are listed.
Second, the purpose of the tool, as well as its limitations and assumptions, are stated. It is logical that the tool has its own scope and is therefore limited in some way, and it is useful to know where that scope lies as a basis for the tool that will be created in the following chapter.

3.2. Description of the tool

The *KIDV Calculation tool for CO_2 impact of reusable packaging* is a tool developed by Utrecht University and Partners for Innovation (PfI) that simplifies the CO_2 calculation process of reusable packaging. It uses standard parameters that are usually known by the user, such as weight, cost, packaging material, and mode of transportation. The tool is made in Excel, using 6 separate tabs. Screenshots of every tab of the tool can be found in Appendix B.

'User guide'
This tab does not use any calculations, but functions as an explanation of the tool and how to use it. This adds value to the usability of the tool, and makes the user experience more clear. Furthermore, a section of the tab states all of the assumptions used in this tool; to keep it relatively simple for the user, some assumptions and conditions are set up to make the process more streamlined. This will be elaborated on in a later paragraph.

'INPUT'

In this tab, the user can fill in all of the necessary parameters such as 'weight', production method', or 'kilometres per transport step'. This is done per category, which are listed in the tables in appendix B. It is filled for a *reusable* packaging and a *single-use* one. The parameters are sorted in a structured way, making it easy to understand for the user. Furthermore, this tab contains a separate area where the calculations as well as data that is not necessary for the user to see are shown. This area is hidden and can only be viewed by entering a password. However, the calculations are applied even when the area is hidden.

The different parameters also affect each other; for some options for one parameter, other parameters become irrelevant. For example, when choosing 'glass' as a material the 'recycled content' parameter is left out, as in that case the industry average is taken into account.

'More reference packaging'

This tab gives the user the option to add more products to use as a reference for the reusable packaging. It provides two boxes for two more single-use packagings to be added.

'Results CO_2 impact'

Here, the output parameters are shown. They are the CO_2 emissions of every stage (production, transportation, return transportation, cleaning, end-of-life) and total sum of the CO_2 emissions. Each output parameter is calculated in the INPUT tab using the input parameters and the accompanying data from the 'data' tab. The data is visualized in a bar chart that explains the CO_2 emissions per trip in each stage. Furthermore, a line graph is shown explaining the break-even point of CO_2 emissions per number of trips for all of the packagings that were analysed. The calculation of the break-even point is given in a hidden part of the sheet, invisible for the user.

'Results costs'

This tab displays the total costs of each stage and the combined costs for the full life cycle of each packaging that is analysed. It also shows a line graph of all the alternatives that were analysed, and shows the break-even point of the two packagings. In the hidden section of the tab the calculations for the break-even point are shown.

'Data'

All CO_2 emissions needed in the calculation are shown in this tab. It shows the necessary data for all materials, production processes, transportation types, and cleaning types. Furthermore, it states all the sources that are used to gain this data.

3.3. Purpose of the tool

According to Nelisse (personal interview, 2021) and Keuenhof (2020) the CO_2 calculation tool is meant to be used to have a rough indication of the sustainability of a reusable product, and comparing the product to a single-use alternative. Furthermore, simplicity is focussed on in this tool, creating a clear overview of inputs and outputs instead of creating a complex assessment which can only be used by experts.

3.4. Input and output variables

In appendix A, a list of all the input- and output parameters is shown. They are applied in the 'INPUT' tab, the 'more reference packaging' tab, and the 'results CO_2 impact' tab. The input parameters are applied for both reusable and single-use packaging, with a few exceptions:

- Any checkbox regarding single-use or reuse is left out in the 'single-use' section, as it is assumed that everything is single-use.
- In the single-use section, the 'return transport' and the 'cleaning' section are skipped.

3.5. How does it work?

The tool works in a simple calculating way in Excel. When entering a value in the main section of the input tab, several calculations are applied to other cells in the hidden section of the tab. A simple example is shown in the figures below. (Note: the screengrabs shown below are not from the tool itself, but a simplified example.)

	A	B	C	D
1	Mass total	mass virgin	Mass recycled	Recycled content
2	30	15	=A2*D2	0,5

Figure 6: the mass of the recycled content is calculated.

	A	B	C	D
1	Mass total	mass virgin	Mass recycled	Recycled content
2	30	=A2-C2	15	0,5

Figure 7: the mass of the virgin material is calculated.

In figure 6, it is shown that the mass of the secondary material in the packaging material is calculated by multiplying the total mass with the percentage of recycled content. Next, in figure 7, the mass of the virgin material is calculated by subtracting the recycled mass from the total mass.

The examples in figure 6 and figure 7 are simplified. In the tool, several more complex calculations take place, such as VLOOKUP (where a list from a table is assessed) or ISBLANK (where a certain calculation is only/not performed when a specific cell is empty). These types of calculation add to the clarity of the overall calculation, as well as the usability of the tool.

In some cases, it is also possible for the user not to fill in anything. That is only in the case when that number has already been applied. For example, 'mass of packaging (g)' is a variable in the transportation section, even though that number is already filled in in the production section (figure 8). It is assumed that this is done for clarity for the user.

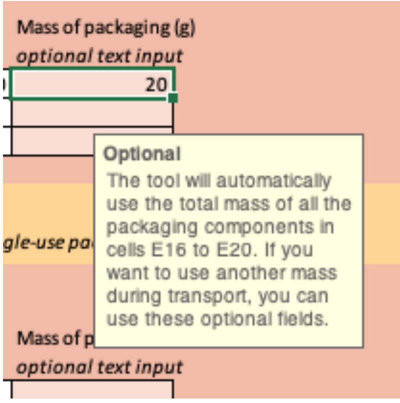


Figure 8: the mass of the packaging is asked for a second time, and is therefore optional to fill in.

Average capacity utilisation factor

The ACUF is of high importance when dealing with reusable products. When used in a background process, the ACUF takes into account a return trip that is empty, which means that the calculation could become incorrect when applied to a reusable product: in the logistical system of said product, the return trip is usually not empty and therefore the ACUF from the background process is no longer accurate.

According to Nelisse (personal interview, 2021) this is solved by leaving out the original ACUF. For example, if the ACUF is in the background process stated to be 62%, the value for kg CO_2 per tonkm found in the 'data' tab is then divided by 0,62, as if the truck is full during the return transport as well. Finally, in the tool an option is given to the user to fill in the return rate of the product. This means that an accurate number is given for how full the truck is during the return transport. It is clear that this is an assumption that makes the result of the tool less accurate. However, this way a method is created to exclude empty return trips from the calculation, which is necessary to make the calculation accurate for reusable products.

3.6. Flowcharts and Allocation

The reusable packaging section of the PfI tool uses twelve processes. In order to clearly visualize them a flowchart is set up. This is shown in figure 9.

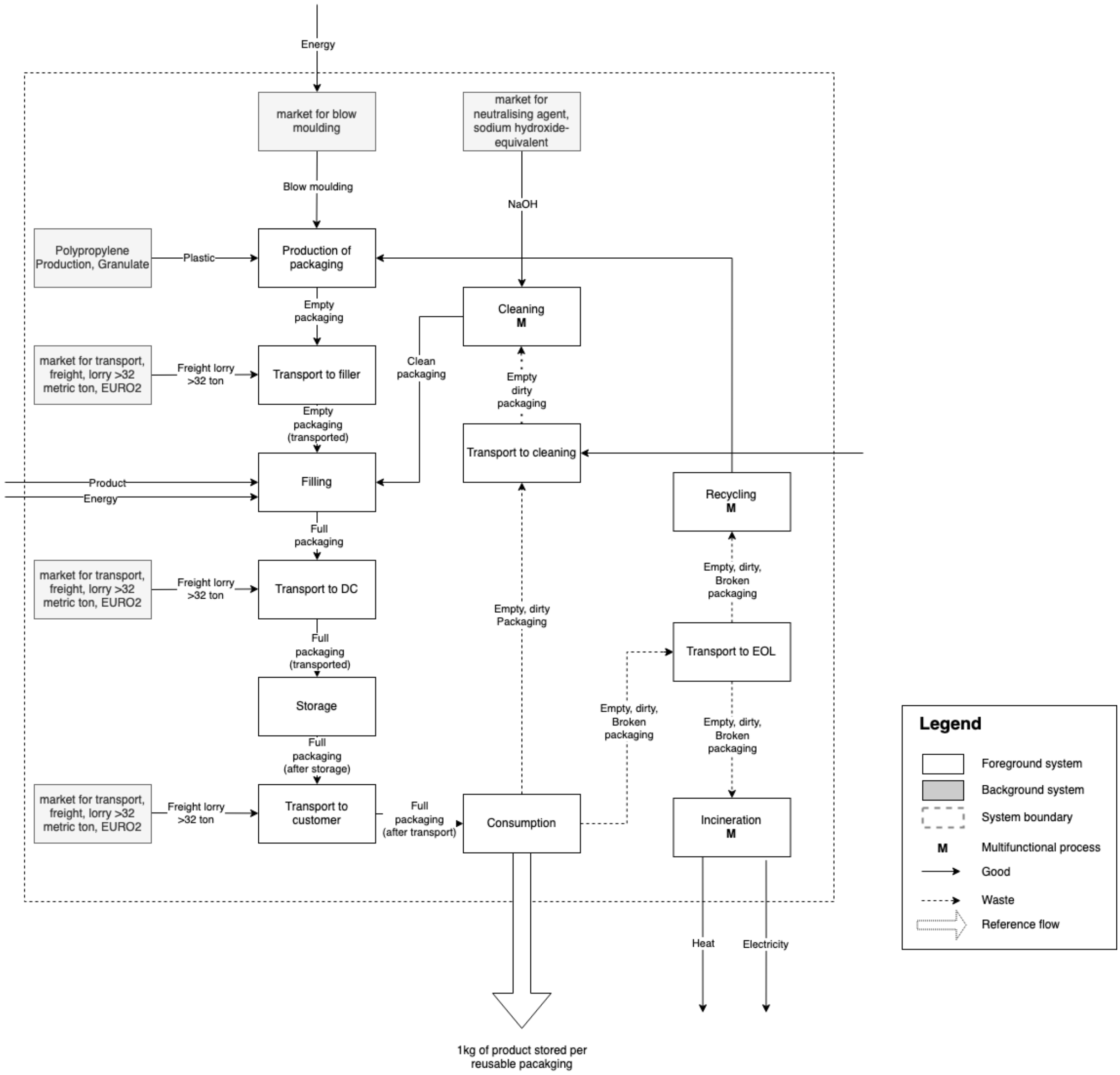


Figure 9: flowchart of the reusable packaging processes in the PfI CO_2 calculation tool.

In this flowchart, the circularity of a system involving a reusable product becomes very apparent. As shown in figure 9, two loops are shown; a reusability loop, and a (potential) recycling loop. This means that the 'cleaning' process, the 'recycling' process, and the 'incineration' process are multifunctional, meaning that an allocation is needed. According to Nelissen (2021) this was done using a PEF (product environmental footprint) calculation (Petcore Europe, 2021) that uses avoided burden, a substitution method commonly used in recycling or reuse steps (Guinée et al., 2002).

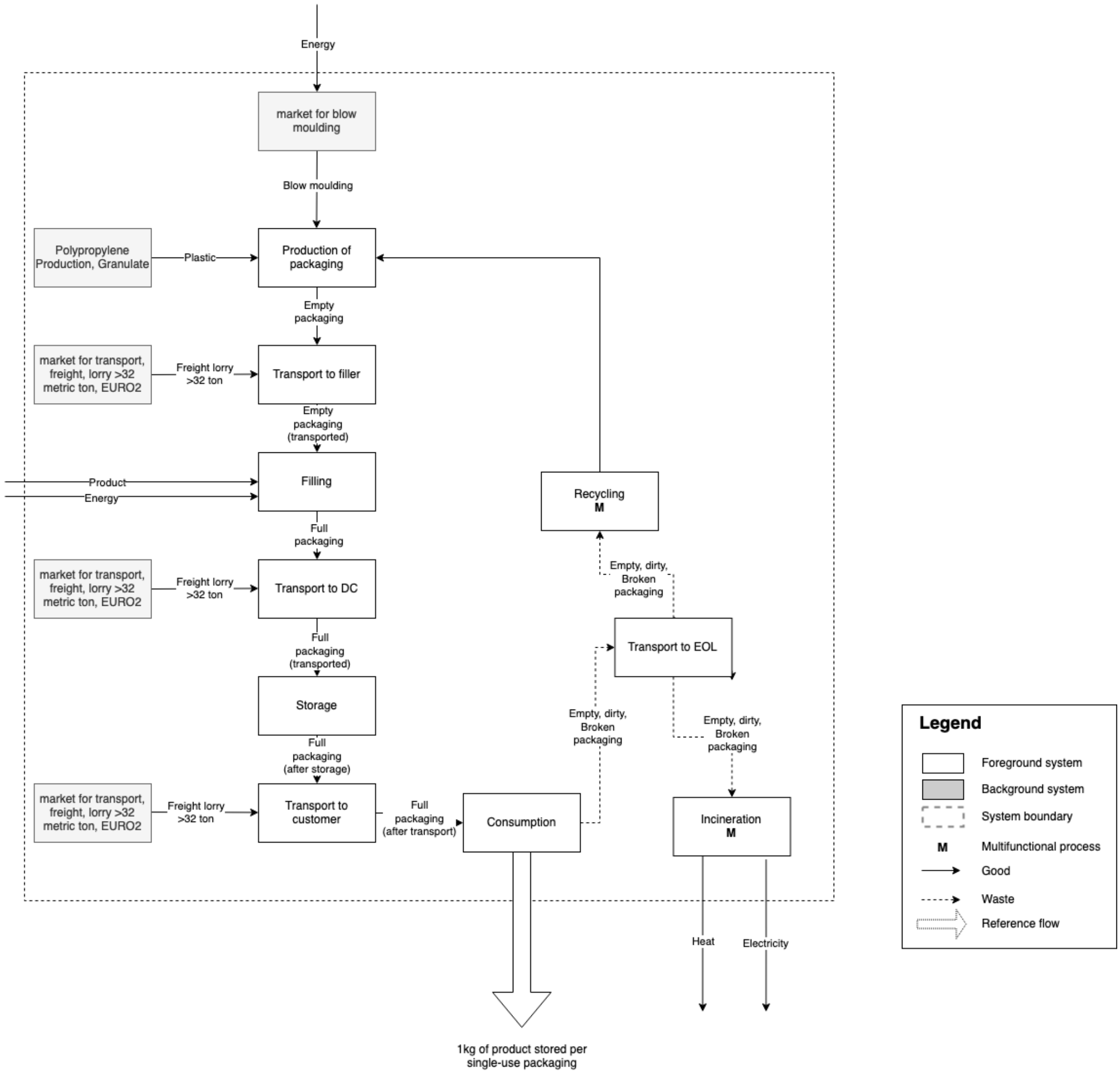


Figure 10: flowchart of a single-use packaging process analysed in the original PfI tool.

In figure 10, the flowchart for a single-use product is shown. The flowchart is again based on the original tool. Here it becomes clear that apart from the recycling step, there is no circularity in the system.

3.7. Assumptions and limitations

In order to make the calculation process more streamlined and clear for the consumer, several assumptions are set up. The assumptions that are considered the most relevant in this case are discussed in this paragraph.

Firstly, the 'User guide' tab states that volume is not taken into account, and that the calculation might not be accurate when applied to a low density, voluminous packaging. This limits the tool to only certain types of packaging, and should therefore always be considered before using this tool. Logically this is an assumption of high relevance, as this is the topic that is discussed in this thesis.

Secondly, it is stated that only a rough indication of the environmental sustainability of the product is given. The reason for this is the fact that the tool relies on simple data applied by the user. The more assumptions the user makes in filling in this data, the less accurate the result of the tool becomes. This is important to know for the consumer, as it again emphasizes that the tool is merely used as an indication. Moreover, as only CO_2 emissions are addressed, other environmental issues that could be relevant, such as nitrogen emissions, are left out.
Thirdly, several external sources are used to retrieve data for some parameters. The Ecoinvent LCA database is used for the transportation process. It is stated that in this case, vehicles with the highest standard in Europe (Euro6) are used. Furthermore, the end-of-life is assumed to be in the Dutch municipal waste stream. All of the external sources used for that type of data are listed in the final tab of the tool.
The allocation within the original PfI tool is performed using a PEF calculation. This does not change when creating a tool that is based on this calculation, and is therefore not focussed on.

3.8. Conclusion of the analysis of the original CO_2 calculation tool

The PfI CO_2 calculation tool is most suitable to be used as a rough indicator on the environmental sustainability of a reusable packaging compared to a single-use alternative. The inputs that are shown in a structured way, as well as the outputs that clearly show the result in a table and graph, make the tool appropriate for a quick sustainability indicator. However, the tool cannot be used as a substitute for a full LCA. The tool does give a clear result of the CO_2 emissions, but no impact assessment is performed. Moreover, *only* CO_2 and cost are given as a result, and a significant amount of assumptions are made from the beginning, meaning that the final result cannot be as accurate as a full LCA.

The input parameters are listed in a clear way, categorized per life-cycle step and clearly explained so that the user knows what they are. The output parameters are clear as well, and are shown in numbers as well as graphs, making the result of the analysis performed in this tool clear for the user.
All of the calculations in the tool are done within Excel, using a relatively simple method of calculating. Using simple Excel commands, clarity of the calculation as well as the usability of the tool are optimised.

The tool covers the environmental sustainability of reusable packaging in a standard way. It covers the basic steps within the life cycle of a reusable product, and uses this to give a standard result. This does mean, however, that the tool is still lacking in several aspects. It is apparent that volume is difficult to take into account, and that voluminous packagings with a low density require additional calculations. This is solved in the following chapter.

4. A tool for change in volume

4.1. Introduction

The original CO_2 calculation tool lacks in the aspect of voluminous, low-density packagings, as stated in the previous chapter. In this chapter, a new tool is developed in which new parameters are applied and possible reduction of environmental impact due to a more efficient transport by reducing the volume of the packaging is modelled. Together with the creation of the new tool, the following research question will be answered:

- *How can the calculation of change in volume within the transport phase be optimised for reusable products that become more compact when empty?*

This is done through several steps. First, a calculation is created that converts volume to mass in order to make the new tool compatible with the original tool as well as Ecoinvent. All of the necessary steps and new parameters in this calculation are explained using text, formulas, and drawings. Next, the usability of the new tool is shown, focussing on the clarity of the new parameters and calculation as well as layout of the new tool. Furthermore, several different cases are discussed to highlight different logistical systems. In this step, the versatility of the tool is emphasized; the tool is applicable to multiple types of logistical systems, and this is shown in these different examples. Finally, the research question is answered and a conclusion is drawn.

4.2. Tool explanation

The main purpose of the tool is to give the user a quick overview of the CO_2 emissions of their reusable packaging product. This is the same purpose as the original tool; the new tool is given as an extension on the original tool, making the original tool more precise in its calculations by taking into account change in volume. The exact calculations that are added, as well as the calculations needed to combine the extension with the original tool, are explained in paragraph 4.3.

4.3. Calculations for change in volume

The main difference between the new tool and the original tool lies in the calculations. The parameters used in the original tool are mostly used in the new tool as well, and therefore they will not be focussed on. Instead, new calculations that come in play when analysing change in volume will be discussed.

4.3.1. Definitions and distinctions

In the following paragraph, new parameters are introduced and new concepts are described.
First, a distinction between primary and secondary packaging must be made, as both will be important in the calculations in the following paragraphs. A primary packaging is a packaging used to contain a product, and a secondary packaging is used to contain a number of primary packagings (Cartier, 2019). When describing the product that is analysed in a calculation,

‘primary packaging’ is used. When describing the packaging in which said primary packagings are carried, ‘secondary packaging’ is used.
Secondly, ‘nesting’ is used to describe primary packagings that fold or fit into each other, therefore reducing in volume. ‘stacking’ is used to describe (primary or secondary) packagings that are *not* nested. Furthermore, ‘nesting’ is used to describe *optimally stacked* primary packagings. Here, ‘optimal’ and ‘efficient’ refer to volume: the more efficient, the more compact and therefore the lower the volume.
When referring to any type of transportation, ‘truck’ is used. In most cases it could be possible that products are carried in a different type of transportation such as a cargo bike. However, a truck is used in most cases, and therefore ‘truck’ is used to maintain consistency.

4.3.2. The use of volume in the calculation
The way that primary packaging is nested when empty can vary widely. The shape of each packaging is an important contributing factor. For example, a jar with a conical shape can be nested in two different ways (nesting them as well as placing them upside down next to each other) (Figure 11), both optimizing the space used in a truck. However, the formulas needed for the calculation of the nesting of this product are drastically different than for a rectangular packaging that folds. This is shown in figure 12.

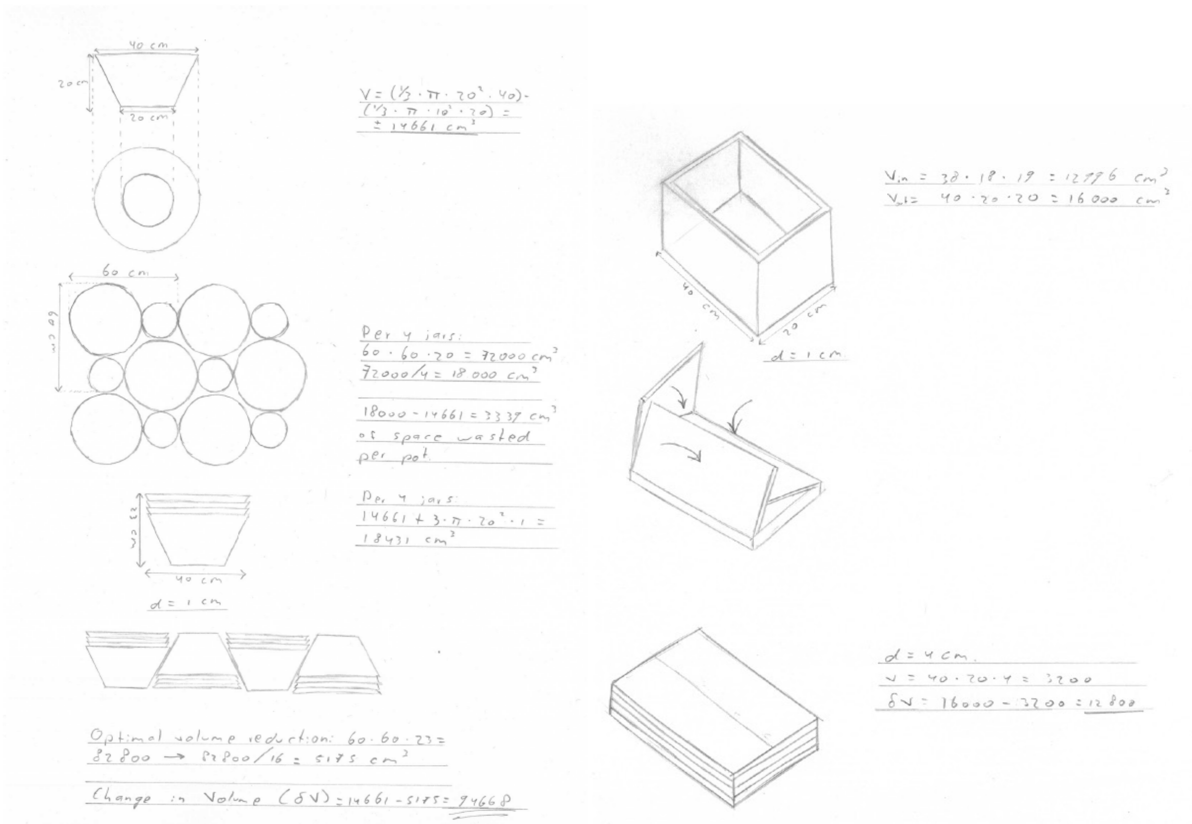


Figure 11 & 12: two calculations for the reduction of volume for two differently shaped products.

The shape, the way that they are arranged, and the way they are stacked all need to be taken into account in order to calculate the change in volume. As this varies per packaging, it is considered too complicated to add this to the new calculation tool. Moreover, the addition of these calculations would mean that the tool could only be applied to a packaging of that

specific shape. This would make the tool too specific, which in turn reduces its chances to be standardized.
Instead, the volume within a secondary packaging is used as a parameter. It is expected that in most cases the secondary packaging is a box, and that the user of the tool knows the number of primary packagings in one box. That number can be easily used to calculate the difference in volume in a truck. If no boxes are used in transportation, the inner volume of the truck is used as a parameter in the calculation.

4.3.3. From change in volume to tonkm
The original tool as well as LCA databases such as Ecoinvent use tonkm as a unit to measure the transportation process. Furthermore, as shown in chapter 2 this is also the unit that is used in most LCA studies. It is therefore important that the unit of change in volume (∂V) is converted to tonkm.

In this calculation the following aspects are taken into account. Firstly, the level of efficiency of stacking the packagings within the truck is determined in order to analyse to what extent they become compact when empty. This is necessary to determine the next aspect, which is the number of trips that is saved by nesting the packagings when empty. If the packagings are stacked inefficiently, a value is calculated for an extra number of trips needed. This is a key aspect, as saving trips within a logistical system makes a huge impact on the overall CO_2 emission. This is another aspect in which the volume-based calculation is more accurate than the calculation based on weight. To what extent it makes a difference is calculated by the weight factor. This factor describes how heavy the load of the truck is compared to the truck itself. All of the aforementioned aspects are used to create the *final factor*: a factor that is multiplied with the value for tonkm of the original calculation. By doing it this way the new calculation serves as an extension to the original one. This way, the original calculation is still valid. Furthermore, the use of Ecoinvent is now still possible, as it also uses tonkm as a unit.

The first parameter used in this calculation is V_1. This is the volume *surrounding* one packaging, which in this case means the space that the packaging would take up if it was not nested. V_1 is calculated by multiplying the longest measurement of the product for each dimension. This is visualized in figure 13. The second parameter is U: the number of primary packagings that go in a secondary packaging, realistically. This number is simply filled in by the user of the tool; this is information that all companies have of their product (Poirier, personal interview, 2021). The third parameter is the inner volume of the secondary packaging, which is called V_2. This too is filled in by the user. When dividing V_2 by V_1, a unitless number is found which describes the amount of primary packagings that would fit in a secondary packaging if they are *not* nested. It is important to note that this number is *not* the amount of packagings that go in a box: this is further explained in the next paragraph.
When the actual number of packagings in a box (U) is divided by this number, the *efficiency factor (φ or 'fi')* is found. This is shown in formula 1. The efficiency factor describes to what extent more efficient loading is possible in case the packaging is empty. For example, an efficiency factor of 5 means that five packagings could fit in the place of one packaging if they are folded or nested.

$$\Phi 1 = \frac{U}{V2/V1}$$

U = number of primary packagings in a secondary packaging
V2 = inner volume of the secondary packaging
V1 = Surrounding volume of the primary packaging

Formula 1: the formula of efficiency factor φ_1.

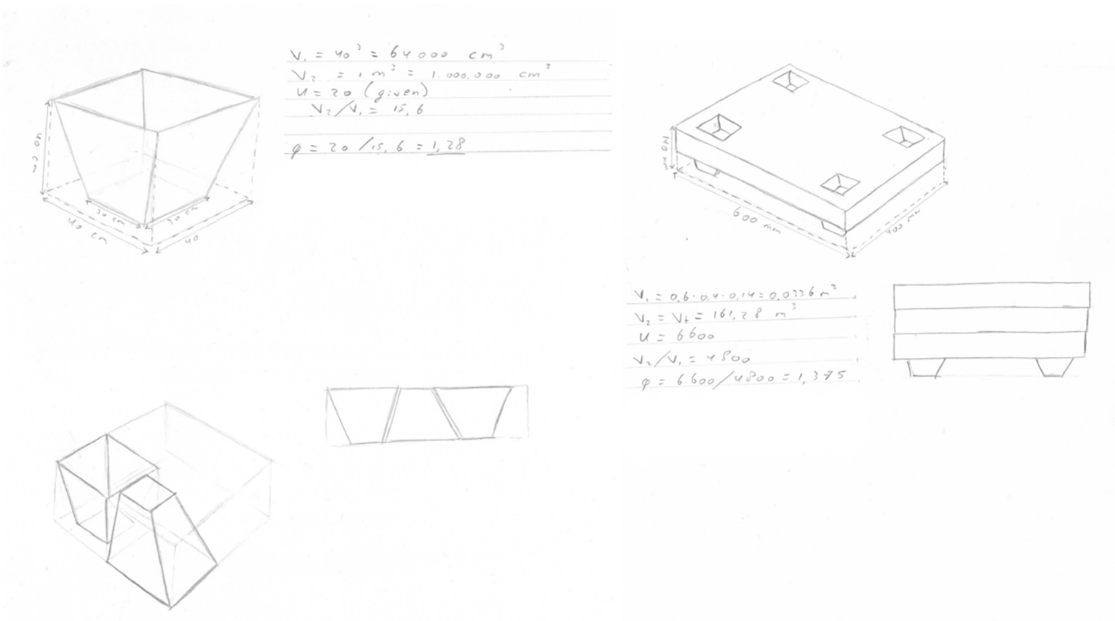


Figure 13: the calculation of the efficiency factor for two different products.

4.3.4. Elaboration on the efficiency factors

As stated in the previous paragraph, the efficiency factor describes to what extent the primary packaging reduces in volume when empty and nested. This number also takes into account the empty space within the secondary packaging. In figure 10, the answer to V_2/V_1 is stated to be 15,6. It is important to note that 15,6 is *not* a realistic amount that would fit in the secondary packaging. In fact, 8 primary packagings would fit in the secondary packaging, with spare space on the side and top. 15,6 is still used in the calculation because it takes into account this extra space as well. This is visualized in figure 14. The actual number of primary packagings is then divided by this number (20/15,6 in figure 13) and in doing so, the first efficiency factor is found (φ_1).

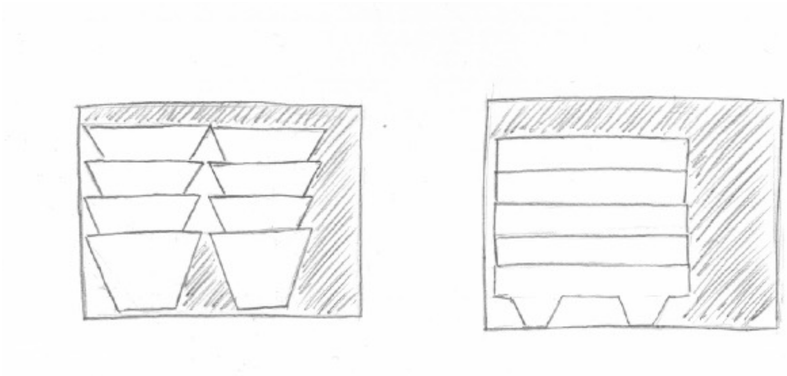


Figure 14: two primary packagings as they are stacked within a box: the nesting increases the efficiency factor, but the empty space within the box means that the efficiency decreases a bit as well.

A second efficiency factor is needed to calculate the empty space within the truck. If all of the boxes are stacked, empty space will occur on the top as well as on the sides. With the second efficiency factor, the number of boxes (U_{box}) as reported by the user to fit in the truck, is divided by the inner volume of the truck (V_t) which is divided by the volume of a box (V_2). This is shown in formula 2. In the end, a total efficiency factor is found (φ_t) by multiplying φ_1 and φ_2. This factor describes the level of efficiency of the primary packagings within the truck.

$$\Phi 2 = \frac{\text{Ubox}}{\text{Vt}/\text{V2}}$$

U_{box} = the number of secondary packagings in the truck
V_t = The inner volume of the truck
V_2 = The inner volume of the secondary packaging.

Formula 2: the formula for the second efficiency factor φ_2.

4.3.5. Number of trips saved

The multiplication of the two aforementioned efficiency factors provides a way to calculate the number of trips that is saved by the nestability of the product. If the total efficiency factor is higher than one, it means that more than one trip would be needed to transport the primary packagings if they were *not* nested. In other words, it would mean that one or more trips were saved by nesting the packagings. For example, in figure 15 it is shown that φ_1 is equal to 4,1, and φ_2 is equal to 0,28. This gives a φ_t of 1,148. The fact that $\varphi_t > 1$ means that if the primary packagings were not nested the total volume of the primary packagings would exceed that of the truck and therefore another trip would be needed. In this case, the amount of saved trips is therefore equal to 1. In a more extreme example shown in figure 16, φ_1 is equal to 4,1 and φ_2 is equal to 0,92, giving a φ_t of 3,772. That means that three additional trips would be needed if the packagings were not nested.
The number of trips is rounded to a whole number because only entire trips are taken into account. If a truck drives from point A to point B this is seen a whole trip. If the trip would not be rounded, the truck would theoretically end up somewhere halfway, which is not the case in a logistical system.

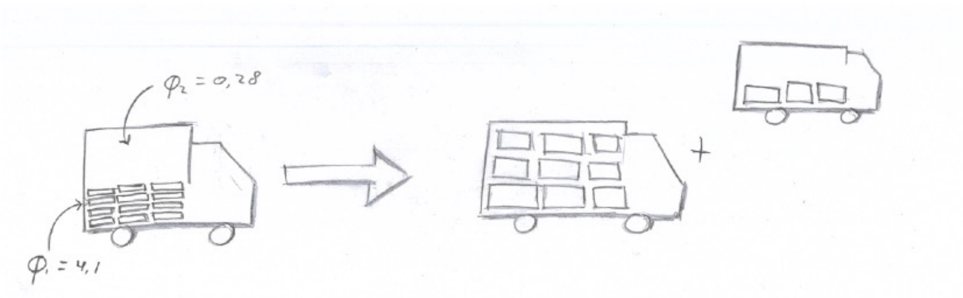


Figure 15: an extra trip is needed when transporting the same packaging that is not folded.

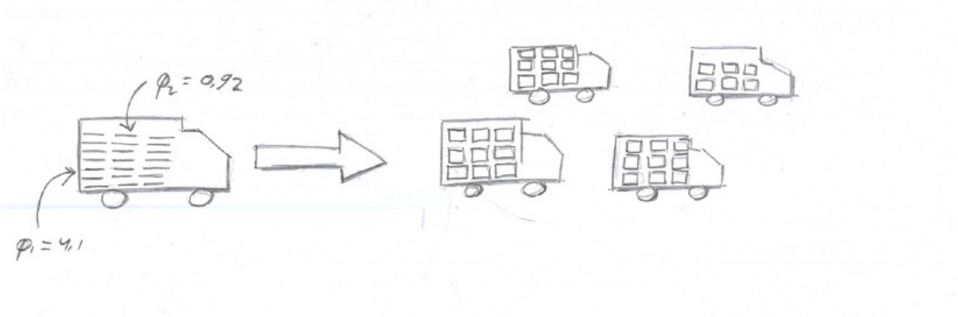


Figure 16: a similar scenario but with a more extreme efficiency factor.

The total efficiency factor φ_t means that more packagings are transported at the same time in case the4 packagings are nested compared to when they are not stacked efficiently. This means that the total weight of the truck increases. However, the number of trips saved means that the number of kilometres travelled decreases. To correctly incorporate both factors in the final CO_2 calculation, the following formula is set up:

$$\varphi f1' = \frac{\varphi t}{ts + 1}$$

φf1' = the factor that connects to the original calculation
φ_t = the two efficiency factors multiplied
ts = the amount of trips saved by nesting

Formula 3: the formula for the final factor when a number of trips is saved.

In this formula, 'φ_t' is the two efficiency factors multiplied, and 'ts' is the amount of trips saved. The extra '1' added to the trips saved is the initial trip that is always used. The 'φ_{f1}'' parameter is called the final factor and is multiplied to the tonkm value of the transport step. In doing so, the mass is multiplied by the total efficiency factor, and the distance is divided by the trips saved plus the initial trip. This is explained in the following formula:

$$(load * distance) * \left(\frac{\boldsymbol{\varphi t}}{\boldsymbol{ts + 1}}\right) = \frac{distance}{ts + 1} * (load * \varphi t)$$

Formula 4: an explanation that the final factor causes the load to be divided by the amount of trips, and the distance to be multiplied by the total efficiency factor.

φ_{f1}' is the final parameter that connects the additional tab with the original tool by PfI. This is explained in the next paragraph.

4.3.6. Extra trips needed

In contrast to the previous paragraph, a formula is set up for a transport step in which the products are *not* stacked efficiently; when 'φ_t' < 1. In this case, the aforementioned formula (formula 4) does not apply, as the 'trips saved' is equal to zero regardless of the exact value of φ_t. To solve this, a new parameter is set up which describes the amount of *extra trips needed*. This value is found by dividing 1 by φ_t and rounding down the answer:

$$tn = \frac{1}{\varphi t}$$

Formula 5: a formula to find the amount of extra trips needed when φ_t <1.

For the final factor, the following formula is used:

$$\varphi f2' = \varphi t * (tn + 1)$$

φf2' = the final factor that is connected to the original calculation if extra trips are needed.
φ_t = the two efficiency factors multiplied
tn = the amount of extra trips needed when not nesting

Formula 6: the formula for the final factor when extra trips are needed.

For example, if φ_t is equal to 0,21 the process is not very efficient and 4 extra trips are needed (1/0,21 = 4,8). The connection factor 'φ_{f2}' then becomes 0,21*5 = 1,05.

4.3.7. The importance of distance

In the aforementioned formula (formula 3 and 6) for the final factor, the extra weight and the extra amount of kilometres are linearly related. However, this is not the case in practice. In this calculation, an additional factor must be added to the value for 'trips saved' or 'extra trips needed' to take into account the weight of the truck, instead of just the weight of the load. This factor shows how important the weight of the truck is compared to the weight of the load. The factor is called 'wf' and is defined by the following formula:

$$wf = \frac{GVW - AFL}{load}$$

wf = weight factor
Load = the weight of all of the primary packagings on the truck combined.
GVW = gross vehicle weight: the total weight of the truck including everything carried by the truck: the weight of the truck itself, the gasoline, the weight of the driver, etc.
AFL = average freight load: an average weight value used in Ecoinvent.

Formula 7: formula describing the 'weight factor'.

In this formula, 'load' is the mass of all of the primary packagings in the truck, GVW (gross vehicle weight) is the total weight of the truck including the cargo. In the case of the GVW an AFL (average freight load) is used, which is therefore subtracted by the GVW leaving the weight of the truck including additional weight such as gasoline, but excluding the average freight load.

The weight factor is applied to the calculation in the following formulas:

When trips are saved:

$$\varphi f1 = \frac{\varphi t}{(ts + 1) * wf}$$

When extra trips are needed:

$$\varphi f2 = \varphi t * (tn + 1) * wf$$

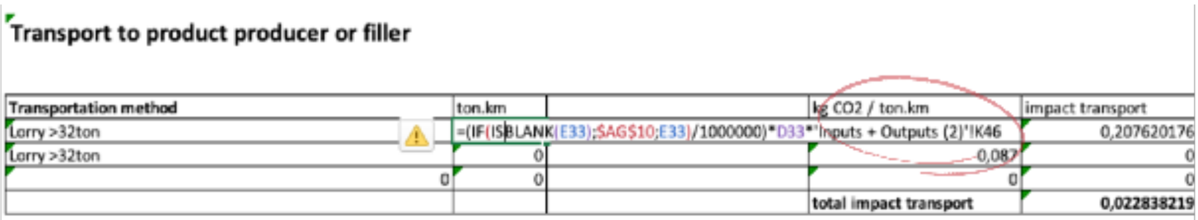
φf1 or φf2 = the final factor used in the calculation
φ_t = the two efficiency factors multiplied
ts = the amount of trips saved
tn = the amount of extra trips needed
wf = the weight factor.

Formula 8 & 9: the two final factors that are used in the new calculation.

Only one of these two final factors is multiplied by the tonkm calculation of the original tool (depending on whether trips are saved or extra trips are needed) to get a more precise answer that takes into account volume.

4.4 Incorporation within the tool by Partners for Innovation

The φ_f is set up so that the user of the tool can fill in the original weight and distance of the transport step while the tool does the rest of the calculation. In the tool, the multiplication with the final factor takes place in the calculation section of the 'INPUT' tab. An example of this is shown in figure 17. In this figure, 'Inputs + Outputs (2)'!K46' is the cell in the new calculation tab where the final factor is found. This is how it is connected to the original calculation.



Transport to product producer or filler

Transportation method		ton.km		kg CO2 / ton.km	impact transport
Lorry >32ton		=(IF(ISBLANK(E33);AG10;E33)/1000000)*D33*'Inputs + Outputs (2)'!K46			0,207620176
Lorry >32ton		0		-0,087	0
	0	0		0	0
				total impact transport	0,022838219

Figure 17: the 'final factor' parameter is taken from the additional tab and used in the calculation section of the INPUT tab.

In the tables below, this is shown in an example.

Original:

Ton:	Kilometre:	Tonkm:
200	360	720

New:

Ton:	Kilometre:	**Final factor**	Tonkm:
200	360	**0,41**	720*0,41 = **295,2**

This section is hidden in Excel, and therefore the user does not see how the calculation takes place. The user only sees their own input in both the 'INPUT' tab and the additional tab, and the more precise result of the CO_2 calculation when it takes into account volume.

4.5. Overview of parameters

In Appendix C and D, full tables describing every input- and output parameter can be found. Every input parameter is assumed to be data that the user has readily available (Poirier, personal interview, 2021), and every output parameter is explained in the tool.

4.6. Usability

In this paragraph, the usability of the new tool is discussed. Just as the original tool, simplicity and clarity are seen as highly important, which is why the usability of the tool is a main focus.

4.6.1. Logical order of parameters

To make the new tool as clear as possible, all of the parameters are sorted in the same way as they appear in the calculation. It is assumed that this makes the process of filling in the parameters more intuitive. This is shown in figure 18. A larger screenshot is shown in Appendix D.

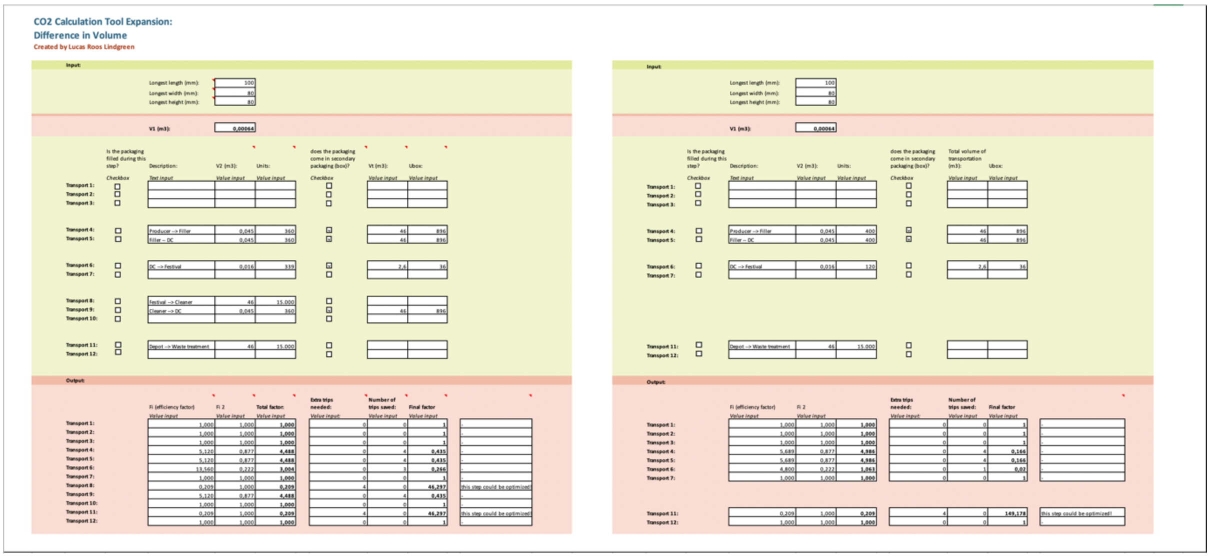
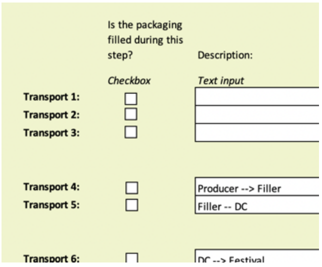


Figure 18: a screenshot of the full calculation tab of the new tool.

The output parameters are shown in the bottom of the screen because they appear after the user has filled in the input parameters. V_1 is an exception because it is already the outcome of three input parameters above. Furthermore, V_1 functions as an input parameter for the final calculation as well.

4.6.2. Additional functions

For each transport step the user can mark a checkbox if the packaging is filled with a product in this step. This is shown in figure 19. When the checkbox is marked, it is clear that said transport step cannot be optimised; because the packaging is full at that moment, it cannot be nested. However, when a checkbox for a transport step is unmarked *and* the total efficiency factor is lower than one, the tool notifies the user that this transport step could still be optimised. This is shown in figure 20.



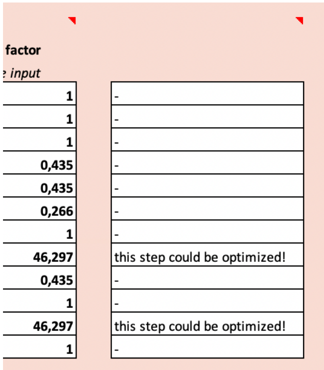


Figure 19 and 20: screenshot of the area in the new tool where the user can mark if the packaging is full for each transport step (left). When the box is not checked and the transport step is inefficient the user is notified (right).

4.6.3. colour pallet

The colours of the new tool are chosen to be similar to the original tool, yet slightly different. This signifies that the new tool works in a different way than the original tool, but is still used within the same Excel file. The new colour scheme is shown in figure 21.

Colour pallet
Of new tool

Colour pallet
Of original tool

Figure 21: the colour pallet of the new tool compared to that of the original one.

4.6.4. Parameter explanation

The parameters used in the new tool are explained in two different ways. First, every parameter shows an explanation when the user hovers their mouse over it. This is shown in figure 22.

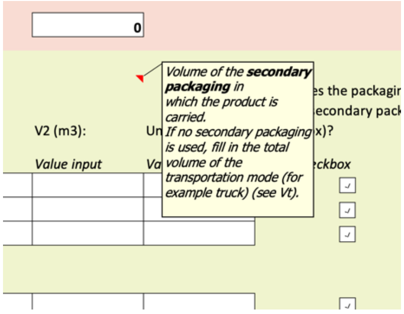
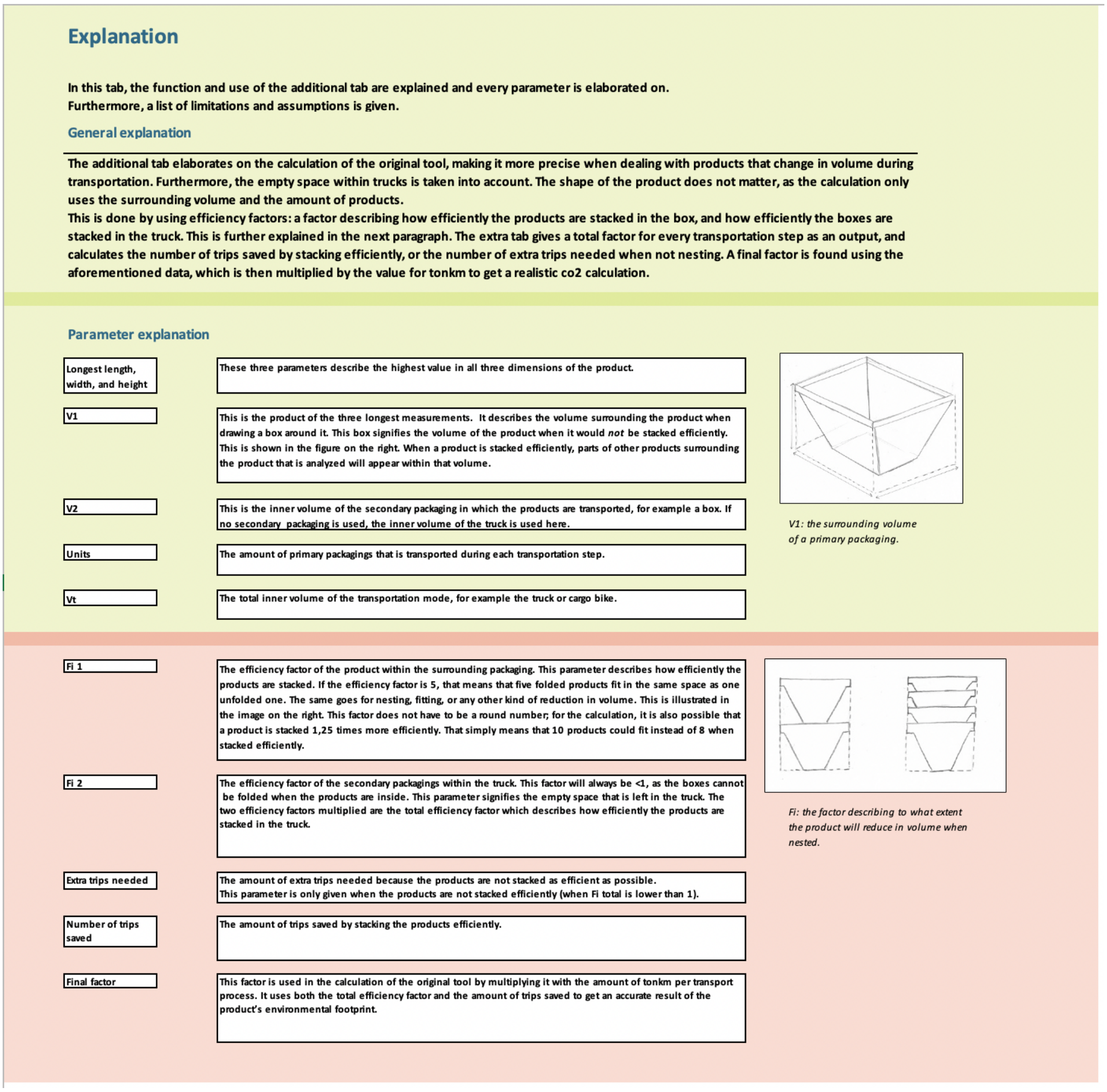


Figure 22: an explanation of the parameter is given when hovering a cursor over the cell.

Furthermore, an additional tab is given in which all of the parameters, together with a general explanation of the new tool, are given. This tab includes drawing to elaborate on the parameters. This tab is shown in figure 23.



Explanation

In this tab, the function and use of the additional tab are explained and every parameter is elaborated on.
Furthermore, a list of limitations and assumptions is given.

General explanation

The additional tab elaborates on the calculation of the original tool, making it more precise when dealing with products that change in volume during transportation. Furthermore, the empty space within trucks is taken into account. The shape of the product does not matter, as the calculation only uses the surrounding volume and the amount of products.
This is done by using efficiency factors: a factor describing how efficiently the products are stacked in the box, and how efficiently the boxes are stacked in the truck. This is further explained in the next paragraph. The extra tab gives a total factor for every transportation step as an output, and calculates the number of trips saved by stacking efficiently, or the number of extra trips needed when not nesting. A final factor is found using the aforementioned data, which is then multiplied by the value for tonkm to get a realistic co2 calculation.

Parameter explanation

Longest length, width, and height	These three parameters describe the highest value in all three dimensions of the product.
V1	This is the product of the three longest measurements. It describes the volume surrounding the product when drawing a box around it. This box signifies the volume of the product when it would *not* be stacked efficiently. This is shown in the figure on the right. When a product is stacked efficiently, parts of other products surrounding the product that is analyzed will appear within that volume.
V2	This is the inner volume of the secondary packaging in which the products are transported, for example a box. If no secondary packaging is used, the inner volume of the truck is used here.
Units	The amount of primary packagings that is transported during each transportation step.
Vt	The total inner volume of the transportation mode, for example the truck or cargo bike.
Fi 1	The efficiency factor of the product within the surrounding packaging. This parameter describes how efficiently the products are stacked. If the efficiency factor is 5, that means that five folded products fit in the same space as one unfolded one. The same goes for nesting, fitting, or any other kind of reduction in volume. This is illustrated in the image on the right. This factor does not have to be a round number; for the calculation, it is also possible that a product is stacked 1,25 times more efficiently. That simply means that 10 products could fit instead of 8 when stacked efficiently.
Fi 2	The efficiency factor of the secondary packagings within the truck. This factor will always be <1, as the boxes cannot be folded when the products are inside. This parameter signifies the empty space that is left in the truck. The two efficiency factors multiplied are the total efficiency factor which describes how efficiently the products are stacked in the truck.
Extra trips needed	The amount of extra trips needed because the products are not stacked as efficient as possible. This parameter is only given when the products are not stacked efficiently (when Fi total is lower than 1).
Number of trips saved	The amount of trips saved by stacking the products efficiently.
Final factor	This factor is used in the calculation of the original tool by multiplying it with the amount of tonkm per transport process. It uses both the total efficiency factor and the amount of trips saved to get an accurate result of the product's environmental footprint.

V1: the surrounding volume of a primary packaging.

Fi: the factor describing to what extent the product will reduce in volume when nested.

Figure 23: an additional tab in the new tool explaining every parameter.

4.7. Logistics

For reusable products, the logistical system becomes more complex, as it requires a reverse logistics system (Dekker & van der Laan, 2003). This describes the transportation process that is required to take the reusable packaging from the consumer back to the producer (Gonzalez-Torre et al., 2004). In the case of reusable packaging, the reverse logistics process adds two levels of complexity. Firstly, the amount of packagings of the reverse supply chain is often times either higher or lower than the forward supply chain. The packaging may be kept at the retailer or the user stage for a longer time, depending on the logistical system and the exact function of the packaging. For example, the user needs to keep the packaging at home to store the goods, or a pallet needs to stay in the distribution centre for extra cleaning. In order to optimise the reverse supply chain, most companies create a more complex logistical system. This way the amount of trips is reduced and time, money, and CO_2 emissions are saved. Secondly, the packaging might be more compact when empty. This means that there is more space during the reverse supply chain, meaning that a more complex system is required to reduce the amount of trips.
The combination of the aforementioned complexities leads to widely varying complex logistical systems. Several examples are shown in figure 24, 25, and 26.

The product-service system of RePack (RePack, 2021) describes a system in which packages are sent through the mail using a reusable case instead of a disposable box. The cases are sent back to the retailer by mail, where it is checked for damage and cleaned (Coelho, 2020). In this case, the deliverer visits many addresses on the forward supply chain. The reverse supply is outsourced to a local mailing service. This is visualised in figure 24. Here, it becomes more difficult to argue whether the reduction of volume causes a reduction in total carbon emissions by reducing the amount of trips.

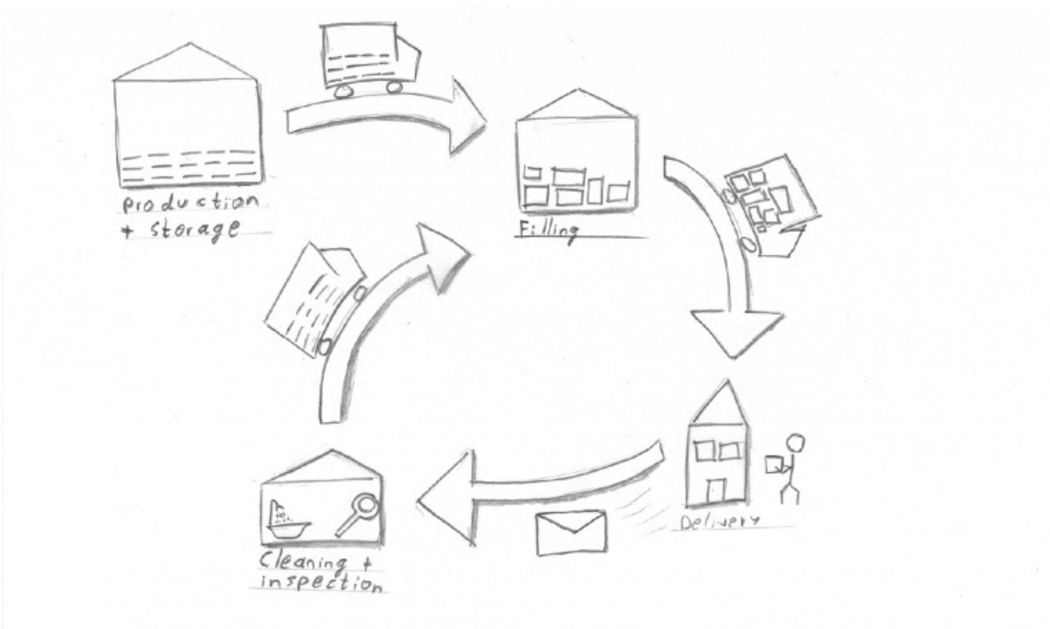


Figure 24: the logistical system of Repack visualized.

Another example of a logistical system including reusability is a pooling system for reusable pallets introduced by Faber Group (Schröder, 2021). In this logistical system, the pallets are returned by the (business) consumer to a collection point, at which they are picked and returned to the distribution centre. An important aspect of this system is that the return trip from the pallet collection point to the distribution centre is always full, meaning that the reduction of volume of the pallets (if applicable) can make a relatively big difference for the number of trips in an uncomplicated way. This is shown in figure 25.

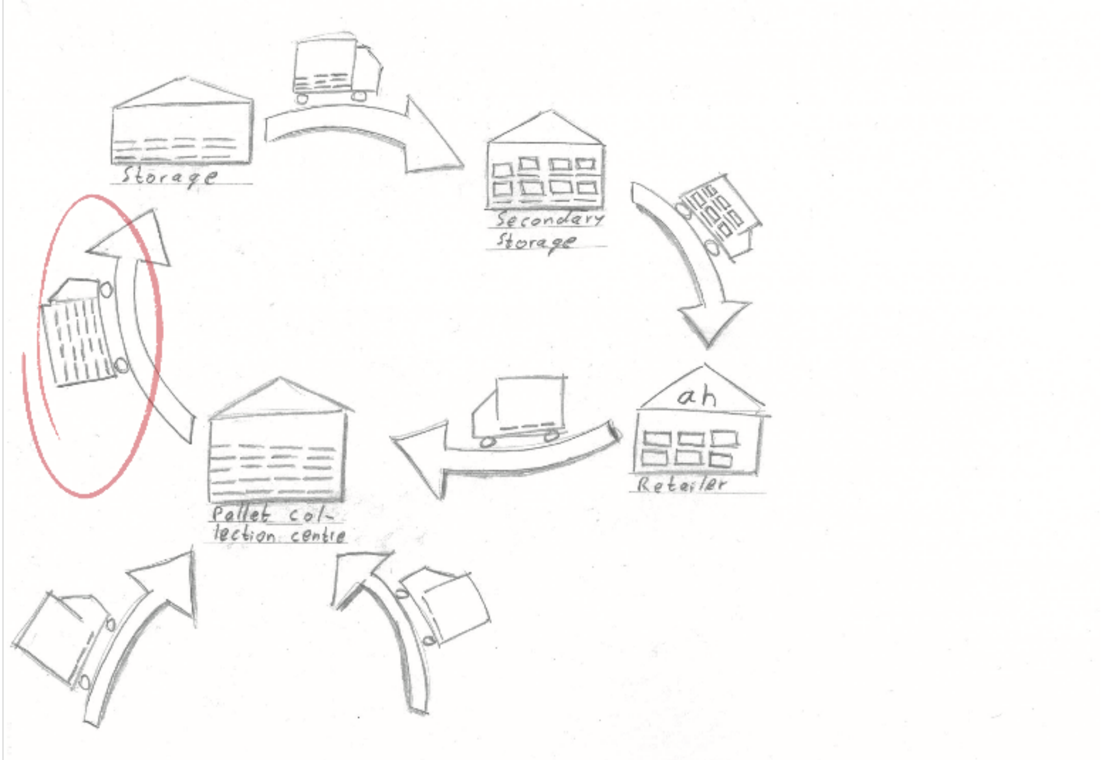


Figure 25: the logistical system of Faber Group visualized. The circled transport step is one that is always full and the pallets are stacked efficiently, meaning that much optimisation takes place here.

A third example is based on the logistical system of Pieter Pot (Pieter Pot, 2021) (figure 26). This example is used because here it varies widely how long the packaging stays with the consumer. This makes the reverse logistics very complicated and difficult to optimise. Moreover, this system includes a cleaning step. However, from a logistical standpoint it can be seen as a packaging collection point. Lastly, during the reverse supply chain the truck can visit more than one household to pick up empty jars. How many households they visit depends on the route, the amount of space in the truck, and the amount of houses that have empty jars to pick up.

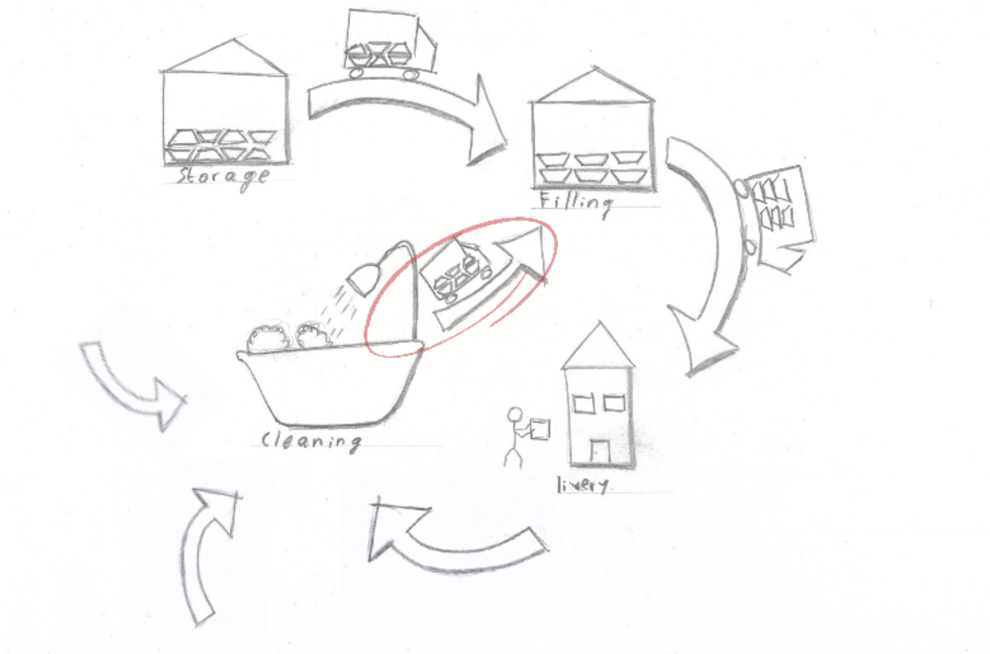


Figure 26: the logistical system of Pieter Pot visualized. The circled transport step is always full and therefore has the most potential to be optimised.

When looking at the aforementioned logistical systems, it can be assumed that reduction in volume could make a significant impact on the environmental footprint of the system. For example, in figure 25 the trip from the pallet collection centre to the storage centre is always full, meaning that reduction in volume would make the trip more efficient, and therefore fewer trips are needed. However, it varies per logistical system exactly how big the positive impact will be, and therefore it is impossible to definitively conclude in this report. In the next chapter, several scenarios will be set up as examples to see how big the impact could be in different cases.

4.8. Conclusion of the new CO_2 calculations

The new CO_2 calculation tool that has been created functions as an extension on the original tool by Partners for Innovation. The new tool has the same function as the original tool: give a quick overview of the carbon footprint of a reusable packaging and compare it to a single-use alternative. The new tool is designed to make the input- and output parameters as clear as possible, and to fit the aesthetic of the original tool.

An additional calculation is set up so that it takes into account the reduction of volume of a primary packaging and converts it to mass to fit the original calculation as well as any data taken from LCI databases. To do so, V_1 was set up. V_1 describes the surrounding volume of a primary packaging, and is calculated by multiplying the largest value in all three dimensions.

Efficiency factors are used to calculate to what extent the packagings reduce in volume when transported. Two efficiency factors are used; one to calculate the efficiency of the primary packagings within the secondary packaging, and one to calculate the efficiency of the secondary packagings within the truck. The latter is always lower than one, because the secondary packagings cannot be folded when they are filled with primary packagings.

Two final factors are set to connect the volume calculation with the original calculation that uses tonkm:

When trips are saved:

$$\varphi f1 = \frac{\varphi t}{(ts + 1) * wf}$$

When extra trips are needed:

$$\varphi f2 = \varphi t * (tn + 1) * wf$$

φ_{f1} and φ_{f2}= the final factor used in the calculation
φ_t = the two efficiency factors multiplied
ts = the amount of trips saved
tn = the amount of extra trips needed
wf = the weight factor.

Simplicity and usability are key properties of the new tool. To enhance these aspects, the layout of the new tool as well as its explanation of every parameter are made as clearly as possible.

Several examples of logistical systems show that optimisation of volume reduction would make a significant impact on a logistical system. There are usually one or more transportation steps in which the products are nested and therefore in that case the new CO_2 calculation tool will give a more precise result.
Using this calculation, a more precise CO_2 emission for a packaging is given. By using all of the aforementioned parameters every aspect of reduction of volume is used to create an accurate representation of the CO_2 footprint of the packaging. To check if the tool is applicable in different situations, several scenarios are set up. This is shown in the next chapter.

5. Applying case studies using real and fictitious scenarios

5.1. Introduction

In chapter 4, a new tool was set up that takes into account reduction of volume during the transportation steps within a CO_2 calculation. Because this is a calculation method that is not commonly used, the next step is to apply existing data to this tool. In doing so, the validity of the calculation is substantiated. This answers the following research question:

- *When applying different scenarios to the new CO_2 calculation tool, what does the difference in outcome with the original tool signify?*

First, a scenario of reusable festival cups is applied to the original and the new tool. In this analysis, a comparison is made between the results of the old tool and the new tool. This is done for the reusable cup as well as a single-use alternative. The purpose of this analysis is to check whether the calculation works properly and if any errors or uncertainties arise when using the tool. In comparing the results of the old and new tool the difference in CO_2 emissions is highlighted and a conclusion is drawn stating if the result of the new tool is realistic.
Second, a scenario of reusable, foldable supermarket crates is applied. Here, two scenarios are applied: one where the crates are foldable and reduce in size when empty, and one where the crates stay the same size. This distinction is made to determine to what extent nesting the packagings makes a difference in CO_2 emission. In this scenario, no focus is put on the single-use alternative.
Third, an existing scenario of the product of Cabka is used to analyse the result of the tool when used in a real-life situation. This will more definitively conclude to what extent the tool could be used for existing products, and which problems might occur.

It is assumed that the scenarios that are applied in this chapter will show a more precise result in the CO_2 calculation. The calculations that were described in chapter 4 use more parameters, for example the 'number of trips saved' parameter, and therefore presumably perform a more thorough calculation. Furthermore, it is expected that this precision with respect to the old tool will show that the new tool is indeed a better way to calculate the CO_2 emission of a reusable packaging that nests than the original tool.

In the first two case studies (festival cup, supermarket crate) all data is made up but based on either real situations found online, or based on an educated guess. It is important to highlight that the case studies are merely used as an additional set of data to check if the tool works for products with a broadly different function, shape, and logistical system. They do not show a real situation. The data used in the third scenario (Cabka pallet) comes from classified documents provided by Cabka and reflect an existing situation.

5.2. Adding data to the new CO_2 calculation tool. Scenario 1: festival cup.

In the first case study, the life-cycle of a plastic, reusable festival cup (figure 27) is shown, with an emphasis on the transportation steps. The data that is shown is then applied to the original PfI CO_2 calculation tool, as well as the newly created CO_2 calculation tool. A comparison is made between the results of the new tool and that of the old one, and a conclusion is drawn. This is done for the reusable cup, as well as a single-use alternative. This paragraph serves as a test if the tool works properly and if any illogicalities or uncertainties arise. As comparing a reusable product with a single-use alternative is one of the main functions of both tools, this is the main focus of this paragraph. Different levels of nesting are not analysed in this paragraph to avoid confusion.

5.2.1. Description of the case study.

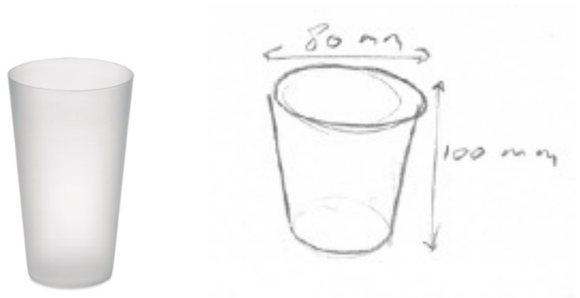


Figure 27: the reusable festival cup as analysed in this paragraph (left) with its measurements (right).

The cup is produced in a factory in Lithuania. It is made of polypropylene (PP), and it uses 50% recycled material. The cup is 29 grams Promofit, 2022), has a height of 100 mm, and the top of the cup has a diameter of 80 mm (based on assumptions). After production and inspection it is transported by truck to the Netherlands (16.000 km.). The cups are nested and transported in boxes. The truck has a carrying space of 46 cubic metres (Jonk, 2022). 896 boxes fit into the truck. The boxes are 50x30x30 cm which means that 360 cups fit in one box, leaving a bit of space on each side, as well as in between each nested stack of cups.
Once the truck has arrived at the distribution centre in the Netherlands, it is stored for three days after which it is transported to the storing facility of a secondary party (48 km.). This transportation step takes place in the same truck type, and the same number of boxes is transported. At the secondary storing facility in the city of Delft the cups are unboxed and placed in smaller boxes: these boxes are 40x20x20 cm meaning that 100 cups fit in one box. These boxes are transported by electrical cargo bike (1,6 km.) with a loading volume of 2,6 m^3 (1,5x1,5x1 m) which means that 36 small boxes fit in one cargo bike. The cups are transported to a small festival venue where they are used for one day. The next day, they are picked up by a large truck. In this stage, the cups are not stacked as compactly as in the previous transportation steps: they come in plastic bags, unstacked, meaning that instead of roughly 300.000 cups only 15.000 are transported in a fully loaded truck (12 km.). They are transported to a cleaning facility in The Hague where they are checked for damage, cleaned, and stored in a compact way. From here, they are transported in boxes again to the same storage facility in Delft (11 km.). The cups that are damaged or in any other way unusable are shipped to a plastic recycling plant in The Hague (2,1 km.). This is done in a large truck, also in a non-compact manner. Again, 15.000 cups are transported at the same time. On average, 10% of the cups that are checked are deemed unusable. The life span of one cup is approximately 40 cycles.

In the tables below (table 2-4), the data explained in this paragraph is shown.

Weight:	29 g
Volume of packed product:	0,5 L
Return rate:	90%
Technical lifespan	40 cycles
Material	Polypropylene (PP)
Recycled content	50%
Process	Injection moulding
Cleaning process	Industrial washing
% of products cleaned	100%
End-of-life scenario	Average Dutch waste scenario

Table 2: data of the first scenario as applied in the '1. INPUT' tab of the new tool.

Longest length (mm):	100
Longest width (mm):	80
Longest height (mm):	80

	Distance (km)	Mass (g)	V_2 (m^3)	Units	V_t (m^3)	U_{box}
T4	16.000	29	0,045	360	46	896
T5	48	29	0,045	360	46	896
T6	1,6	29	0,016	100	2,6	36
T8	12	29	46	15.000	-	-
T9	11	29	0,045	360	46	896
T11	2,1	29	46	15.000	-	-

Table 3-4: the data of the first scenario as applied to the 'New volume calculation; tab of the new tool.

Single use alternative

Figure 28: a single-use plastic cup.

The aforementioned reusable festival cup is compared to a single-use festival cup. This cup has the same dimensions. It is assumed that this cup has the same forward logistical system as the reusable cup except for some specific adjustments. These adjustments are listed below. The reason for this is that it will make the comparison of the two products easier. As stated in the introduction of this chapter, the purpose of this comparison is to analyse the functionality of the new tool, and giving the two products a similar logistical system makes that easier, as well as more accurate.

The single-use cup is made of 50% recycled polyethylene terephthalate (PET) and weighs approximately 9 grams. Because the cups are thinner than the reusable ones, a higher number can be transported at the same time. In this case, 400 cups fit in one box of the same size as for the reusable ones (50x30x30 cm). For the smaller boxes, 120 cups fit in a one box. Furthermore, this cup lacks a cleaning step as well as a return transport step, as they are not relevant for a single-use product.

Weight:	**9 g**
Volume of packed product:	0,5 L
Return rate:	**N.A.**
Technical lifespan	**N.A.**
Material	polyethylene terephthalate (PET)
Recycled content	50%
Process	Injection moulding
Cleaning process	**N.A.**
% of products cleaned	**N.A.**
End-of-life scenario	Average Dutch waste scenario

Table 5: data of the single-use alternative of the first scenario as applied in the '1. INPUT' tab of the new tool. The values that are different from the reusable cup are highlighted.

Longest length (mm):	100
Longest width (mm):	80
Longest height (mm):	80

	Distance (km)	Mass (g)	V_2 (m^3)	Units	V_t (m^3)	U_{box}
T4	16.000	29	0,045	**400**	46	896
T5	48	29	0,045	**400**	46	896
T6	1,6	29	0,016	**120**	2,6	36
T8	12	29	46	15.000	-	-
T9	11	29	0,045	**400**	46	896
T11	2,1	29	46	15.000	-	-

Table 6 and 7: the data of the single-use alternative of the first scenario as applied to the 'New volume calculation; tab of the new tool. The values that are different from the reusable cup are highlighted.

5.2.2. Calculations that take place when applying the 'festival cup' data.

In this paragraph, every calculation that takes place is explained in order of which they appear. For each formula, the transport step T4 is used as an example of how the values are applied. The full list of calculations can be found in appendix G.

First, V_1 is calculated. This is simply done by multiplying the longest length, width, and height of the cup. This is shown in figure 29.

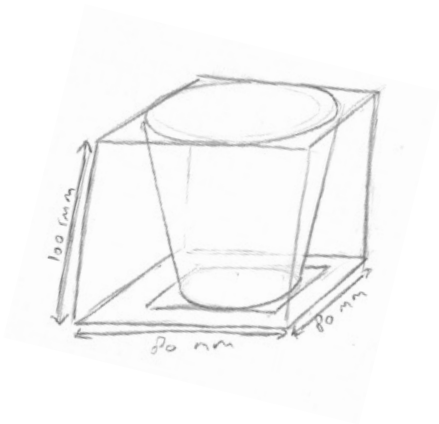


Figure 29: the surrounding volume of the cup.

This is done using the following formula:

T4: $V1 = l * b * h = 0{,}1 * 0{,}08 * 0{,}08 = 0{,}00064\ m3$

l = longest length
b = longest width
h = longest height

Next, the efficiency factors are calculated. For each transport step, it is calculated how efficiently the cups are stacked within the box (φ_1), and how efficiently the boxes are stacked within the truck (φ_2). This is shown in figure 30.

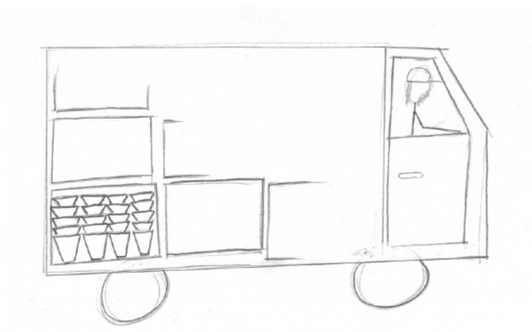


Figure 30: the cups are stacked nested in the boxes, and the boxes fit unnested in the truck.

Applying the values of T4 looks like this:

T4: $\varphi t = \frac{U}{V2/V1} * \frac{Ubox}{\frac{Vt}{V2}} = \frac{360}{\frac{0{,}045}{0{,}00064}} * \frac{896}{\frac{46}{0{,}045}} = 5{,}12 * 0{,}877 = 4{,}488$

U = number of primary packagings in a secondary packaging
V2 = inner volume of the secondary packaging
V1 = Surrounding volume of the primary packaging
U_{box} = the number of secondary packagings in the truck
V_t = The inner volume of the truck
V_2 = The inner volume of the secondary packaging.

In some cases (T8 and T11) no boxes are used. In that case the value input for Vt and Ubox are left empty.

Next, it is shown whether the transport step either saves an amount of trips by being efficient, or requires more trips because it is inefficient. This is shown in figure 31. This is determined by rounding down the total efficiency factor. For example, for T4 'φ_t' = 4,488, and therefore the number of trips that is saved is 4. When extra trips are needed, that value is found by dividing 1 by the total efficiency factor. For T6 'φ_t' = 0,88, therefore the number of extra trips needed is 1/0,88 = 1,13 = 1.

Output:

	Fi (efficiency factor) *Value input*	Fi 2 *Value input*	**Total factor:** *Value input*	**Extra trips needed:** *Value input:*	**Number of trips saved:** *Value input*	**Final factor** *Value input*	
Transport 1:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 2:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 3:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 4:	5,120	0,877	**4,488**	0	4	**0,435**	-
Transport 5:	5,120	0,877	**4,488**	0	4	**0,435**	-
Transport 6:	4,000	0,222	**0,886**	1	0	**16,976**	this step could be optimized!
Transport 7:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 8:	0,209	1,000	**0,209**	4	0	**46,297**	this step could be optimized!
Transport 9:	5,120	0,877	**4,488**	0	4	**0,435**	-
Transport 10:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 11:	0,209	1,000	**0,209**	4	0	**46,297**	this step could be optimized!
Transport 12:	1,000	1,000	**1,000**	0	0	**1**	-

Figure 31: lists of number of extra trips needed or number of trips saved per transport step.

Next, for every transport step a weight factor is calculated that describes how heavy the load is compared to the weight of the truck. This is done by dividing the total weight of all of the packagings combined by the weight of the truck that is given from Ecoinvent. For T4 that looks like this:

T4: $wf = \frac{GVW-AFL}{Load} = \frac{19.300}{322560*2,9E-6} = 2,063.$

wf = weight factor
Load = the weight of all of the primary packagings on the truck combined.
GVW = gross vehicle weight: the total weight of the truck including everything carried by the truck: the weight of the truck itself, the gasoline, the weight of the driver, etc.
AFL = average freight load: an average weight value used in Ecoinvent.

A final factor is given that will be multiplied with the original CO_2 calculation. This is done by using formula 8 and 9 from chapter 4:

When trips are saved:

$$\varphi f1 = \frac{\varphi t}{(ts + 1) * wf}$$

When extra trips are needed:

$$\varphi f2 = \varphi t * (tn + 1) * wf$$

$\varphi f1$ or $\varphi f2$ = the final factor used in the calculation
φ_t = the two efficiency factors multiplied
ts = the amount of trips saved
tn = the amount of extra trips needed
wf = the weight factor.

With the found values of every output parameter, the following final factor is found for T4:

T4: $\varphi f1 = \frac{4,488}{(4+1)*2,063}$ = 0,435.

Lastly, it is stated if the transport step could still be optimised. This is only the case if the process is inefficient, *and* the primary packagings are not full during this step. This is displayed as shown in figure 32.

Final factor *Value input*	
1	-
1	-
1	-
0,435	-
0,435	-
16,976	this step could be optimized!
1	-
46,297	this step could be optimized!
0,435	-
1	-
46,297	this step could be optimized!
1	-

Figure 32: list from the new tool showing whether or not each transport step could still be optimised regarding volume.

In table 8, every output from the 'volume calculation' tab is shown. By looking at the total efficiency factor it can be seen here that transport step 4, 5, and 9 are relatively efficient, as their respective total efficiency factors are relatively high. Transport step 6 could have been more efficient, but the cargo bike is in that case not as full with boxes as possible; this is shown by the second efficiency factor, which is only 0,222.

	V_1 (m^3)	Fi_1	Fi_2	Fi_t	Extra trips needed?	Trips saved?	Final factor	Could this step be optimised?
T4	0,00064	5,12	0,877	**4,488**	-	4	0,435	-
T5	"	5,12	0,877	**4,488**	-	4	0,435	-
T6	"	4,000	0,222	0,886	1	-	16,976	Yes
T8	"	0,209	-	0,209	4	-	46,297	Yes
T9	"	5,12	0,877	**4,488**	-	4	0,435	-
T11	"	0,209	-	0,209	4	-	46,297	Yes

Table 8: list of all of the output parameters when applying the 'festival cup' scenario.

This output table already shows a few things. Firstly, there are three transport steps (T6, T8, and T11) that could be optimised. The reason for this is that the cups are empty, and they are not stacked efficiently during that stage. Secondly, there are three other transport steps (T4, T5, and T9) that are already very efficiently stacked; four trips are already saved by stacking the cups efficiently.

The same process takes place for the single-use cup:

	V_1 (m^3)	Fi_1	Fi_2	Fi_t	Extra trips needed?	Trips saved?	Final factor	Could this step be optimised?
T4	0,00064	5,689	0,877	4,986	-	4	0,166	-
T5	"	5,689	0,877	4,986	-	4	0,166	-
T6	"	4,800	0,222	1,063	-	1	0,02	Yes
T11	"	0,209	-	0,209	4	-	149,178	Yes

Table 9: list of all of the output parameters when applying the single-use alternative to the 'festival cup' scenario.

For the single-use alternative, the same calculation steps are used. As previously mentioned, some aspects of this cup are different from the reusable one. Therefore, the outcome of the calculation is different. Because the calculation steps are still the same, only the output table for the single-use cup is listed in table 9.

5.2.3. CO_2 emissions per transport step

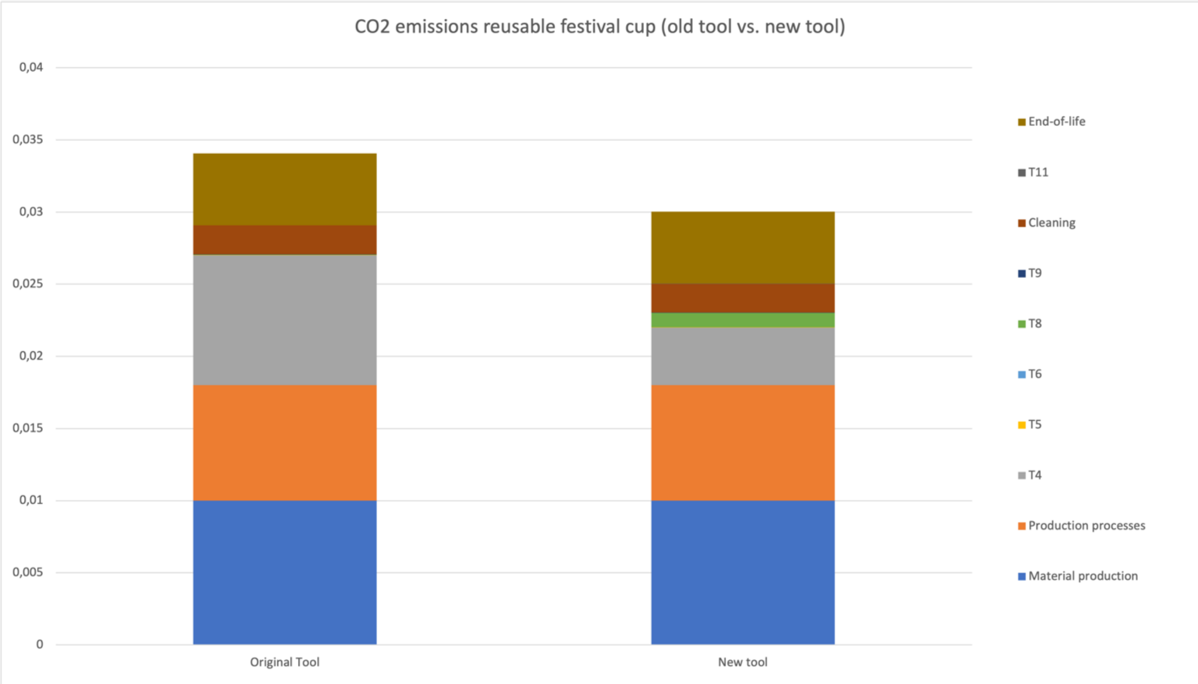


Figure 33: the result of applying the ***reusable festival cup*** *scenario to the old and new tool.*

In figure 33, the result of applying the reusable cup scenario to the old and new CO_2 calculation is shown. The results are also shown in table 10. The results as shown in both the original and new tool is shown in appendix F.

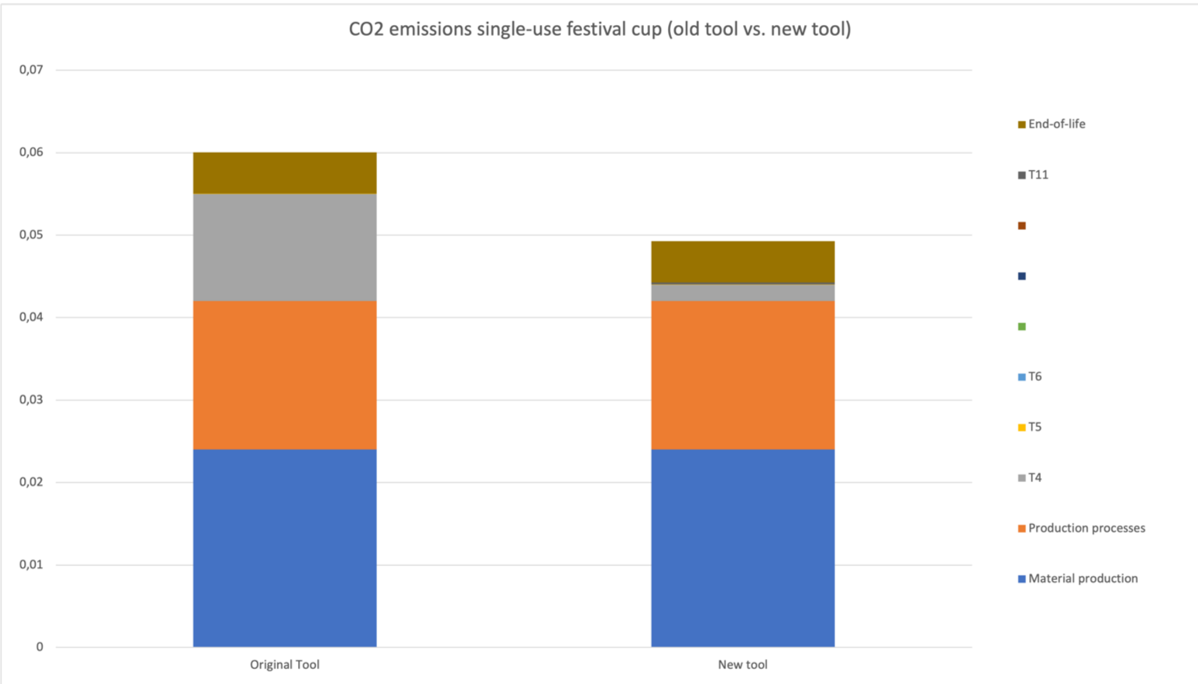


Figure 34: *the result of applying the* ***single-use festival cup*** *scenarios to the old and new tool.*

Figure 34 shows the result when applying the single-use cup scenario to the original and new CO_2 calculation tool. A list of the results is shown in table 11.

Reusable:

	Original CO_2 emission (kg CO_2)	Final factor	New CO_2 emission (kg CO_2)
Material production	0,010	-	0,010
Production processes	0,008	-	0,008
T4	0,009	0,435	0,004
T5	2,422E-5	0,435	1,05E-5
T6	3,712E-7	16,976	6,302E-6
T8	2,422E-5	46,297	0,001
T9	2,220E-5	0,435	9,657E-6
Cleaning	0,002	-	0,002
T11	1,701E-7	46,297	7,875E-6
End-of-life	0,005	-	0,005
Total CO_2 emissions (kg)	0,034		0,031

Table 10: the original CO_2 emissions, the final factor, and the new CO_2 emissions listed per step.

Single-use:

	Original CO_2 emission (kg CO_2)	Final factor	New CO_2 emission (kg CO_2)
Material production	0,024	-	0,024
Production processes	0,018	-	0,018
T4	0,013	0,166	0,002
T5	3,758E-5	0,166	6,239E-6
T6	1,152E-7	0,02	2,3E-9
T11	1,644E-6	149,178	2,453E-4
End-of-life	0,005	-	0,005
Total CO_2 emissions (kg)	0,059		0,045

Table 11: the original CO_2 emissions, the final factor, and the new CO_2 emissions of the single-use alternative listed per step.

Table 10 and 11 show the CO_2 emissions per step of the original tool when applying the 'festival cup' scenario. Next, it shows the final factor for every transport step. For every non-transport step this factor is not used. Finally, it shows the emissions when the final factor is applied. In the last column, the values where the final factor has a positive impact (meaning that the CO_2 emissions are lower when using the final factor) are coloured blue, whereas the steps where the final factor has a negative impact are coloured orange. Again, blue means that the packagings are transported efficiently, and orange means that they are transported inefficiently.

5.2.4. Take-aways from the results

Overall, the result of the CO_2 calculation for the reusable cup is slightly lower when applying the volume calculation in comparison to the original tool which is mass-based. However,

when looking at the final factors used in the volume calculation this should not be the case. For example, the final factor of T4 is 0,435 meaning that the CO_2 emission is approximately two times lower when applying the volume calculation than when using a mass-based calculation, whereas T8 has a final factor of 46,297 meaning that the CO_2 emission is higher by a factor of approximately 50 when using the volume calculation than when using a mass-based calculation.
The reason that the total CO_2 emission is still slightly lower when applying the volume calculation lies with T4. This is a transportation step that takes 16.000 km (table 7), and therefore has by far the biggest impact on the total life-cycle. In other words, reducing the CO_2 emission of T4 by a factor of 2 makes more impact than increasing the CO_2 emission of T8 by a factor of 50. This means that the distance is still very important in this calculation.

Besides the aforementioned distinction between high final factors, it is important to determine *why* they are of that proportion. The reason for this can be found in the calculation of the weight factor (appendix F). In these cases, the truck is not optimally filled, as φ_f is higher than 1. This means that a relatively low number of packagings is transported, which in turn means that the weight of the load is low compared to that of the truck; this results in a high weight factor.

Another interesting take away is that it is clearly stated which transport steps could still be optimised. In this specific scenario, for the ones that are not yet optimised that is presumably because this way it is quicker or cheaper. However, by stating that they could be optimised, the potential for decrease in CO_2 emission is highlighted.

In table 10 and 11 it can be seen that most transport steps have a relatively low CO_2 emission compared to other steps such as material production or cleaning. The reason for this is that these transport steps are relatively short (12 km, for example).
This is further proven by T4. Here, the distance is much higher (16.000 km) which gives a higher CO_2 emission. In order to analyse a more realistic outcome, a new scenario is set up where the distance for each transport step is higher. This is shown in paragraph 5.3.1.

Adjusting the number of packagings in a box shows that this has a significant impact on the final factor of a transport step, and therefore also on the CO_2 emission of said transport step. The number of cups carried per box is 120, resulting in a total factor of 1,063. As stated before, a total efficiency factor higher than 1 means that the trip is considered efficient, and one trip is saved by nesting the product. If the amount is changed to 112, the total factor is lower than 1, and an extra trip is needed again. When applying this change, the final factor changes to an extreme extent. This is shown in table 12, 13, and 14.

	Distance (km)	Mass (g)	V2 (m^3)	U	Vt (m^3)	Ubox
T6	1,6	9	0,016	**120**	2,6	36

Table 12: inputs of T6 of the single-use cup

	V1	Fi1	Fi2	Fi total	Extra trips needed?	Trips saved?	Final factor	Could this step be optimised?
T6	0,00064	4,000	**0,222**	**1,063**	-	1	**0,02**	No

Table 13: outputs of T6 of the single-use cup

	Units:	**Total factor:**	**Final factor:**	**Extra trips needed or trips saved?**
T6 (1)	112	0,992	54,7	One extra trip needed
T6 (2)	113	1,001	0,018	One trip saved
T6 (3)	120	1,063	0,02	One trip saved

Table 14: a comparison of different iterations of T6 of the single-use cup.

This shows that there is a threshold for the number of units that is transported where one extra unit per box makes an extreme difference. For this specific transport step, that threshold is 112 units per box.
For 112 units per box, the tool sees that the packagings are not transported as efficiently as possible and takes into account that an extra trip is needed to transport all of the packagings. For 113 units, however, the tool sees that nesting takes place which is adjusted accordingly in the calculation.
This result may seem counter-intuitive. If 113 units per box is very efficient, why would an extra trip be needed to carry 112 units per box? It is in this case important to clarify that 112 or 113 units does not refer to the exact number of units in a box but to the way that they are transported. A certain number of units must always be transported, but if it is done by transporting 112 units per box instead of 113 an extra trip is needed and the CO_2 emission skyrockets.

Figure 35 and 36 show how the final factor is affected by the number of units per box. The figures show the final factor per number of units per box. In figure 36, 0 – 112 units are left out to show that multiple thresholds appear on a smaller scale. There is a clear tipping point at 113, but there are others at 226 and 339 (and every other multiple of 113). These are the points where an extra trip is saved.

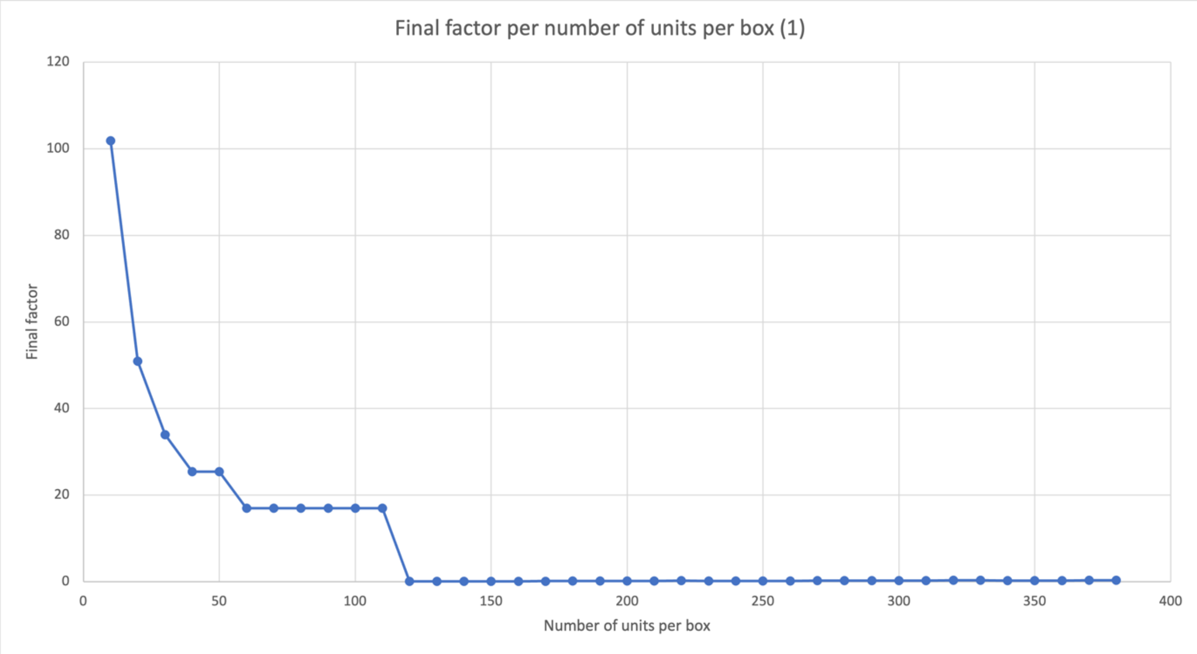


Figure 35: chart showing the final factor of T6 of the single-use festival cup per 10 units per box.

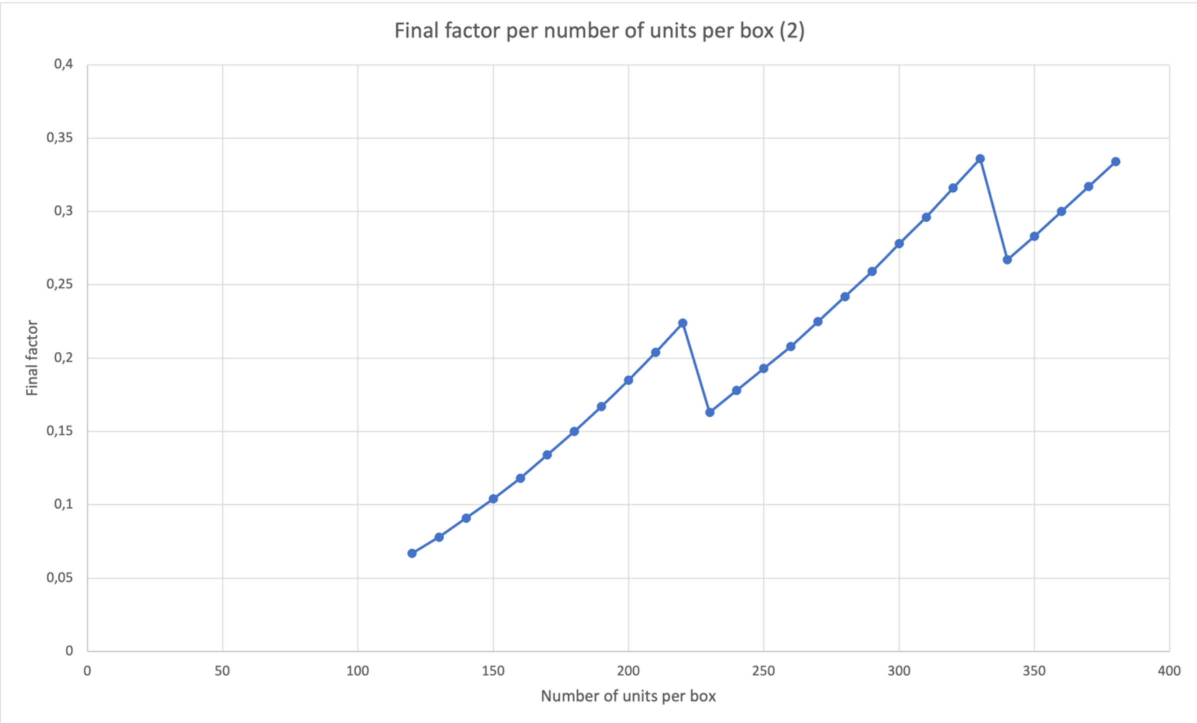


Figure 36: chart showing the final factor of T6 of the single-use festival cup per 10 units per box starting at 113 units.

The situation analysed here is very specific, and for several reasons it can be assumed that this would likely not happen in a real life scenario. Firstly, it is unlikely that a client using this tool has set up a logistical system in which an extra trip is needed for only a few more products. The point just before the big tipping is therefore not relevant in practical cases. Secondly, Several other ways of optimizing a logistical system are possible, but are not discussed in this thesis as they do not fall within the scope of this project. For example, a logistical company could fill the truck for one part with the packaging analysed here, and fill the other part with a product of a different company.

5.3. Adding data to the new CO_2 calculation tool. Scenario 2: Albert Heijn crate.

In this scenario, foldable crates used by Dutch supermarket chain Albert Heijn (figure 37) are analysed. The crates can fold when empty, which makes them relevant for this research. The results of the old tool and the new tool are compared and a conclusion is drawn. With this scenario an additional comparison is made: within the new tool, an additional scenario is created where the crates would *not* nest. This is also done in the new tool. To make this overview more clear, no single-use alternative is given in this scenario.

5.3.1. Description of the case study

Figure 37: reusable Albert Heijn crate.

The crates are produced and assembled in Germany. They are made of polyethylene (PE) and weigh 2,6 kg. They are made of 60% recycled content. Unfolded, the crates are 320 x 400 x 600 mm and when folded 53 x 400 x 600 mm (Manutan, 2022). When produced, they are shipped in folded state to a distribution centre in Hengelo in the Netherlands. This trip is 510 kilometre. This is done in a jumbo truck with an inner volume of 123,75 m^3 (2,5 x 3 x 16,50 m) (Lis, 2022). In this stage, 8100 crates are fitted in the truck.
From this distribution centre, the crates are (still folded) transported to a filling station. This happens in a smaller truck (46 m^3) (2,5 x 2,5 x 7,3) in which 2400 crates are transported at once. The trip is 55 km. Once they are filled, they are carried in the same type of truck (46 m^3) to the supermarket, which is 12 kilometres away. A total of 300 full crates are transported here. On the way back, the truck takes all of the empty crates that the supermarket has. Furthermore, the truck passes 4 other supermarkets that still have empty crates that can be returned. In total, the truck carries 1200 empty crates in the end. They end up back in the distribution centre. The broken crates are set aside and taken from the DC to a recycling plant 23 kilometres away. During this trip, 360 crates are transported. On average, 5% of the crates are deemed unusable per cycle. A crate lasts for 20 cycles on average.

Weight:	2600 g
Volume of packed product:	76 L
Return rate:	95%
Technical lifespan	20 cycles
Material	HDPE
Recycled content	60%

Process	Injection moulding
Cleaning process	Industrial washing
% of products cleaned	10%
EOL scenario	Average Dutch waste scenario

Table 15: data of the second scenario as applied in the '1. INPUT' tab of the new tool.

Longest length (mm):	600
Longest width (mm):	400
Longest height (mm):	320

	Distance (km)	Mass (g)	V_2 (m^3)	Units		V_t (m^3)	U_{box}
T1	510	2600	123,75	8.100	***1323***	-	-
T4	55	2600	46	2.400	***504***	-	-
T6	12	2600	46	300		-	-
T8	26	2600	46	1.200	***504***	-	-
T11	23	2600	46	360		-	-

Table 16-17: the data for the second scenario as applied to the 'volume calculation' tab of the new tool. The highlighted values for U are in a case where the crates are not folded.

In table 17, the values for the 'volume of the truck' and 'number of units' are listed under 'V_2' and 'Units'. This is done this way because the calculations in the tool will now correctly. For clarity, it is important to mention that these values refer to the inner volume of the truck and the number of crates in each truck.

5.3.2. Calculations that take place when applying the 'Albert Heijn crate' data.

In this paragraph, every calculation that takes place in applying this scenario to the tool is explained. In this case, when a comparison is made between nested and not nested, both calculations are given.

First, V1 is calculated. This is simply done by multiplying the longest length, width, and height of the crate in an unnested state. This is shown in figure 38.

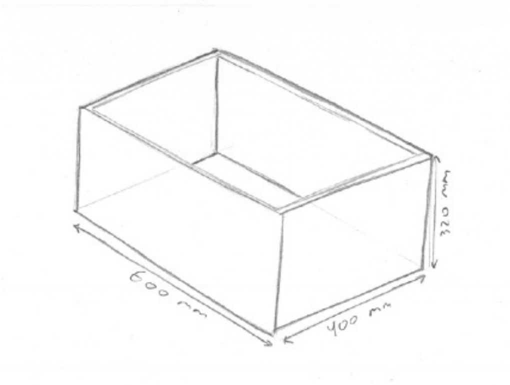


Figure 38: measurements of the Albert Heijn crate.

This is done using the following formula:

$$V1 = l * b * h = 0{,}6 * 0{,}4 * 0{,}32 = 0{,}0768\ m3$$

l = longest length
b = longest width
h = longest height

Next, the two efficiency factors as well as the total factor are calculated. In this step, there is a difference between nested and unnested states. Therefore, two examples of calculation are given:

T1 (nested): $\varphi t1 = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{8.100}{\frac{123{,}75}{0{,}0768}} * 1 = 6{,}221$

T1 (unnested): $\varphi t2 = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{\mathbf{1323}}{\frac{123{,}75}{0{,}0768}} * 1 = 0{,}821$

U = number of primary packagings in a secondary packaging
V2 = inner volume of the secondary packaging
V1 = Surrounding volume of the primary packaging
U_{box} = the number of secondary packagings in the truck
V_t = The inner volume of the truck
V_2 = The inner volume of the secondary packaging.

For the calculation, V_1 stays the same for both the nested and unnested scenario. Instead, whether the packaging is nested is reflected in the number of units that is transported. For the nested version, that unit is given by the user (in this case 8.100). When unnested, that number is calculated by dividing the inner measurements of the truck (for T1: '16,5 x 3 x 2,5') by the measurements of V_1 (0,6 x 0,4 x 0,32) rounding down to whole numbers. This results in 1323 units: (16,5/0,6)*(3/0,4)*(2,5/0,32) = 27*7*7 = 1323.
As previously mentioned, T1 uses a larger truck than the other transport steps (123,75 m^3 and 46 m^3 respectively). The smaller trucks have measurements of 7,3 * 2,5 * 2,5 meaning that (7,3/0,6) * (2,5/0,4) * (2,5/0,32) = 504 crates fit in the truck.

In this scenario, no secondary packagings are used. That is confusing, as a crate is commonly seen as a secondary packaging (Cartier, 2019). However, because the crate in this case is the main packaging analysed in the calculation, it is seen as a primary packaging.

Next, it is determined if trips are saved, or a number of extra trips is needed. This list is shown in figure 39 and 40. For T1, T4, and T8 the number of units changes when unnested. For the other transport steps, either the crates are filled and therefore already unnested, or the number of crates transported when nested is already lower than when unnested.

Output:

	Fi (efficiency factor) *Value input*	Fi 2 *Value input*	Total factor: *Value input*	Extra trips needed: *Value input:*	Number of trips saved: *Value input*	Final factor *Value input*	
Transport 1:	5,027	1,000	**5,027**	0	5	**0,914**	-
Transport 2:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 3:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 4:	4,007	1,000	**4,007**	0	4	**0,259**	-
Transport 5:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 6:	0,501	1,000	**0,501**	1	0	**24,787**	-
Transport 7:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 8:	2,003	1,000	**2,003**	0	2	**0,108**	-
Transport 9:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 10:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 11:	0,601	1,000	**0,601**	1	0	**24,787**	this step could be optimized!
Transport 12:	1,000	1,000	**1,000**	0	0	**1**	-

Output:

	Fi (efficiency factor) *Value input*	Fi 2 *Value input*	Total factor: *Value input*	Extra trips needed: *Value input:*	Number of trips saved: *Value input*	Final factor *Value input*	
Transport 1:	0,821	1,000	**0,821**	1	0	**9,214**	this step could be optimized!
Transport 2:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 3:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 4:	0,841	1,000	**0,841**	1	0	**24,787**	this step could be optimized!
Transport 5:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 6:	0,501	1,000	**0,501**	1	0	**24,787**	-
Transport 7:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 8:	0,841	1,000	**0,841**	1	0	**24,787**	this step could be optimized!
Transport 9:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 10:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 11:	0,601	1,000	**0,601**	1	0	**24,787**	this step could be optimized!
Transport 12:	1,000	1,000	**1,000**	0	0	**1**	-

Figure 39 and 40: the table from the new tool showing the list of number of extra trips needed or number of trips saved per transport step nested (left) and unnested (right).

Next, for every transport step a weight factor is calculated that describes how heavy the load is compared to the weight of the truck. This is done by dividing the total weight of all of the packagings combined by the weight of the truck that is given from Ecoinvent. For T1 that looks like this:

T1 (nested): $wf1 = \frac{GVW-AFL}{Load} = \frac{19.300}{8100*2,6} = 0,916.$

T1 (unnested): $wf2 = \frac{GVW-AFL}{Load} = \frac{19.00}{1323*2,6} = 5,611.$

wf = weight factor
Load = the weight of all of the primary packagings on the truck combined.
GVW = gross vehicle weight: the total weight of the truck including everything carried by the truck: the weight of the truck itself, the gasoline, the weight of the driver, etc.
AFL = average freight load: an average weight value used in Ecoinvent.

A final factor is given that will be multiplied with the original CO_2 calculation. This is done by using formula 8 and 9 from chapter 4:

When trips are saved:

$$\varphi f1 = \frac{\varphi t}{(ts + 1) * wf}$$

When extra trips are needed:

$$\varphi f2 = \varphi t * (tn + 1) * wf$$

φf1 or φf2 = the final factor used in the calculation
φ_t = the two efficiency factors multiplied
ts = the amount of trips saved
tn = the amount of extra trips needed
wf = the weight factor.

With the found values of every output parameter, the following final factor is found for T1:

T1 (nested): $\varphi f1 = \frac{6{,}221}{(6+1)*0{,}916}$ = 0,435.

T1 (unnested): $\varphi f2 = 0{,}821 * (1 + 1) * 5{,}611 = 9{,}214$

Lastly, it is stated if the transport step could still be optimised. This is only the case if the process is inefficient, *and* the primary packagings are not full during this step. This is displayed as shown in figure 41.

actor	
input	
0,135	-
1	-
1	-
0,259	-
1	-
24,787	-
1	-
0,108	-
1	-
1	-
24,787	this step could be optimized!
1	-

factor	
input	
9,214	this step could be optimized!
1	-
1	-
24,787	this step could be optimized!
1	-
37,18	-
1	-
24,787	this step could be optimized!
1	-
1	-
24,787	this step could be optimized!
1	-

Figure 41: list from the new tool showing whether or not each transport step of the nested crate (left) and unnested crate (right) could still be optimised regarding volume.

Table 18 and 19 show a full list of the outputs of the 'Albert Heijn crate' scenario, nested and unnested, respectively.

	V_1 (m^3)	Fi_1	Fi_2	Fi_t	Extra trips needed?	Trips saved?	Final factor	Could this step be optimised?
T1	0,0768	5,027	-	5,027	-	5	0,914	-
T4	"	4,007	-	4,007	-	4	0,259	-
T6	"	0,501	-	0,501	1	-	24,787	-
T8	"	2,003	-	2,003	-	2	0,108	-
T11	"	0,601	-	0,601	1	-	24,787	Yes

Table 18: a list of outputs of the nested version of the 'Albert Heijn crate' scenario.

	V_1 (m^3)	Fi_1	Fi_2	Fi_t	Extra trips needed?	Trips saved?	Final factor	Could this step be optimised?
T1	0,0768	0,821	-	0,821	1	-	9,214	Yes
T4	"	0,841	-	0,841	1	-	**24,787**	Yes
T6	"	0,501	-	0,501	1	-	**24,787**	-
T8	"	2,003	-	2,003	1	-	**24,787**	Yes
T11	"	0,601	-	0,601	1	-	**24,787**	Yes

Table 19: a list of outputs of the unnested version of the 'Albert Heijn crate' scenario.

One remarkable result that becomes apparent instantly is the recurring value of '24,787'. This happens because both the total efficiency factor and the weight factor rely on the 'number of units' parameter. This is further explained in paragraph 5.3.4.

5.3.3. CO_2 emissions per transport step

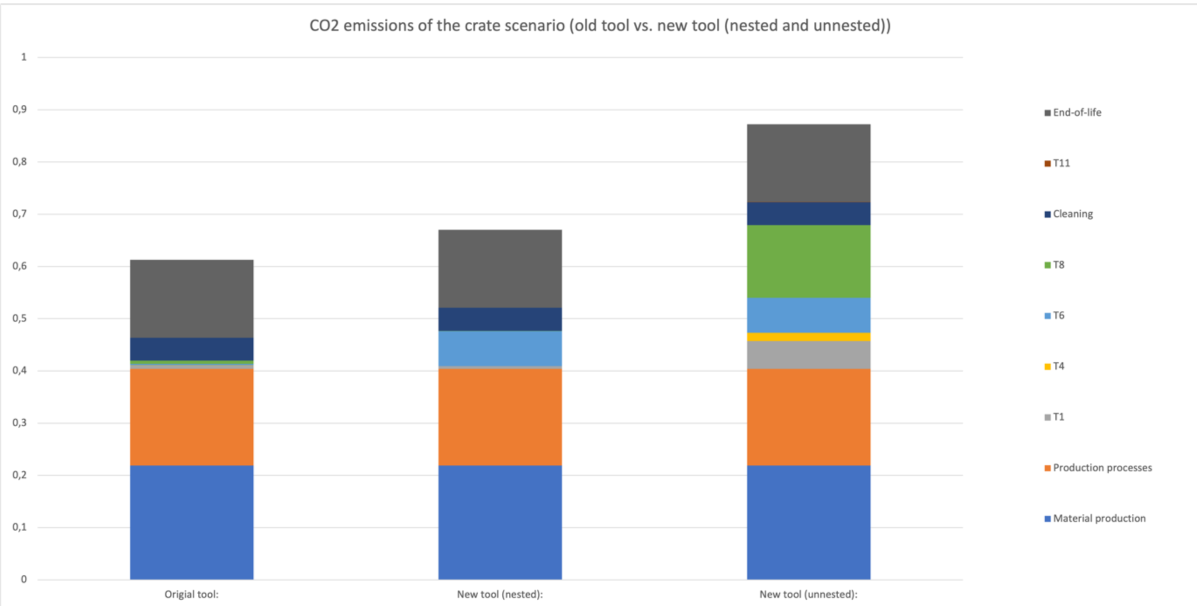


Figure 42: *the result of applying the Albert Heijn crate scenarios to the old tool and the new tool when nested and unnested.*

Figure 42 shows the result of applying the crate scenario to the old tool, as well as the new tool in a scenario where it nests when empty and when it does not nest. The full results are shown in table 20. Screenshots from the results of tools themselves can be found in appendix F.

Reusable:

	Original CO_2 emission (kg CO_2)	Final factor (nested)	New CO_2 emission (nested) (kg CO_2)	Final factor (unnested)	New CO_2 emission (unnested) (kg CO_2)
Material production	0,219	-	0,219	-	0,219
Production processes	0,185	-	0,185	-	0,185
T1	0,006	0,194	0,005	9,214	0,053
T4	6,22E-4	0,259	1,611E-4	24,787	0,016
T6	0,003	24,787	0,067	24,787	0,067
T8	0,006	0,108	6,034E-4	24,787	0,139
Cleaning	0,044	-	0,044	-	0,044
T11	1,236E-5	24,787	3,063E-4	24,787	3,063E-4
End-of-life	0,149	-	0,149	-	0,149
Total CO_2 emissions (kg)	0,612	-	0,671	-	0,872

Table 20: the original CO_2 emissions, the final factor, and the new CO_2 emissions listed per step.

5.3.4. Take-aways from the results of applying the second scenario.

When applying the volume-based calculation to this scenario, the total CO_2 emission becomes slightly higher. Similar to the first scenario, the reason for this is that some transport steps (T1, T4, T8) are efficient, and some are inefficient (T6, T11), some are high in CO_2 emission and some are low. Because of this, the CO_2 result of some transport steps is higher than the original calculation, and for some it is lower. Looking at the first two scenarios applied to this tool, it can be stated that the volume-based calculation will give a more precise result as more parameters are taken into account. However, with the second scenario it is shown that this does not always mean that the CO_2 impact will be lower. Applying the scenario where the crates do not nest at all gives a higher result in the CO_2 emissions. This is to be expected, as every transport step is now inefficient, meaning that more trips are needed overall.

The unnested scenario does show one remarkable result: the final factor of '24,787' appears four times. All of these transport steps have a different efficiency factor making this final factor counter-intuitive. The reason for this lies with the number of units that are transported. On one hand, fewer units means less efficient and therefore a lower efficiency factor (φ_t). However, it also means a lower weight of the freight, and therefore a higher weight factor (wf). As the number of units is the only factor that changes, these two factors cancel each other out and the final result is the same. An elaboration is given in the table below.

Parameter:	Formula:	Values:
φt	$\frac{U}{V2/V1} * \frac{Ubox}{\frac{Vt}{V2}}$	$\frac{504}{\frac{46}{0{,}0768}} * 1 = 0{,}841$
wf	$\frac{GVW - AFL}{m * U}$	$\frac{19{,}3}{504 * 2600} = 14{,}728$
φf	$\frac{U}{V2/V1} * (tn + 1) * \frac{GVW - AFL}{m * U}$	$\frac{504 * (1 + 1) * 19{,}3}{\frac{46}{0{,}0768} * 1 * 2.600 * 504}$

Table 21: when calculating the final factor of T4(unnested) when extra trips are needed, 'U' is cancelled out of the equation.

The parameter for the number of units 'U' appears in the numerator as well as the denominator of the equation, and is therefore cancelled out. 'U' does, however, affect the number of extra trips needed, which does in turn affect the outcome of the final factor of that transport step. Figure 43 shows how the parameter 'U' can be taken out of the equation for the final factor.

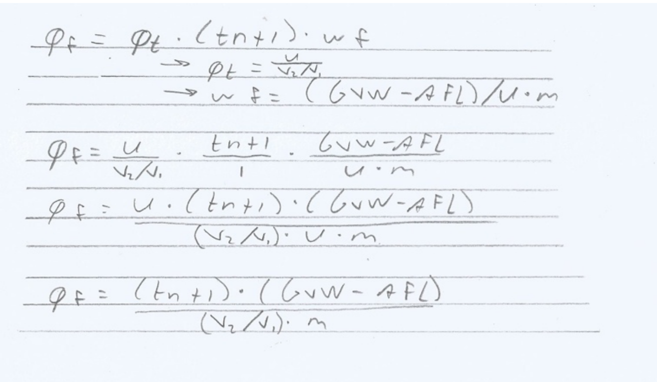


Figure 43: parameter 'U' (the number of units per box) can be taken out of the equation for the final factor and therefore does not affect the value of the final factor.

This is not the case when trips are saved: in that case the efficiency factor is divided by the weight factor, and therefore 'U' stays in the formula and has a direct effect on the final factor. This is shown in table 22.
The practical reason why this is the case for 'extra trips needed' and not for 'trips saved' is still unclear and needs to be solved in a further iteration of the tool. This is further elaborated on in the discussion in chapter 7.

Parameter:	Formula:	Values:
φt	$\frac{U}{V2/V1} * \frac{Ubox}{\frac{Vt}{V2}}$	$\frac{2.400}{\frac{46}{0{,}0768}} * 1 = 5{,}027$
wf	$\frac{GVW - AFL}{m * U}$	$\frac{19{,}3}{2.400 * 2600} = 3{,}093$
φf	$\frac{\frac{U}{V2/V1}}{(ts + 1) * \frac{GVW - AFL}{m * U}}$	$\frac{\frac{2.400}{46/0{,}0768}}{(4 + 1) * \frac{19{,}3}{2.600 * 2.400}}$

Table 22: when calculating the final factor of T4(nested) when extra trips are needed, 'U' cannot be cancelled out of the equation.

5.4. *Adding data to the new CO_2 calculation tool. Scenario 3: Cabka Endure i9 pallet.*

For a third scenario, a product of Cabka is analysed. In this case, the Cabka Endure i9 pallet is used as an example (figure 43). Here, a logistical system for an unknown chemicals company is used. The data used in this analysis is listed in the tables below. All data from this scenario is retrieved from classified documents provided by Cabka, or technical data from the Cabka website (Cabka, 2022). The purpose of this scenario is to check if the tool works for a realistic scenario.

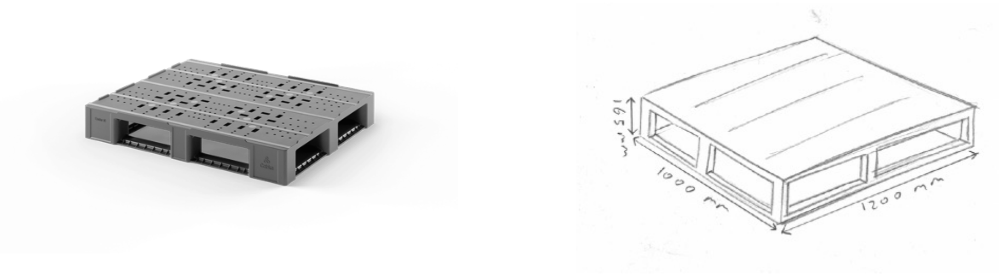


Figure 43: the Cabka Endure i9 pallet (left) and its measurements (right).

5.4.1. Description of the scenario

First, the pallet is transported from the producer to the filler. The location of both stations are unknown. However, it is known that the trip takes 200 km. In this step, 300 pallets are transported. Next, the pallet is taken from the filling station to a distribution centre. During this transport step, the pallet is filled with the product that it is supposed to carry. This time 40 pallets are carried. This trip is 50 km. Next, the pallet is taken to the releaser, which is 1000 km away. During this trip the pallets are also filled, and again 40 pallets are transported. After that, the pallet is empty again and transported back to the filler, again with 300 pallets in the truck. This also takes 1000 km. All of the unusable pallets are transported to the waste treatment, again 1000 km away. 300 pallets fit in this truck. No cleaning step takes place in this scenario. The pallets are assumed to last 40 cycles.
For each transport step, a truck with an inner volume of 81,63 m^3 (13,6 x 2,45 x 2,45) is used.

Weight:	13.000 g
Volume of packed product:	1.800 L
Return rate:	89%
Technical lifespan	40 cycles
Material	HDPE
Recycled content	100%
Process	Injection moulding
Cleaning process	-
% of products cleaned	0%
EOL scenario	Recycling

Table 23: the values for the Cabka Endure i9 pallet as filled in the 'INPUT' tab.

Longest length (mm):	1200
Longest width (mm):	1000
Longest height (mm):	1665

	Distance (km)	Mass (g)	V_2 (m^3)	Units	V_t (m^3)	U_{box}
T1	200	13.000	81,63	300	-	-
T4	50	13.000	81,63	40	-	-
T6	1000	13.000	81,63	40	-	-
T8	1000	13.000	81,63	300	-	-
T11	1000	13.000	81,63	300	-	-

Table 24 and 25: the values for the Cabka Endure i9 pallet as filled in the 'volume calculation' tab.

'Single use' alternative

Figure 44: wooden pallet

The Endure i9 pallet is in this case compared to a wooden pallet (figure 44). This is technically not a single-use product, as wooden pallets are reused as well. According to Poirier (personal interview, 2022) they have a damage rate of 25%, meaning that during one cycle 25% of the pallets are damaged. Reparation is not possible for wooden pallets, and therefore the broken pallets are considered lost. Furthermore, the wooden pallets have a loss rate of 2% per cycle. A wooden pallet lasts approximately 4 cycles on average. Because they do have a return rate, as well as a number of cycles, the data for the wooden pallet is filled in in a separate Excel file for both the original tool and the new tool.
This pallet has different measurements than the Endure i9 (1200 x 800 x 150) and is heavier (25 kg) (Kruizinga, 2022). All other data used for the wooden pallet is provided by Cabka.

Weight:	25.000 g
Volume of packed product:	1.800 L
Return rate:	73%
Technical lifespan	4 cycles
Material	Wood
Recycled content	0%
Process	Wood sawing
Cleaning process	-
% of products cleaned	0%
EOL scenario	Average Dutch waste scenario

Table 26: the values for the wooden pallet as filled in the 'INPUT' tab.

5.4.2. Calculations that take place when applying the 'Cabka' data.

In this paragraph, every calculation that takes place is explained in order of which they appear. For each formula, the transport step T1 is used as an example of how the values are applied. The full list of calculations can be found in appendix F.

The Cabka Endure i9 pallet is compared to a standard wooden pallet. For the first few steps (V_1, efficiency factor, number of trips saved or needed) the calculation is the same for both alternatives, and therefore only one example will be given for each calculation.

First, V_1 is calculated. This is done using the following formula:

$$V1 = l * b * h = 1 * 1{,}2 * 0{,}165 = 0{,}198\, m3$$

l = longest length
b = longest width
h = longest height

Next, the total efficiency factor is calculated. In this case there is no secondary packaging, and therefore the first efficiency factor is the same as the total efficiency factor:

$$\text{T1: } \varphi t1 = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{300}{\frac{81{,}63}{0{,}198}} * 1 = 0{,}728$$

U = number of primary packagings in a secondary packaging
V2 = inner volume of the secondary packaging
V1 = Surrounding volume of the primary packaging
U_{box} = the number of secondary packagings in the truck
V_t = The inner volume of the truck
V_2 = The inner volume of the secondary packaging.

In this scenario, no secondary packagings are used. Similar to the previous scenario this might seem confusing, as a pallet is commonly seen as a tertiary packaging (Cartier, 2019). However, because the pallet in this case is the main packaging analysed in the calculation, it is seen as a primary packaging.

Next, it is determined if trips are saved, or a number of extra trips is needed. This list is shown in figure 45 and 46.

Output:

	Fi (efficiency factor) Value input	Fi 2 Value input	Total factor: Value input	Extra trips needed: Value input:	Number of trips saved: Value input	Final factor Value input	
Transport 1:	0,728	1,000	**0,728**	1	0	**7,202**	this step could be optimized!
Transport 2:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 3:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 4:	0,097	1,000	**0,097**	10	0	**39,612**	-
Transport 5:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 6:	0,097	1,000	**0,097**	10	0	**39,612**	-
Transport 7:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 8:	0,728	1,000	**0,728**	1	0	**7,202**	this step could be optimized!
Transport 9:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 10:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 11:	0,728	1,000	**0,728**	1	0	**7,202**	this step could be optimized!
Transport 12:	1,000	1,000	**1,000**	0	0	**1**	-

Output:

	Fi (efficiency factor) Value input	Fi 2 Value input	Total factor: Value input	Extra trips needed: Value input:	Number of trips saved: Value input	Final factor Value input	
Transport 1:	0,529	1,000	**0,529**	1	0	**2,724**	this step could be optimized!
Transport 2:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 3:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 4:	0,071	1,000	**0,071**	14	0	**20,428**	-
Transport 5:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 6:	0,071	1,000	**0,071**	14	0	**20,428**	-
Transport 7:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 8:	0,529	1,000	**0,529**	1	0	**2,724**	this step could be optimized!
Transport 9:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 10:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 11:	0,529	1,000	**0,529**	1	0	**2,724**	this step could be optimized!
Transport 12:	1,000	1,000	**1,000**	0	0	**1**	-

Figure 45 and 46: the table from the new tool showing the list of number of extra trips needed or number of trips saved per transport step for the Cabka Endure i9 pallet (left) and for the wooden pallet (right).

Next, for every transport step a weight factor is calculated that describes how heavy the load is compared to the weight of the truck. This is done by dividing the total weight of all of the packagings combined by the weight of the truck that is given from Ecoinvent. In this step, there is a difference between the endure i9 pallet and the wooden pallet, as they have a different weight. For T1 that looks like this:

T1 (Endure) : $wf1 = \frac{GVW-AFL}{load} = \frac{19.300}{300*13}$ = 4,949.

T1 (wood) : $wf2 = \frac{GVW-AFL}{load} = \frac{19.300}{300*25}$ = 2,573.

wf = weight factor
Load = the weight of all of the primary packagings on the truck combined.
GVW = gross vehicle weight: the total weight of the truck including everything carried by the truck: the weight of the truck itself, the gasoline, the weight of the driver, etc.
AFL = average freight load: an average weight value used in Ecoinvent.

This means that for the wooden pallet, an extra trip is not as important compared to the weight of the freight, because the pallets are relatively heavy.

A final factor is given that will be multiplied with the original CO_2 calculation. This is done by using formula 8 and 9 from chapter 4:

When trips are saved:

$$\varphi f1 = \frac{\varphi t}{(ts + 1) * wf}$$

When extra trips are needed:

$$\varphi f2 = \varphi t * (tn + 1) * wf$$

φf1 and φf2 = the final factor used in the calculation
φ_t = the two efficiency factors multiplied
ts = the amount of trips saved
tn = the amount of extra trips needed
wf = the weight factor.

With the found values of every output parameter, the following final factors are found for T1:

T1 (Endure): $\varphi f1 = 0{,}728 * (1 + 1) * 4{,}949$ = 7,202.

T1 (wood): $\varphi f1 = 0{,}582 * (1 + 1) * 2{,}573$ = 2.996.

Finally, it is checked whether there are transport steps that could still be optimised. In both scenarios, this is the case for T1, T8, and T11. This is shown in figure 47 and 48.

ıctor	
nput	
7,202	this step could be optimized!
1	-
1	-
39,612	-
1	-
39,612	-
1	-
7,202	this step could be optimized!
1	-
1	-
7,202	this step could be optimized!
1	-

ıctor	
nput	
2,996	this step could be optimized!
1	-
1	-
19,474	-
1	-
19,474	-
1	-
2,996	this step could be optimized!
1	-
1	-
2,996	this step could be optimized!
1	-

Figure 47 and 48: for both the endure pallet (left) as well as the wooden pallet (right) no transport steps can be optimised.

In table 27 and 28 a full list of the outputs of both alternatives is given.

	V_1 (m^3)	Fi_1	Fi_2	Fi_t	Extra trips needed?	Trips saved?	Final factor	Could this step be optimised?	Weight factor:
T1	**0,198**	0,728	-	0,728	1	-	7,202	Yes	4,949
T4	''	0,097	-	0,097	10	-	39,612	-	37,115
T6	''	0,097	-	0,097	10	-	39,612	-	37,115
T8	''	0,728	-	0,728	1	-	7,202	Yes	4,949
T11	''	0,728	-	0,728	1	-	7,202	Yes	4,949

Table 27: a list of outputs of the 'Endure i9 pallet' scenario.

	V_1 (m^3)	Fi_1	Fi_2	Fi_t	Extra trips needed?	Trips saved?	Final factor	Could this step be optimised?	Weight factor:
T1	**0,144**	0,529	-	0,529	1	-	2,724	Yes	2,573
T4	''	0,071	-	0,071	14	-	20,428	-	19,3
T6	''	0,071	-	0,071	14	-	20,428	-	19,3
T8	''	0,529	-	0,529	1	-	2,724	Yes	2,573
T11	''	0,529	-	0,529	1	-	2,724	Yes	2,573

Table 28: a list of outputs of the 'wooden pallet' scenario.

5.4.3. CO_2 emissions per transport step

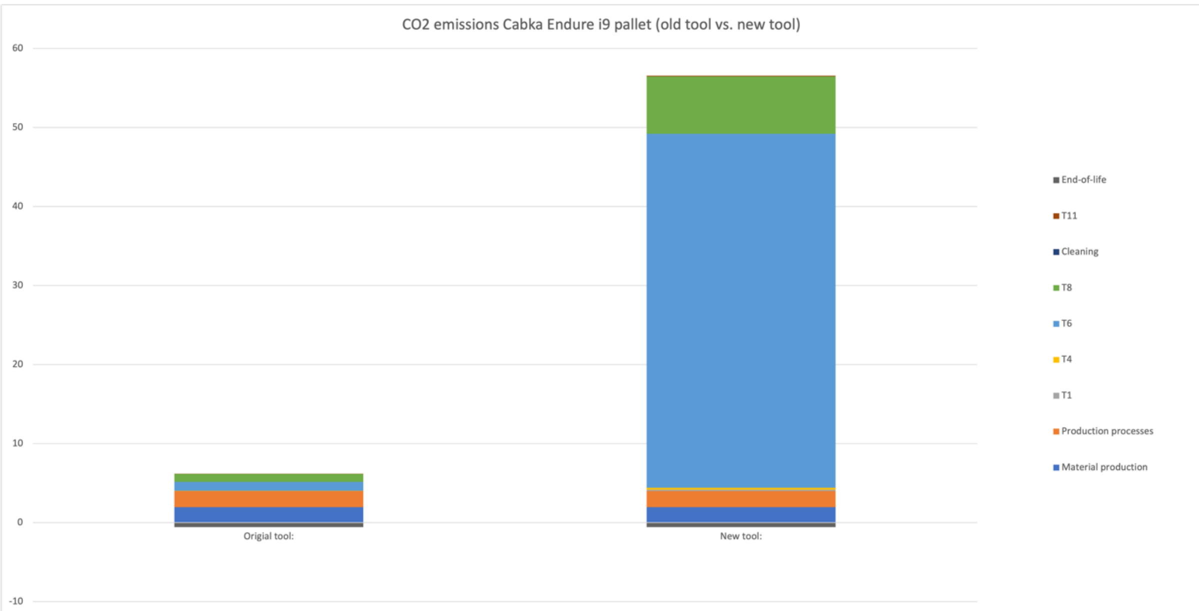


Figure 49: CO_2 emissions of the endure i9 in the old and new tool.

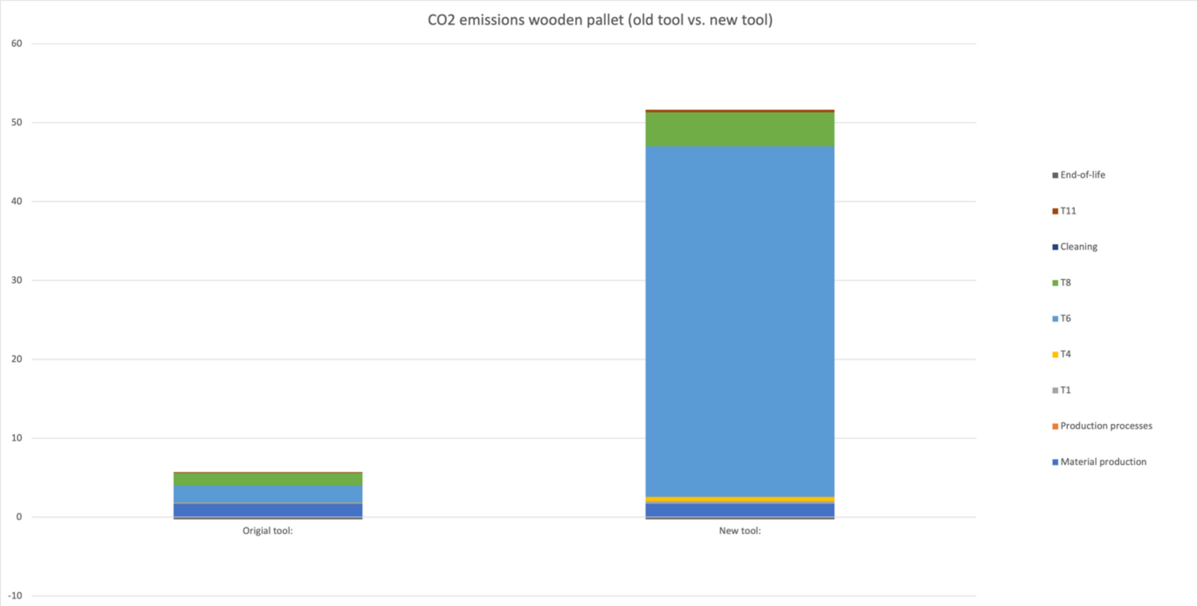


Figure 50: CO_2 emissions of the wooden pallet in the old and new tool.

Figure 49 and 50 show the CO_2 emission of the Endure i9 pallet in both tools and the CO_2 emission of the wooden pallet in both tools, respectively. The full results are also displayed in table 29 and 30. Screenshots of applying this data to both tools can be found in appendix F.

Endure:

	Original CO_2 emission (kg CO_2)	Final factor	New CO_2 emission (kg CO_2)
Material production	1,944	-	1,944
Production processes	2,039	-	2,039
T1	0,025	7,202	0,179
T4	0,006	39,612	0,245
T6	1,131	39,612	**44,801**
T8	1,007	7,202	7,250
Cleaning	0,000	-	0,002
T11	0,012	7,202	0,089
End-of-life	-0,570	-	-0,570
Total CO_2 emissions (kg)	5,594		55,977

Table 29: the original CO_2 emissions, the final factor, and the new CO_2 emissions listed per step.

Wooden:

	Original CO_2 emission (kg CO_2)	Final factor	New CO_2 emission (kg CO_2)
Material production	1,701	-	1,701
Production processes	0,000	-	0,000
T1	0,118	2,996	0,320
T4	0,029	19,474	0,560
T6	2,175	19,474	**44,431**
T8	1,588	2,996	4,325

Cleaning	0,000	-	0,000
T11	0,116	2,996	0,315
End-of-life	-0,275	-	-0,275
Total CO_2 emissions (kg)	5,451		51,417

Table 30: the original CO_2 emissions, the final factor, and the new CO_2 emissions listed per step.

5.4.4. Take-aways from the results of applying the third scenario.

One thing that becomes apparent in both the endure pallet as well as the wooden pallet is the extreme increase in CO_2 emissions for T6. With a value of 44,801 and 42,356 the CO_2 emission of said transport step is approximately a factor 100 higher than any other transport step. There are two factors causing this. Firstly, the pallets are full in this stage meaning that they cannot be stacked efficiently. This gives a relatively high final factor, which in turn means that the CO_2 emission is relatively high. Secondly, transport step T6 takes 1000 km. This is also relatively high. This means that disproportionate transport steps appear in existing scenarios too.

According to the result of the new tool, transport steps T1, T8, and T11 could still be optimised regarding volume. This is in contrast with the information provided by Cabka; Poirier (personal interview, 2022) has stated that these steps could not be further optimised. There are several reasons for this. Firstly, the inside of the truck needs a bit of empty space at the top to make loading possible. In order to carry the pallets they need to be picked up, usually with a forklift, and that requires extra space above the pallets. Secondly, the door of the truck is smaller than the room itself. Therefore, the stacks of pallets cannot be as high as the inside of the truck either. This existing scenario shows that the 'could this transport step be optimised?' section of the tool is not always accurate and needs to be reconsidered if a further iteration of the tool were to be used by a client.

The CO_2 emissions of the endure pallet and the wooden pallet are very similar. They are both not nestable and therefore the only difference lies with the weight and the slightly different measurements. However, because all of the data used in this scenario comes from an existing situation the conclusion drawn from this step is still considered valid.

5.5. Conclusion to the applying of scenarios

The scenarios that are applied to both the original CO_2 calculation tool by PfI and the newly developed tool show that the new tool gives a more precise result to the CO_2 calculation. By including volume in the calculation the transport steps that are inefficient (meaning that the packagings are not nested) will show a higher CO_2 emission because more trips are needed to transport the packagings. Furthermore, the applying of the scenarios shows that nesting does indeed make a significant difference on the CO_2 emission of the packaging.
Lastly, by applying an existing scenario it is shown that the new tool also works in a real situation.

Several new findings were found in the process of applying scenarios. Firstly, multiple thresholds appear in the final factor when adjusting the number of units transported. When the total efficiency factor is slightly below 1 the final factor is very low, resulting in a low CO_2 footprint. However, when the efficiency factor is slightly higher than 1 an extra trip is needed, which is reflected in a high final factor. A similar threshold, although to a smaller extent, appears for each time an extra trip is saved or needed. The logical reasoning behind this is that just below this threshold an extra trip is needed, but only to transport a few more products. This is then considered very inefficient. It can be assumed that this does not happen often in real situations, as a transportation company usually optimises their logistical system so that this does not occur.

In the calculation of the final factor for transport steps where extra trips are needed the specific value for 'U' (number of units per box or number of units per truck) does not matter anymore. In this formula, the total efficiency factor is multiplied with the weight factor. In the former, 'U' appears in the numerator, and in the latter 'U' appears in the denominator. Therefore, 'U' is cancelled out. The number of units does, however, affect the value for extra trips needed, which does affect the final factor.

The real life scenario that is applied (Cabka Endure i9, scenario 3) shows that several transport steps could be optimised regarding volume. However, the company that provided the data for this system (Cabka) also claims that no further optimisation is possible for several practical reasons. This shows that this section of the tool might have some limitations when used by a client.

6. Discussion

During the making of this report, several discussion points arose.
The literature study conducted in this report shows that transportation can be taken more into account in LCA studies. It is a key aspect of LCA, yet many LCA studies gloss over the transportation process, downplaying its impact in the overall study. Especially in LCA's regarding reusable products transportation is one of the most important aspects, and the result of the study performed in this thesis shows that optimisation in this aspect could have an immense impact.
The calculations described in this report are found by a means of trial and error. This means that there is a possibility that the calculation is more complex than necessary. There are several examples of irregularities in the calculation that may be caused by this.
Firstly, the 'number of trips saved' and 'extra trips needed' parameters are rounded off. It is calculated as such because of its practical logicality: within a logistical system a trip from point A to point B must always be made. If this number is not rounded, the truck would theoretically end up somewhere halfway. However, this addition to the calculation does create a remarkable irregularity in the CO_2 outcome, and it is therefore necessary to analyse further in a later iteration.
Secondly, in some cases the parameter 'U' becomes irrelevant for the final factor. A mathematical explanation is given: 'U' appears in the numerator and denominator of the final factor and is therefore cancelled out. However, it is unclear why this is only he case for 'extra trips needed' and not for 'trips saved'. In order to further analyse this, a more thorough analysis with scenarios must be performed in future studies.

The research shown in this thesis encourages companies to focus on transportation as well as volume when analysing the environmental sustainability of their product. This will improve the environmental footprint of the product, but hopefully also the people's mindset; it encourages people to think about every aspect of sustainability, and this is one of the key aspects of changing the world for the better. Hopefully, the result of this thesis will be used as a building block for future studies.

7. Conclusion and recommendation

7.1. Answering each sub-research question.

To definitively conclude the research performed in this report, each sub-research question is answered.

7.1.1. How is transport modelled and quantified in Ecoinvent?

Ecoinvent uses tonkm (ton kilometre) as a unit to measure the environmental impact of a transport process. In that calculation, the GVW (gross vehicle weight) is taken into account as well. This value describes the total weight of what is transported, including the freight, the weight of the truck, an average amount of gasoline, etc. Furthermore, an estimation on the total weight of the freight is made using an AFL (average freight load) and an ACUF (average capacity utilization factor). The former describes the weight of an average amount of freight that is carried, and the latter is a percentage of how much the truck is filled on average.
Not all background reports cover all of the aforementioned values, in which case an assumption must be made based on values found in an additional study.

7.1.2. How is transport currently modelled in LCA studies?

In all articles found in this study, tonkm, or a variation that also describes weight times distance, is used. The level of detail varies per article. However, when an article describes a reusable product or a product including a reverse supply chain, the environmental footprint of the transportation processes are described in more detail. Despite this, volume is never used as a way to quantify it.

7.1.3. How does the CO2 calculation tool by Partners for Innovation measure and show the environmental footprint of a product?

The original CO_2 calculation tool is suited to be used as a rough indicator of the environmental footprint of a reusable product. The tool displays all of the input parameters in a clear, structured way, which, in combination with the layout and the streamlined calculations, make the tool easy to use and well-organized.
However, the result of the tool is merely an indication. It cannot be used as a substitute for a detailed LCA.

7.1.4. What are the limits of this tool?

The limited scope of the output (CO_2 emissions) is the biggest limitation of the tool. Furthermore, several calculations are included in the data that is given in the 'data' tab. For example, the ACUF is included in the list of kg.CO_2/tonkm. This makes the calculation of the tool simpler, but less precise. Lastly, volume is not taken into account making the tool less accurate, as well as unusable for light, voluminous packagings.

7.1.5. How can the calculation of volume within the transport phase be optimised for reusable products that become more compact when empty?

A new CO_2 calculation tool is created in which volume is taken into account in the calculation. This is done by creating an additional calculation resulting in a final factor that is multiplied with the value for tonkm from the original calculation. Two efficiency factors are set up for the packaging that is analysed. The first efficiency factor describes to what extent the primary packagings are nested within the secondary packaging. The second efficiency factor describes how much space is left when stacking the secondary packagings in the truck. If the two efficiency factors multiplied are higher than one, that means that one or more trips are saved. In that case, the final factor is described with the following formula:

$$\varphi f = \frac{\varphi t}{(ts + 1) * wf}$$

When the two efficiency factors multiplied are lower than one, that means that an extra trip is needed. The final factor is then described using the following formula:

$$\varphi f = \varphi t * (tn + 1) * wf$$

φ_f = the final factor used in the calculation
φ_t = the two efficiency factors multiplied
ts = the amount of trips saved
tn = the amount of extra trips needed
wf = the weight factor.

With the new tool, simplicity and clarity are key aspects. The tool is created to be as clear as possible to the user.

7.1.6. When applying different scenarios to the new CO_2 calculation tool, what does the difference in outcome with the original tool signify?

The new CO_2 calculation tool gives a more precise result of CO_2 emission for a packagings that reduces in volume when empty. When a packaging is transported efficiently this is reflected in the final factor of the calculation which in turn is reflected in the CO_2 emission output. An inefficiently transported packaging will result in a high final factor, which is reflected in a high CO_2 emission. A nested and unnested variant of the same scenario shows that reduction in volume does indeed make a significant impact on its CO_2 emission.
Highlighting the number of trips that is linked to the level of nesting of a product serves as an argument for why the new type of calculation is more accurate. The number of trips is shown to be of high importance in the CO_2 calculation of a product, and this is an aspect that is not used in the original calculation created by Partners for Innovation.
During the applying of several scenarios to the old and the new tool, several findings arose within the calculation. For example, there is a sharp decline in the final factor at a point where an extra trip is saved or an extra trip is needed. Even though some findings seem counter-intuitive, each one has a logical explanation and does not subvert the logicality of the new tool.

7.2. Overall conclusion

The newly developed CO_2 calculation tool shows a new way of incorporating volume in an environmental calculation of a packaging. The new calculation is more precise than that of the original tool as it takes more parameters into account, and is therefore more suited to use for packaging that nests when empty. Furthermore, the new tool does have an additional function of highlighting optimisation regarding volume, which is useful for all packaging that nests. However, as the main function of the original tool is to create a simple overview, a more precise calculation is not always necessary and will only make the result more complex for the user.

7.3. Recommendation

After concluding the research performed in this report, several additional points can be made. These points of limitation in regard to the scope of this thesis are mentioned in the form of a recommendation to future studies.

The tool created in this report lays the focus on optimisation and saving trips. However, not all sub-optimal transportation steps can be optimised. For example, when the primary packagings are full, they cannot be nested. This puts an unnecessary blame on the user of the tool, and should be solved in a further iteration of the tool.
Cost is an aspect that is not focused on in this thesis because of its scope. It did not fit in the timeframe of this thesis process. Moreover, the main focus of this thesis is the sustainability aspect of the optimisation step, not the financial aspect. However, it can be assumed that saving trips would save money (Mahmoudi et al., 2020), which would be an interesting parameter for the user to see. This too is an improvement for a later iteration of the tool.

The calculation created in this report originates from a process of trial and error. It is possible that a more simple, or a more precise method of calculating CO_2 emissions for packagings that reduce in volume exists. However, because of the scope of this project this is not researched.
Furthermore, it is still uncertain whether there are scenarios or packagings in which the mass-based calculation is more suited. The purpose of this report is to show a new type of calculation that takes into account volume during transportation. It is recommended that it is analysed in further research If this is the best option in every case.

8. References

Alfonso, V., Boar, C., Frost, J., Gambacorta, L., & Liu, J. (2021). E-commerce in the pandemic and beyond. *BIS Bulletin*, *36*(9).

Antala, D. K., Satasiya, R. M., & Chauhan, P. M. (2020). Design, development and performance evaluation of transportation container for sapota fruit. *Journal of Food Science and Technology*, 1-10.

Beemsterboer, S., Baumann, H., & Wallbaum, H. (2020, November). Bridging the gap between assessment and action: recommendations for the effective use of LCA in the building process. In *IOP Conference Series: Earth and Environmental Science* (Vol. 588, No. 2, p. 022007). IOP Publishing.

Cabka (2022), *'homepage'*, retrieved on 06-12-21 at https://cabka.com/

Campbell et al. (2020), *A study of the waste free cup systems at events as commissioned by Rijkswaterstaat in cooperation with Plastic Promise*, retrieved on 13-10-21 at https://www.rijksoverheid.nl/documenten/rapporten/2021/02/10/bijlage-4-lca-centre-lca-study-of-waste-free-cup-system-at-dutch-events-by-the-lca-centre

Cartier (2019), 'Primary, secondary and tertiary packaging: What's the difference?', retrieved on 27-11-20 at https://www.emballagecartier.com/en/article/primary-secondary-and-tertiary-packaging-whats-the-difference/

Chow, C. F., So, W. M. W., Cheung, T. Y., & Yeung, S. K. D. (2017). Plastic waste problem and education for plastic waste management. In *Emerging practices in scholarship of learning and teaching in a digital era* (pp. 125-140). Springer, Singapore.

Cleary, J. (2013). Life cycle assessments of wine and spirit packaging at the product and the municipal scale: a Toronto, Canada case study. *Journal of Cleaner Production*, *44*, 143-151.

Coelho, P. M., Corona, B., ten Klooster, R., & Worrell, E. (2020). Sustainability of reusable packaging-Current situation and trends. *Resources, Conservation & Recycling: X*, 100037.

Cottafava, D., Costamagna, M., Baricco, M., Corazza, L., Miceli, D., & Riccardo, L. E. (2021). Assessment of the environmental break-even point for deposit return systems through an LCA analysis of single-use and reusable cups. *Sustainable Production and Consumption*, *27*, 228-241.

Dekker, R., & Van Der Laan, E. (2003). Inventory control in reverse logistics. *Business aspects of closed-loop supply chains*, *2*, 175-202.

Ecoinvent (2021), *'Homepage'* retrieved on 03-04-2021 on
https://www.ecoinvent.org/

Ehrenfeld, J. (2004). Industrial ecology: a new field or only a metaphor?. *Journal of cleaner production*, *12*(8-10), 825-831.

EPA (2022), *'Sources of Greenhouse Gas Emissions'*, retrieved on 14-03-2022 at https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#colorbox-hidden

Ferrara, C., De Feo, G., & Picone, V. (2021). LCA of Glass Versus PET Mineral Water Bottles: An Italian Case Study. *Recycling*, *6*(3), 50.

Gonzalez-Torre, P. L., Adenso-Dıaz, B., & Artiba, H. (2004). Environmental and reverse logistics policies in European bottling and packaging firms. *International Journal of Production Economics*, *88*(1), 95-104.

Guinée, J. B., & Lindeijer, E. (Eds.). (2002). *Handbook on life cycle assessment: operational guide to the ISO standards* (Vol. 7). Springer Science & Business Media.

Hekkert, M. P., Joosten, L. A., Worrell, E., & Turkenburg, W. C. (2000). Reduction of CO2 emissions by improved management of material and product use: the case of primary packaging. *Resources, Conservation and Recycling*, *29*(1-2), 33-64.

Jonk (2022), *'vrachtwagen 46 m^3 laadklep'* retrieved on 28-01-22 at https://www.bertjonk-autoverhuur.nl/vrachtwagen-huren/vrachtwagen-46-m3

Katephap, N., & Limnararat, S. (2017). The operational, economic and environmental benefits of returnable packaging under various reverse logistics arrangements. *Int. J. Intell. Eng. Syst*, *10*, 210-219.

Keuenhof, M. (2020), KIDV Calculation tool for CO2 impact of reusable packaging, retrieved on 15-11-21 at https://kidv.nl/reusable-packaging-calculation-tool

Kočí, V. (2019). Comparisons of environmental impacts between wood and plastic transport pallets. *Science of the total environment*, *686*, 514-528.

Kruizinga (2022), *'Gebruikte pallet, houten pallet 4*-weg', retrieved on 29-04-22 at https://www.kruizinga.nl/pallet/houten-pallet/0718/gebruikt/99-718gb?qty=1&gclid=Cj0KCQjwma6TBhDIARIsAOKuANwlajfcLP0muETZkj2njGkGLRNXlJ3-x5yZyyyOVOBV5mrc5X_LAakaAkA6EALw_wcB

Lee, H., Seo, H., & Geum, Y. (2018). Uncovering the topic landscape of product-service system research: From sustainability to value creation. *Sustainability*, *10*(4), 911.

Lis (2022), *'Jumbo Truck',* retrieved on 07-02-22 at https://www.lis.eu/en/lexikon/jumbo/

Liu, G., Li, L., Chen, J., & Ma, F. (2020). Inventory sharing strategy and optimisation for reusable transport items. *International Journal of Production Economics*, *228*, 107742.

Mahmoudi, M., & Parviziomran, I. (2020). Reusable packaging in supply chains: A review of environmental and economic impacts, logistics system designs, and operations management. *International Journal of Production Economics*, *228*, 107730.

Manutan (2022), *'Vouwkrat 60 tot 68 L'*, retrieved on 07-02-22 at https://www.manutan.nl/nl/mnl/vouwkrat-blauw-60-tot-68-l-a025989?gclid=CjwKCAiAo4OQBhBBEiwA5KWu_5yYhHoVcJBZqcA-Pnvk7mYY6ewLIcbCmr0Jb4Os4pbFuHXxbfHHpBoC5kIQAvD_BwE

Motta (2021), *'ecoinvent 3.8 Dataset Documentation 'transport, freight, lorry >32 metric ton, EURO1 - BR''*, retrieved on 5-10-21 at https://v38.ecoquery.ecoinvent.org/Home/Index

Petcore, Europe (2021), *'Product Environmental Footprint (PEF) European initiative'* retrieved on 18-11-21 at https://www.petcore-europe.org/projects/33-product-environmental-footprint-pef-european-initiative.html

Pieter Pot (2021), *'Verpakkingsvrije boodschappen. Lekker Duurzaam.'*, retrieved on 04-05-21 on https://www.pieter-pot.nl/?gclid=CjwKCAjwuYWSBhByEiwAKd_n_hLosx8t0e-aZ1IiEH1wMjEA8rGeQqqFfDXsRzEVaD2sU75-eRhg1xoCND8QAvD_BwE

Promofit (2022), 'FESTA CUP Frosted PP cup 550 ml', retrieved on 16-03-22 at https://www.promofit.nl/festa-cup-frosted-pp-cup-550-ml?dfw_tracker=109131-274672&gclid=CjwKCAjwlcaRBhBYEiwAK341jT6Lqf0lauKn-oAU5wVBNPsGmHNglof94UpE2OTXtx_mHqWoklfRVBoCgOkQAvD_BwE

RePack (2021), *'The End of Trash'*, retrieved on 07-12-21 at https://www.repack.com/

Schröder (2021), 'CEO Ingrid Faber: "Hergebruik van pallets is beter voor de klant, het milieu en voor ons een goed businessmodel"', retrieved on 1-12-2021 at https://www.change.inc/circulaire-economie/ceo-ingrid-faber-pooling-is-beter-voor-de-klant-het-milieu-en-voor-ons-een-goed-businessmodel-37412

Shen, L., Worrell, E., & Patel, M. K. (2010). Open-loop recycling: A LCA case study of PET bottle-to-fibre recycling. *Resources, conservation and recycling*, *55*(1), 34-52.

Spielmann, M., Scholz, R., Tietje, O., & De Haan, P. (2005). Scenario modelling in prospective LCA of transport systems. Application of Formative scenario analysis (11 pp). *The International Journal of Life Cycle Assessment*, *10*(5), 325-335.

Statista (2022), *'Distribution of carbon dioxide emissions produced by the transportation sector worldwide in 2020, by subsector'*, retrieved on 14-03-2022 at https://www.statista.com/statistics/1185535/transport-carbon-dioxide-emissions-breakdown/

Tan, R. B., & Khoo, H. H. (2005). An LCA study of a primary aluminum supply chain. *Journal of Cleaner Production*, *13*(6), 607-618.

Valsasina et al. (2016), '*Default transport model for products produced and consumed in Switzerland'*, retrieved on 21-06-21

Wyatt (2021), '*Protecting Conditional Formatting'*, retrieved on 23-03-22 at https://excelribbon.tips.net/T004362_Protecting_Conditional_Formatting.html

Zampori, L., & Dotelli, G. (2014). Design of a sustainable packaging in the food sector by applying LCA. *The International Journal of Life Cycle Assessment*, *19*(1), 206-217.

Zimmermann, T., & Bliklen, R. (2020). Single-use vs. reusable packaging in e-commerce: comparing carbon footprints and identifying break-even points. *GAIA-Ecological Perspectives for Science and Society*, *29*(3), 176-183.

9. Appendix

9.1. Appendix A: full process of the literature study.

LCA transport
When using this search term, several problems arise. Firstly, most articles that are found are not LCA's with a special focus on the transport phase, but rather LCA's on transport-related systems in general. For example, Spielmann et al. (2005) describe an LCA study in which different types of rail transport are compared. In this case mostly the emissions of each transport type are compared which is not the most relevant aspect: it is more important to look for a distinction between different products that use the same type of transport.
In order to obtain more relevant literature, the following search terms are used:

LCA packaging
Although packaging would also be a relevant term in this case, it is purely the transport aspect which is most important in this research. It is apparent that packaging does not add anything relevant to the search term. It is, in fact, clear that many LCA studies do not take into account the transport phase at all. For example, Zampori & Dotelli (2014) perform a comparative LCA study by looking at the production-, use-, and end-of-life stage, thereby leaving out the transport phase. It is presumed that the transport stage was previously found to be negligible, and was therefore left out pre-emptively. No background process or database is mentioned either.

Through the Dutch knowledge institute for sustainable packaging (Kennisinstituut Duurzame Verpakkingen) (KIDV) several LCA studies for a type of reusable packaging were found.
Campbell et al. (2020) show a study in which single-use festival cups were compared to reusable ones. The cups analysed in this study are shaped in a way that they fit into each other when stacked, which means that this study is especially suited as an example for Cabka. Even though the study is quite detailed, it is never shown how many cups can be transported at once. The weight of the material during several transport stages is briefly mentioned. However, no specific number of cups is given and the reader is required to calculate the amount of cups themselves if they are interested. Because of this, it can be assumed that the amount of cups during transport was only estimated in this study.
Campbell et al. describe a reuse system, and therefore they have also taken into account the return trip, which are in this case filled with unclean or unusable cups.
A similar study has been conducted by Cottafava et al. (2021). Within their transport phase they focus on the distance (which is calculated in a detailed manner) but all other aspects of transportation are estimated. It is stated that a freight lorry of 16 -32 ton is used, but the amount of cups that can be transported is unmentioned.

LCA case study
By using this search term, actual LCA studies were found, instead of articles that merely have to do with the concept of LCA.
Tan et al. (2005) describe an LCA study in which aluminium production is assessed. Because most processes are performed in a different location, the transport process is one of high importance. Again, as expected, the distance travelled and the weight of the cargo are determined after which the pollution from the mode of transport is calculated. In the

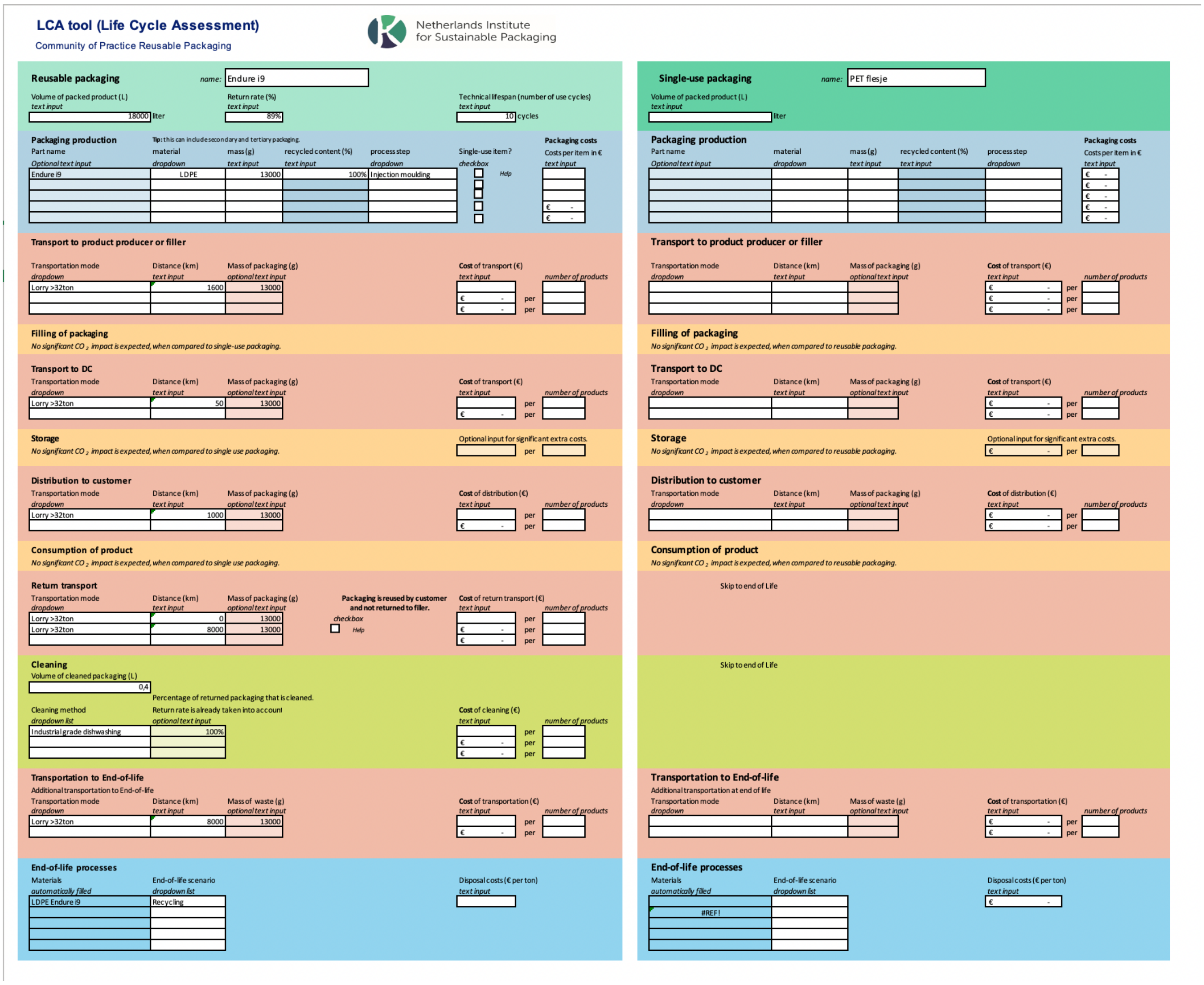
discussion it is mentioned that the transportation process could be optimised by using 'green trucks'. It is never stated that volume could be optimised. However, volume is never mentioned in the article, and therefore it can be assumed that either volume is already in an optimal state during transport, or the writers of the article simply did not think about volume. Logically, bulk aluminium does not have much unused space in it. In the case study on the recycling process of PET bottles performed by Shen et al. (2010) the transportation process is assessed in a similar way. Tonkm is used as a unit, and in this case Ecoinvent is used to find the data on rail transport. Because an Ecoinvent process is used, it can also be assumed that an ACUF was used.

LCA case study reuse
In a study by Ferrara et al. (2021) PET single use drinking bottles are compared with glass reusable ones. Once again the transportation phase is quantified in weight times distance, in this case kgkm. A background process is in this case *not* used; the writers of this paper have created their own transport process, including the accompanying calculations. A reverse supply chain is mentioned, including the fact that the amount of kgkm is significantly lower. This means that there is much more empty space when the bottles are empty, and this step could be optimised. However, as volume is mentioned nowhere in the article, it is assumed that such an optimisation is not used.

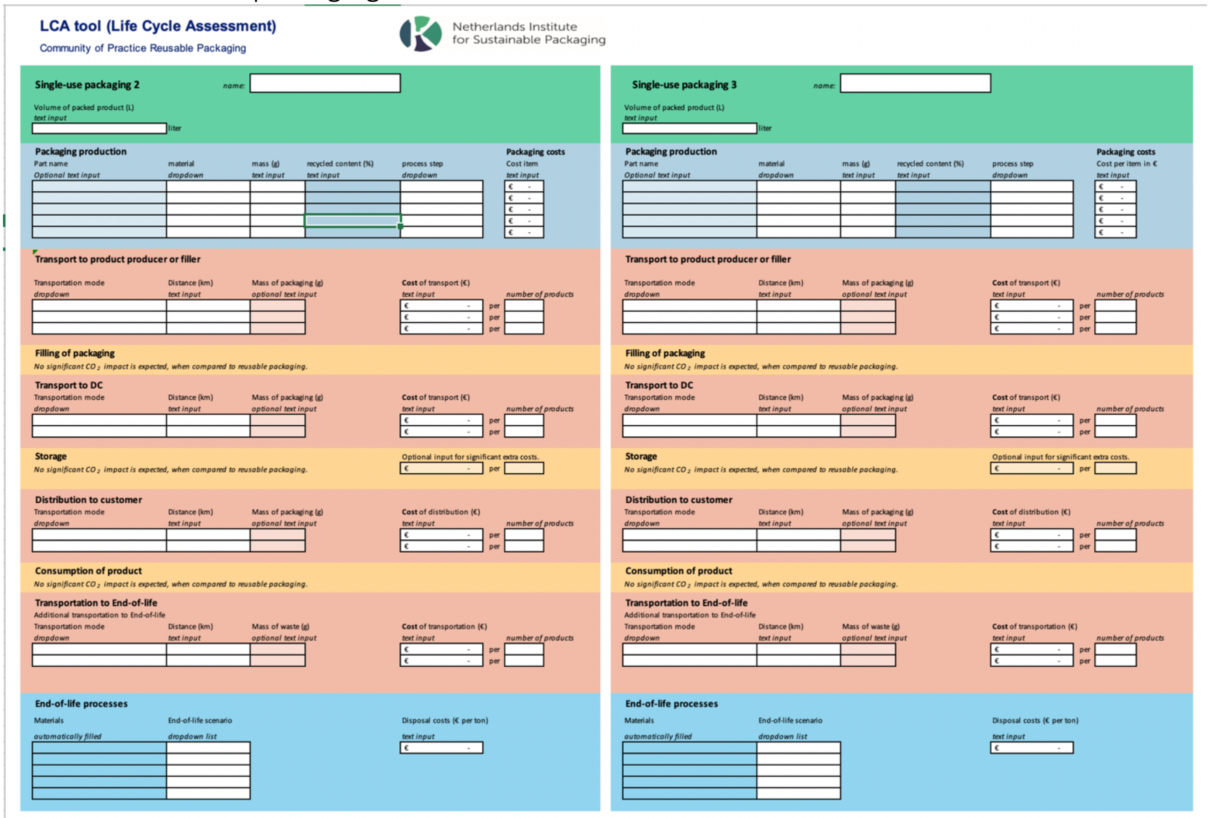
Cleary (2013) shows a study where glass *single use* wine and spirit bottles are compared to plastic and cardboard *reusable* cases. In their sensitivity analysis they address the difference in packaging size; they state that smaller containers require more material per unit, and therefore the material takes up more space during transportation. Even though this is different from packaging that changes in size, a similar calculation is needed. In the background reports it is shown that the weight of each packaging is calculated meticulously. However, it does not further state the result of the sensitivity analysis regarding the different size in packaging. This means that either it is not seen as greatly important and an estimation is made, or the data for this calculation was simply lacking.

9.2. Appendix B: screenshots of the original CO_2 calculation tool by Partners for Innovation.

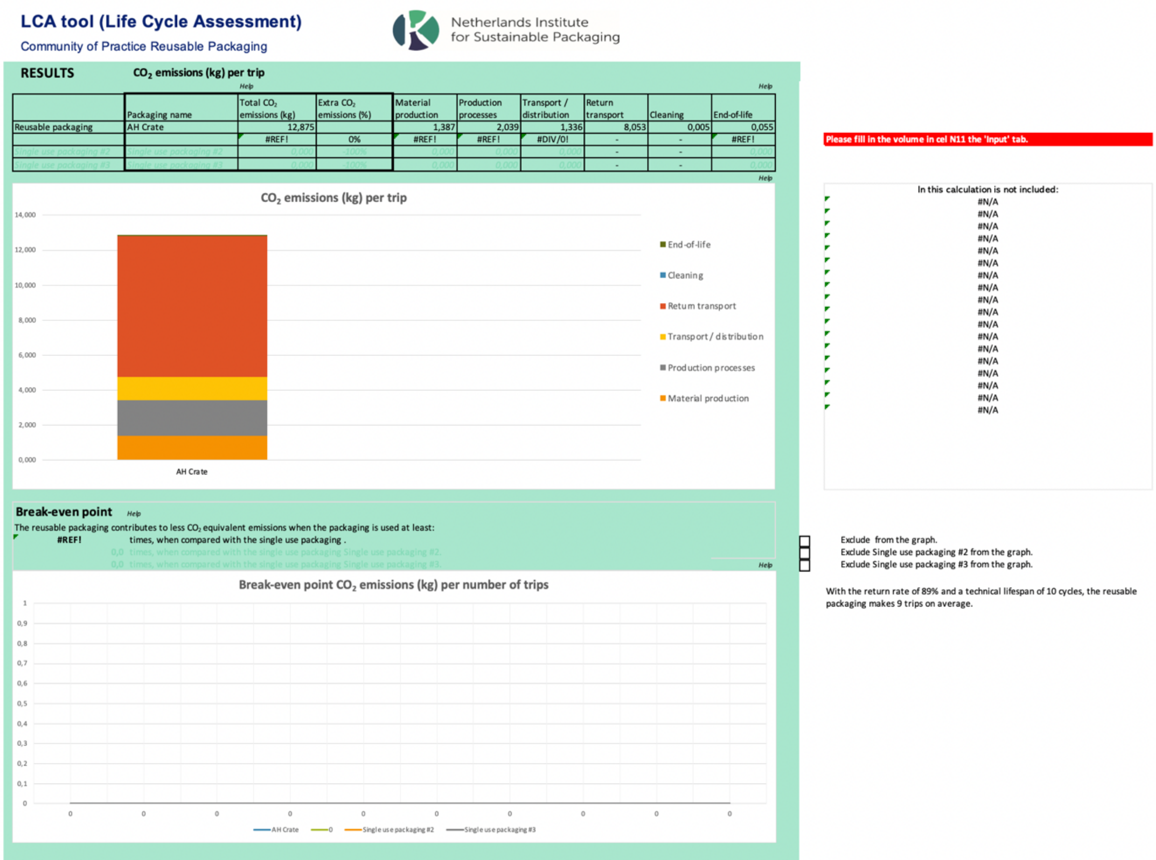
‘1. INPUTS’



‘2. More reference packaging’



‘3. Results CO2 impact’



‘4. Results costs’

LCA tool (Life Cycle Assessment)

Community of Practice Reusable Packaging

Netherlands Institute for Sustainable Packaging

RESULTS **Average cost (€) per packaging item per trip** *Help*

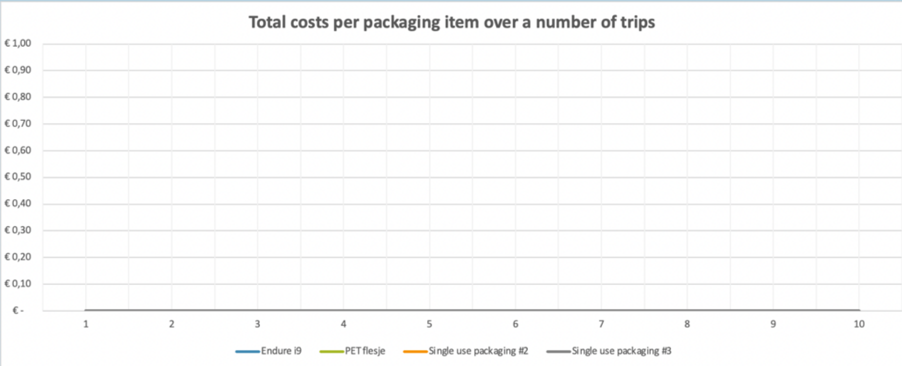
	Packaging name	Total Costs (€)	Total costs per 18000 liter	Production	Transport / distribution	Storage	Return transport	Cleaning	End-of-life	Packaging Volume
Reusable packaging	Endure i9	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	18000 liter
Single use packaging #1	PET flesje	€ -	#DIV/0!	€ -	€ -	€ -	-	-	€ -	unspecified
Single use packaging #2	Single use packaging #2	€ -	#DIV/0!	€ -	€ -	€ -	-	-	€ -	unspecified
Single use packaging #3	Single use packaging #3	€ -	#DIV/0!	€ -	€ -	€ -	-	-	€ -	unspecified

Break-even point *Help*

The reusable packaging is cheaper to use than the single use alternatives when the packaging is used at least:

0,0 times, when compared per liter with the single use packaging PET flesje.

Help



‘5. Data’

DATA sheet *Help*

PEF calculation	$E_v = E^*_v$		$A*E_{recycled} + (1-A)*E_v*(Q_{s,in}/Q_p)$		E_D		$(1-A)*(E_{recyclingEoL} - E^*_v*(Q_{s,in}/Q_p))$				A	$Q_{s,in}/Q_p = Q_{s,out}/Q_p$		$E_{recycled} = E_{recyclingEoL}$	$E_{recyclingEoL}$		
Material	Production CO_2.kg	Source	Recycled CO_2.kg	Source	Incineration CO_2.kg	Source	Recycling CO_2.kg	Source	Average packaging waste CO_2.kg	Source	Allocation factor A	Downcycle factor Q	Source	Impact of recycling process		Source	Sources can be found at the bottom of the page.
PET	3,30	1	2,11	3	2,06	1	-0,86	2	0,54	4	0,5	0,9	13	1,25	1,25	1	
PP	2,19	1	1,37	3	2,56	1	-0,60	2	0,92	4	0,5	0,9	14	0,77	0,77	1	
LDPE	2,36	1	0,97	3	3,03	6	-0,20	2	1,35	4	0,8	0,75	14	0,77	0,77	6	
LLDPE	2,09	1	0,93	3	3,03	6	-0,16	2	1,37	4	0,8	0,75	14	0,77	0,77	6	
HDPE	2,17	1	1,36	3	3,03	1	-0,59	2	1,15	4	0,5	0,9	14	0,77	0,77	1	
PS	3,93	1	1,86	3	3,20	1	-1,09	2	3,20	4	0,5	0,75	14	0,77	0,77	1	
BioPE	-0,16	10	0,31	11	3,03	6	0,46	11	1,69	4	0,5	0,9	14	0,77	0,77	6	
BioPP	-1,91	10	-0,47	11	2,56	1	1,24	11	1,87	4	0,5	0,9	14	0,77	0,77	6	
PLA	1,44	10	0,88	3	2,38	1	-0,11	2	2,38	4	0,8	0,9	13	0,77	0,77	6	
Rubber	2,94	1		5	3,16	1	-0,33	2	3,16	4	0,8	0,75	13	0,54	0,54	1	
Silicone	3,41	1		5	2,38	6	-0,40	2	2,38	4	0,8	0,75	13	0,54	0,54	1	
Corrugated board	1,14	1	0,91	3	0,03	1	-0,21	2	-0,18	4	0,2	0,85	13	0,71	0,71	1	
Folding boxboard	1,59	1	1,23	3	0,03	6	-0,50	2	-0,44	4	0,2	0,85	13	0,73	0,73	6	
bleached paper	1,73	1	1,32	3	0,03	1	-0,60	2	-0,52	4	0,2	0,85	13	0,73	0,73	1	
unbleached paper	1,22	1	0,98	3	0,03	6	-0,25	2	-0,22	4	0,2	0,85	13	0,73	0,73	6	
Glass (white)	1,33	1		5	0,03	1	-1,06	2	-0,91	4	0,2	1	13	0,004	0,004	7	
Glass (green)	1,05	1		5	0,03	6	-0,84	2	-0,72	4	0,2	1	13	0,004	0,004	7	
Wood (soft wood)	0,25	9		5	0,02	1	-0,04	2	-0,03	4	0,8	0,9	13	0,004	0,004	9	
MDF (medium density fibre boa	1,11	15		5	0,02	6	-0,20	2	-0,15	4	0,8	0,9	14	0,004	0,004	6	
Aluminium	19,57	1		5	0,26	1	-15,47	2	-14,68	4	0,2	1	13	0,24	0,24	1	
Carbon steel	2,28	1		5	0,07	1	-1,77	2	-1,68	4	0,2	1	13	0,06	0,06	1	
Stainless steel	4,99	1		5	0,07	6	-3,95	2	-3,75	4	0,2	1	13	0,06	0,06	6	

Process	Production CO_2.kg	Source
Injection moulding	1,43	1
Extrusion blow moulding	1,47	1
Injection blow moulding	1,95	1
Thermoforming	1,18	1
Film extrusion	0,61	1
Calendaring	0,46	1
Cardboard box folding	0,00	12
Deepdrawing aluminium	1,93	1
Deepdrawing steel	1,20	1
Sheet rolling aluminium	0,76	1
Sheet rolling steel	0,44	1
Wood sawing	0,00	12
Glass production	0,00	12

Transportation	CO_2.ton.km	Source
Van (<3,5 ton)	1,97	1
Lorry 7,5-16 ton	0,22	1
Lorry 16-32 ton	0,17	1
Lorry >32ton	0,09	1
Train (freight)	0,05	1
Barge (inland)	0,05	1
Transoceanic container ship	0,01	1
Airfreight	1,12	1
Passenger car	0,34	1
Electric car	0,25	1
Electric bike	0,01	1
Walking or cycling	0,00	

Cleaning	CO_2.liter	Source	use per liter packaging	r use (l)	energy use (MJ)	use (g)	remarks	Tap water (EU) per kg	Soap pe	Sodium hydroxide in 50% s	Electricity (NL-mediun	Electricity (NL-low voltage) per MJ	CO_2 impact
Inspection	0	8	Inspection	0	0	0		0,0004	6,46	1,40	0,17	0,18	
Industrial washing (NaOH solutio	0,006	8	Industrial washing (Na	0,27	0,03	2,08	detergent is 50% NaOH	0,0001	0,00	0,00	0,00	0,00	0,01
Industrial grade dishwashing	0,013	8	Industrial grade dishw	0,43	0,07	1,38	detergent is 50% NaOH	0,0002	0,00	0,00	0,01	0,00	0,01
consumer grade dishwashing	0,031	8	consumer grade dishw	0,49	0,15	0,73		0,0002	0,00	0,00	0,00	0,03	0,03
handwashing	0,103	8	handwashing	3,86	0,46	3,48		0,0015	0,02	0,00	0,00	0,08	0,10

Sources

1. EcoInvent database 3.5, released August 2018
2. Calculation of impact of recycling based on the impact of the recycling process and substitution of virgin material in column P, the allocation factor A in column N, and the downcycle factor Q in column O.
3. Calculation of impact of recycled content based on the impact of virgin material in column B, the impact of the recycling process and substitution of virgin material in column P, the allocation factor A in column N, and the downcycle factor Q in column O.
4. Average Dutch waste scenario based on the 2018 recycling statistics of the Afvalfonds Verpakkingen.
5. Use of industry averages of recycled content are already taken into account in the material, or data is unavailable.
6. Extrapolation of data from similar materials and processes from (1.)
7. Assumption/extrapolation by Partners for innovation based on data from (1.) and sources in the glass industry.
8. Calculation of CO_2 impact of cleaning proces based on average water, detergent, and energy used with LCI data from (1.). Average consumptions based on literature review by Partners for Innovation and Universiteit Utrecht.
9. Calculated impact of softwood per kg based on LCI data from (1.) and the assumption that the wood has a density of 450 kg/m3.
10. Calculation based on values from Chen & Patel (2012) + transport from Brasil to Europe. Does not include effects of land use change. Chen, G. Q., & Patel, M. K. (2012). Plastics derived from biological sources: present and future: a technical and environmental review. Chemical reviews, 112(4), 2082-2099.
11. Calculation and allocation of recycling impact of drop-in bioplastics based on recycling process of fossil based PE and PP. The biobased plastic is regarded as a "carbon sink" as proposed by CE Delft (2017). *Biobased Plastics in a Circular Economy*.
12. The production impact of 'Cardboard box folding' is included in the total impact of Corrugated box and Folding box under Material. The impact of sawing and drying of wood is included in the material too.
13. Default A & Q parameters as suggested by the European Commission's Joint Research Centre.
14. Assumption/extrapolation of A & Q parameters based on data from (13.).
15. Calculated impact of MDF per kg based on LCI data from (1.) and the assumption that the MDF has a density of 720 kg/m3.

9.3. Appendix C: lists of all of the input- and output parameters from the original CO_2 calculation tool by Partners for Innovation.

Inputs

Category	Name	unit	Description
Main	Volume of packed product	Litre	The amount of product that is packed by the packaging.
Main	Return rate	%	The amount of packaging that is returned within the logistical system.
Main	Technical lifespan	Cycles	Number of use cycles.
Production	Part name	N.A.	Name of the packaging part.
Production	Material	N.A.	Material that the packaging part is made of.
Production	Mass	Gram	Total weight of the packaging part.
Production	Recycled content	%	Amount of material within the packaging part that is recycled.
Production	Process step	N.A.	Type of production process needed to create this packaging part.
Production	Single-use item	Yes/no	Whether or not the packaging part is single use.
Production	Cost	Euro	The amount of euros that is needed to produce the packaging part.
Transportation *	Transportation mode	N.A.	The type of transportation that is used with the packaging. The list of possible transportation modes is taken from the Ecoinvent database.
Transportation	Distance	Kilometre	The distance that the packaging needs to be transported.
Transportation	Mass of the packaging	Grams	The total weight of the packaging part.
Transportation	Cost of transport	Euro per *amount of parts* *	The cost of transportation per amount of packagings that is transported at once.
Transportation	Number of products	#	The amount of products per which the cost is defined.
Cleaning	Volume of cleaned packaging	L	Total inner volume of the packaging.
Cleaning	Cleaning method	N.A.	Method that is used to clean the packaging. The dropdown options come from Ecoinvent.
Cleaning	Cost of cleaning	Euro per *amount of parts* *	The cost of cleaning the product.

Cleaning	Amount of parts	#	The amount of products per which the cost of cleaning is defined.
End-of-life processes	Materials (Automatically filled)	N.A.	Name of the part listed in the 'part name' section.
End-of-life processes	End-of-life scenario	N.A.	Process that occurs at the end of the packaging life-cycle.
End-of-life processes	Disposal costs	Euro per ton	Total cost of the disposal of the packaging part.

Outputs

Tab	Name	Unit	Description
Results CO_2 impact	Total CO2 emissions	Kg	The CO_2 emissions of every stage calculated and added up.
Results CO_2 impact	Extra CO2 emissions	%	Extra CO_2 emissions that could occur in the process.
Results CO_2 impact	Material production	Kg	CO_2 emissions of the material production stage.
Results CO_2 impact	Production processes	Kg	CO_2 emissions of the production processes stage.
Results CO_2 impact	Transport / distribution	Kg	CO2 emissions of the transport / distribution stage.
Results CO_2 impact	Return transport	Kg	CO_2 emissions of the return transport stage. For the single-use packaging, this parameter is left out.
Results CO_2 impact	Cleaning	Kg	CO_2 emissions of the cleaning stage. For the single-use packaging, this parameter is left out.
Results CO_2 impact	End-of-life	Kg	CO_2 emissions for the end-of-life stage.
Results CO_2 impact	Break-even point	# of trips	Point of number of trips where the reusable and the single-use packaging have the same CO_2 emissions. This is displayed in a graph.
Results costs	Total costs	Euro	The total estimated cost of the packagings.
Results costs	Total costs per V	Euro	The total estimated cost of the packagings per volume of one packaging given.
Results costs	Production	Euro	The estimated costs of the production stage.

Results costs	Transport / distribution	Euro	The estimated costs of the transport / distribution stage.
Results costs	Storage	Euro	The estimated costs of the storage stage.
Results costs	Return transport	Euro	The estimated costs of the return transport stage. For the single-use packaging, this parameter is left out.
Results costs	Cleaning	Euro	The estimated costs of the cleaning stage. For the single-use packaging, this parameter is left out.
Results costs	End-of-life	Euro	The estimated costs of the end-of-life stage.
Results costs	Packaging volume	Euro	The inside volume of the packagings. This is already given in de INPUT tab.
Results costs	Break-even point	# of trips	Point of number of trips where the reusable and the single-use packaging cost the same. This is displayed in a graph.

9.4. Appendix D: all of the parameters from the new tool explained.

Inputs

Name:	**Type of input:**	**Description:**
'Used'	Checkbox	If this checkbox is checked, the corresponding transport step is used and filled in.
'Description'	Text input	A description of the transport step can be given in this field. This has no function except to give a more clear overview for the user.
'V2'	Value input	Volume of the *secondary packaging* in which the product is transported. If no secondary packaging is used, this parameter describes the inner volume of the transportation mode.
'Longest length'	Value input	The *longest measurement* in the x-axis of the product.
'Longest width'	Value input	The *longest measurement* in the y-axis of the product.
'Longest height'	Value input	The *longest measurement* in the z-axis of the product.
'Units'	Value input	The amount of products that are transported in the secondary packaging.
'Mass'	Value input	The mass of one unit of the product analysed.

'Does the packaging come in a secondary packaging (box)'	Checkbox	If the checkbox is checked, the next two parameters are used. In that case, the secondary packaging as well as the volume of the transportation mode are used in the calculation.
'Vt'	Value input	The total inner volume of transportation mode.
'Ubox'	Value input	The amount of secondary packagings transported in the transportation mode.

Outputs

Name:	Type of output:	Description:
'Used:'	Checkbox	If this checkbox is marked, the user selects the transport step to be used. This checkbox is linked with the 'used:' checkbox in the input section.
'V1'	Value output	This parameter calculates the product of the longest length, width, and height of the product; it describes the *surrounding volume* of the product.
'φ_1'	Value output	The efficiency factor of the the product within the secondary packaging. This value describes how much space there is left in the box, i.e. how 'efficient' the product is stacked.
'φ_2'	Value output	The efficiency factor of the boxes within the transportation mode. This value describes how much space is left in the truck, i.e. how 'efficiently' the boxes are stacked.
'φ_t'	Value output	The total efficiency factor: 'φ_1' and 'φ_2' multiplied.
Extra trips needed	Value output	The number of extra trips that are needed because the primary packagings are not nested.
Trips saved	Value output	The number of trips that are saved by nesting the primary packagings.
'φ_f'	Value output	The final factor, taking into account the amount of trips as well as the weight of the freight and the weight of the truck. This value is multiplied with the tonkm, connecting this tab with the original tool.

9.5. Appendix E: screenshot of the new CO_2 calculation tool.

Appendix E1: left half of the new tool

CO2 Calculation Tool Expansion:
Difference in Volume
Created by Lucas Roos Lindgreen

Input:

Longest length (mm):	600
Longest width (mm):	400
Longest height (mm):	320

V1 (m3): **0,0768**

	Is the packaging filled during this step?	Description:	V2 (m3):	Units:	does the packaging come in secondary packaging (box)?	Vt (m3):	Ubox:
	Checkbox	*Text input*	*Value input*	*Value input*	*Checkbox*	*Value input*	*Value input*
Transport 1:	☐	Producer --> DC	123,75	1.323	☐		
Transport 2:	☐				☐		
Transport 3:	☐				☐		
Transport 4:	☐	DC --> Filler	46	504	☐		
Transport 5:	☐				☐		
Transport 6:	☑	Filler --> Supermarket	46	300	☐		
Transport 7:	☐				☐		
Transport 8:	☐	Supermarket --> DC	46	504	☐		
Transport 9:	☐				☐		
Transport 10:	☐				☐		
Transport 11:	☐	DC --> Waste treatment	46	360	☐		
Transport 12:	☐				☐		

Output:

	Fi (efficiency factor)	Fi 2	**Total factor:**	**Extra trips needed:**	**Number of trips saved:**	**Final factor**	
	Value input	*Value input*	*Value input*	*Value input:*	*Value input*	*Value input*	
Transport 1:	0,821	1,000	**0,821**	1	0	**9,214**	this step could be optimized!
Transport 2:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 3:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 4:	0,841	1,000	**0,841**	1	0	**24,787**	this step could be optimized!
Transport 5:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 6:	0,501	1,000	**0,501**	1	0	**24,787**	-
Transport 7:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 8:	0,841	1,000	**0,841**	1	0	**24,787**	this step could be optimized!
Transport 9:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 10:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 11:	0,601	1,000	**0,601**	1	0	**24,787**	this step could be optimized!
Transport 12:	1,000	1,000	**1,000**	0	0	**1**	-

Appendix E2: right half of the new tool.

Input:

Longest length (mm):	600
Longest width (mm):	400
Longest height (mm):	320
V1 (m3):	**0,0768**

	Is the packaging filled during this step?	Description:	V2 (m3):	Units:	does the packaging come in secondary packaging (box)?	Total volume of transportation (m3):	Ubox:
	Checkbox	*Text input*	*Value input*	*Value input*	*Checkbox*	*Value input*	*Value input*
Transport 1:	☐	Producer --> DC	123,75	24.300	☐		
Transport 2:	☐				☐		
Transport 3:	☐				☐		
Transport 4:	☐	DC --> Filler	46	7.100	☐		
Transport 5:	☑				☐		
Transport 6:	☐	Filler --> Supermarket	46	300	☐		
Transport 7:	☐				☐		
Transport 11:	☐	DC --> Waste treatment	46	360	☐		
Transport 12:	☐				☐		

Output:

	Fi (efficiency factor)	Fi 2		**Extra trips needed:**	**Number of trips saved:**	**Final factor**	
	Value input	*Value input*		*Value input:*	*Value input*	*Value input*	
Transport 1:	15,081	1,000	**15,081**	0	15	**#DIV/0!**	-
Transport 2:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 3:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 4:	11,854	1,000	**11,854**	0	11	**#DIV/0!**	-
Transport 5:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 6:	0,501	1,000	**0,501**	1	0	**#DIV/0!**	this step could be optimized!
Transport 7:	1,000	1,000	**1,000**	0	0	**1**	-
Transport 11:	0,601	1,000	**0,601**	1	0	**#DIV/0!**	this step could be optimized!
Transport 12:	1,000	1,000	**1,000**	0	0	**1**	-

9.6. Appendix F: screenshots of the outcome of both tool when applying the three scenarios.

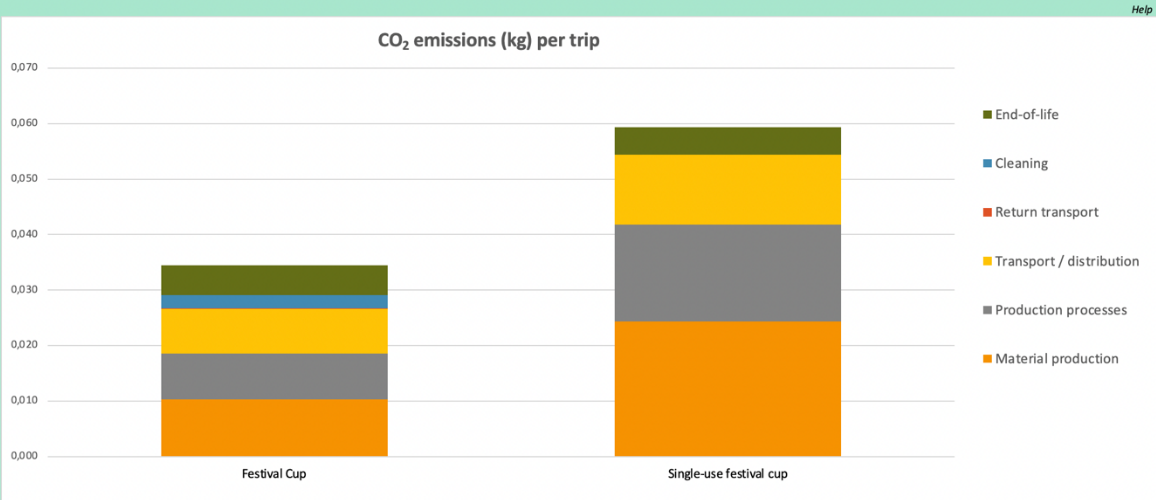
Festival cup scenario:

RESULTS **CO_2 emissions (kg) per trip**

Help *Help*

	Packaging name	Total CO_2 emissions (kg)	Extra CO_2 emissions (%)	Material production	Production processes	Transport / distribution	Return transport	Cleaning	End-of-life
Reusable packaging	Festival Cup	0,034	-	0,010	0,008	0,008	0,000	0,002	0,005
Single-use packaging	Single-use festival cup	0,059	-	0,024	0,018	0,013	-	-	0,005
Single use packaging #2	*Single use packaging #2*	*0,000*	*-100%*	*0,000*	*0,000*	*0,000*	-	-	*0,000*
Single use packaging #3	*Single use packaging #3*	*0,000*	*-100%*	*0,000*	*0,000*	*0,000*	-	-	*0,000*

Help

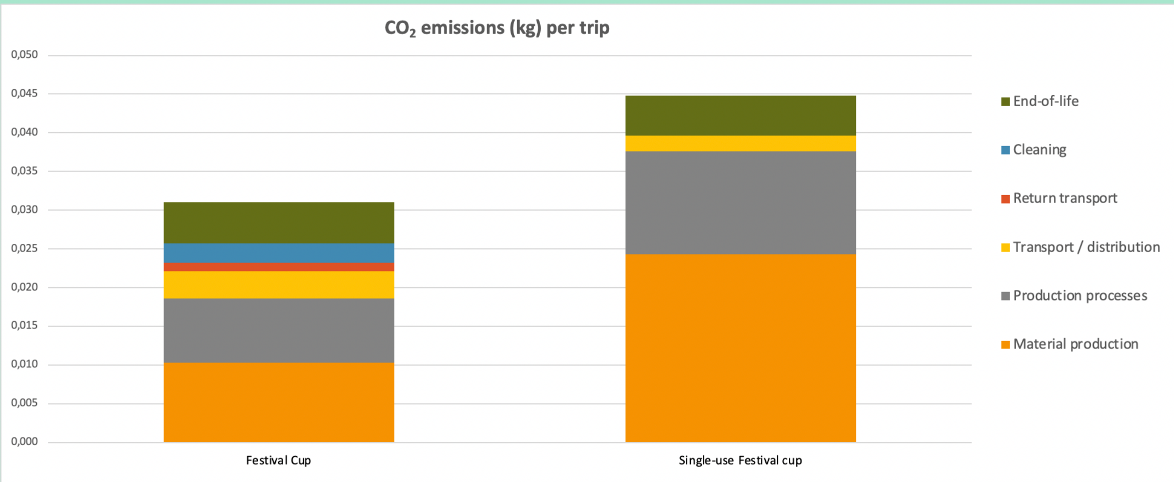


Single-use cup scenario:

RESULTS

	Packaging name	Total CO_2 emissions (kg)	Extra CO_2 emissions (%)	Material production	Production processes	Transport / distribution	Return transport	Cleaning	End-of-life
Reusable packaging	Festival Cup	0,031	-	0,010	0,008	0,004	0,001	0,002	0,005
Single use packaging #1	Single-use Festival cup	0,045	-	0,024	0,013	0,002	-	-	0,005
Single use packaging #2	*Single use packaging #2*	*0,000*	*-100%*	*0,000*	*0,000*	*0,000*	-	-	*0,000*
Single use packaging #3	*Single use packaging #3*	*0,000*	*-100%*	*0,000*	*0,000*	*0,000*	-	-	*0,000*

Help



Crate scenario:

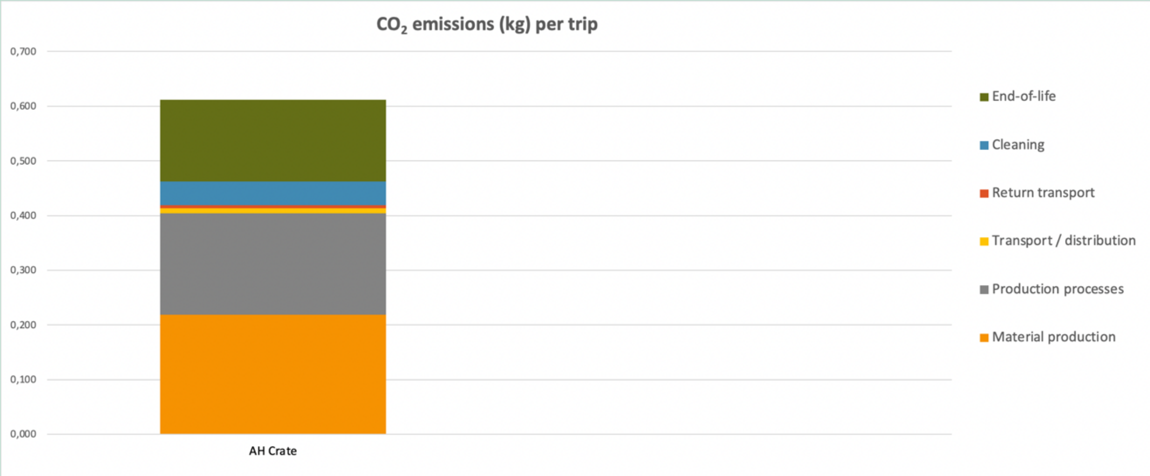
Original tool:

RESULTS **CO_2 emissions (kg) per trip**

Help *Help*

	Packaging name	Total CO_2 emissions (kg)	Extra CO_2 emissions (%)	Material production	Production processes	Transport / distribution	Return transport	Cleaning	End-of-life
Reusable packaging	AH Crate	0,612	-	0,219	0,185	0,009	0,006	0,044	0,149
Single use packaging #2	Single use packaging #2	0,000	-100%	0,000	0,000	0,000	-	-	0,000
Single use packaging #3	Single use packaging #3	0,000	-100%	0,000	0,000	0,000	-	-	0,000

Help

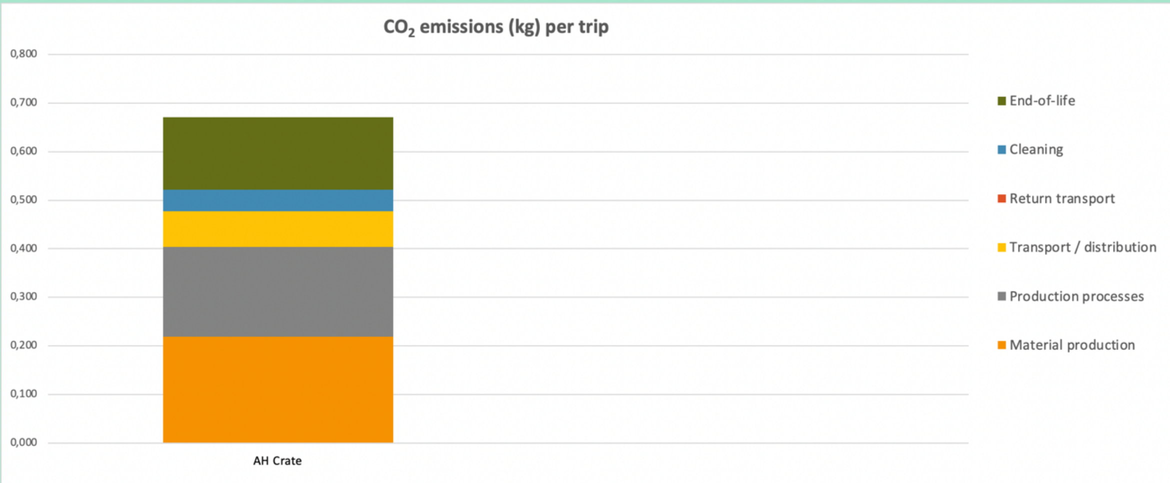


New tool (nested):

RESULTS

	Packaging name	Total CO_2 emissions (kg)	Extra CO_2 emissions (%)	Material production	Production processes	Transport / distribution	Return transport	Cleaning	End-of-life
Reusable packaging	AH Crate	0,671	-	0,219	0,185	0,073	0,001	0,044	0,149
Single use packaging #2	Single use packaging #2	0,000	-100%	0,000	0,000	0,000	-	-	0,000
Single use packaging #3	Single use packaging #3	0,000	-100%	0,000	0,000	0,000	-	-	0,000

Help

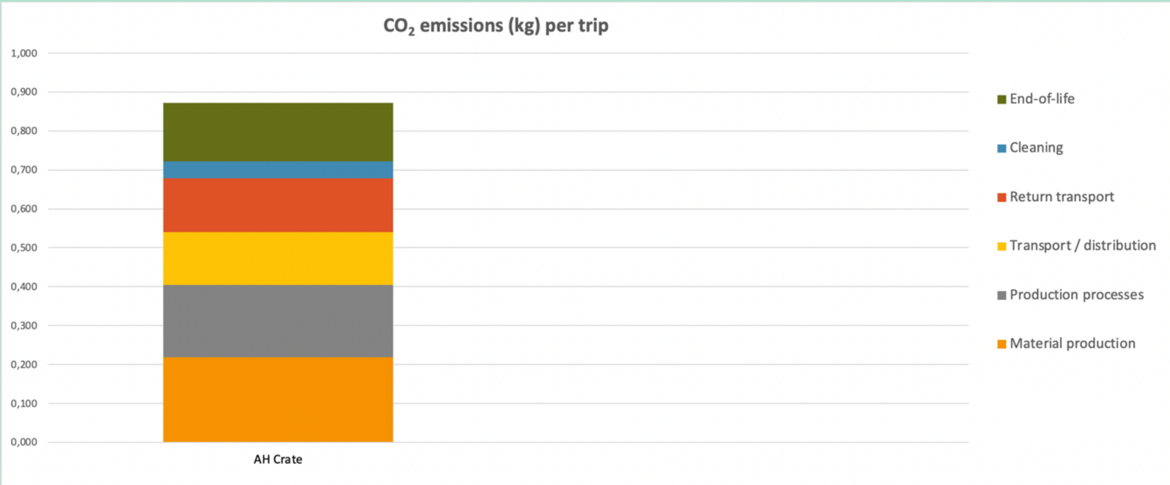


New tool (unnested):

RESULTS

	Packaging name	Total CO_2 emissions (kg)	Extra CO_2 emissions (%)	Material production	Production processes	Transport / distribution	Return transport	Cleaning	End-of-life
Reusable packaging	AH Crate	0,872	-	0,219	0,185	0,136	0,138	0,044	0,149
Single use packaging #2	Single use packaging #2	0,000	-100%	0,000	0,000	0,000	-	-	0,000
Single use packaging #3	Single use packaging #3	0,000	-100%	0,000	0,000	0,000	-	-	0,000

Help



Cabka Endure i9 pallet and wooden pallet:

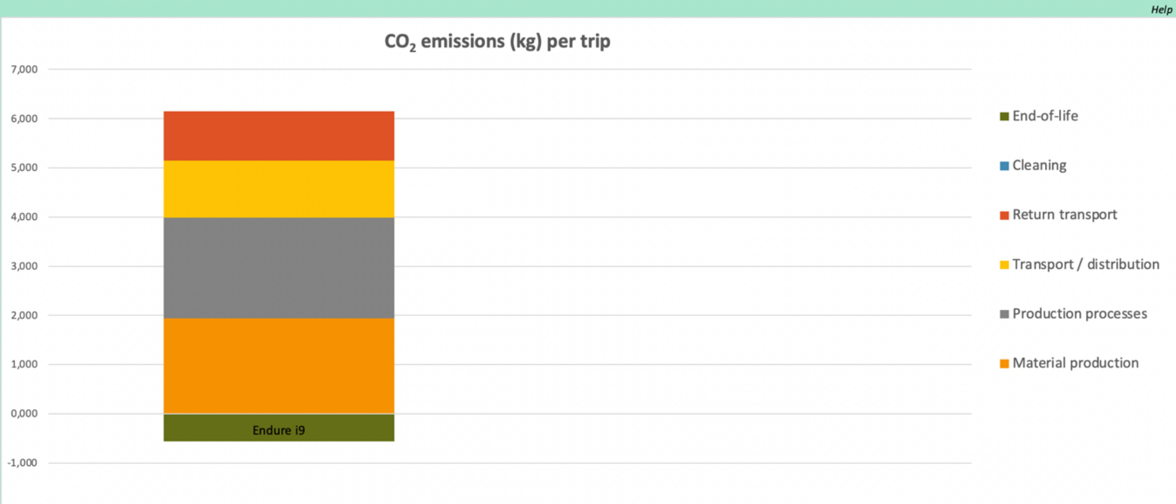
Endure i9 old tool:

RESULTS CO_2 emissions (kg) per trip

Help *Help*

	Packaging name	Total CO_2 emissions (kg)	Extra CO_2 emissions (%)	Material production	Production processes	Transport / distribution	Return transport	Cleaning	End-of-life
Reusable packaging	Endure i9	5,594	-	1,944	2,039	1,162	1,007	0,000	-0,557
Single use packaging #2	Single use packaging #2	0,000	-100%	0,000	0,000	0,000	-	-	0,000
Single use packaging #3	Single use packaging #3	0,000	-100%	0,000	0,000	0,000	-	-	0,000

Help



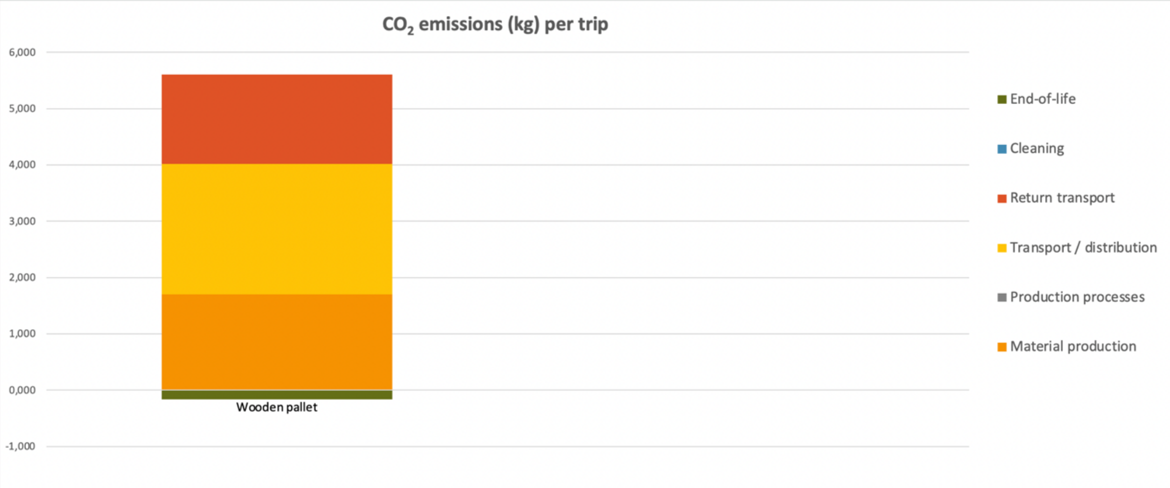
Wooden pallet old tool

RESULTS **CO_2 emissions (kg) per trip**

Help *Help*

	Packaging name	Total CO_2 emissions (kg)	Extra CO_2 emissions (%)	Material production	Production processes	Transport / distribution	Return transport	Cleaning	End-of-life
Reusable packaging	Wooden pallet	5,451	-	1,701	0,000	2,322	1,588	0,000	-0,160
Single use packaging #2	Single use packaging #2	0,000	-100%	0,000	0,000	0,000	-	-	0,000
Single use packaging #3	Single use packaging #3	0,000	-100%	0,000	0,000	0,000	-	-	0,000

Help

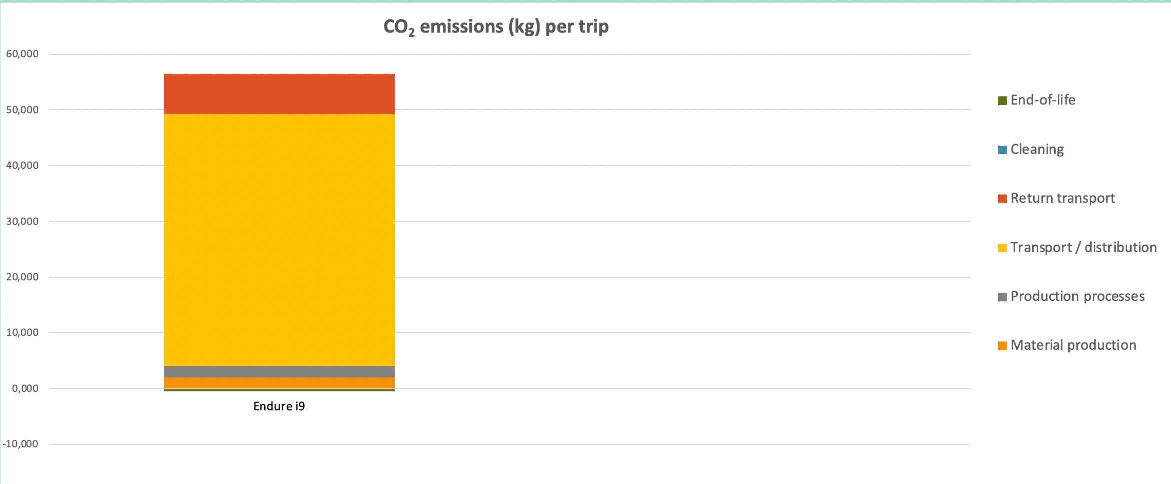


Endure new tool

RESULTS

	Packaging name	Total CO_2 emissions (kg)	Extra CO_2 emissions (%)	Material production	Production processes	Transport / distribution	Return transport	Cleaning	End-of-life
Reusable packaging	Endure i9	55,977	-	1,944	2,039	45,227	7,249	0,000	-0,482
Single use packaging #2	Single use packaging #2	0,000	-100%	0,000	0,000	0,000	-	-	0,000
Single use packaging #3	Single use packaging #3	0,000	-100%	0,000	0,000	0,000	-	-	0,000

Help

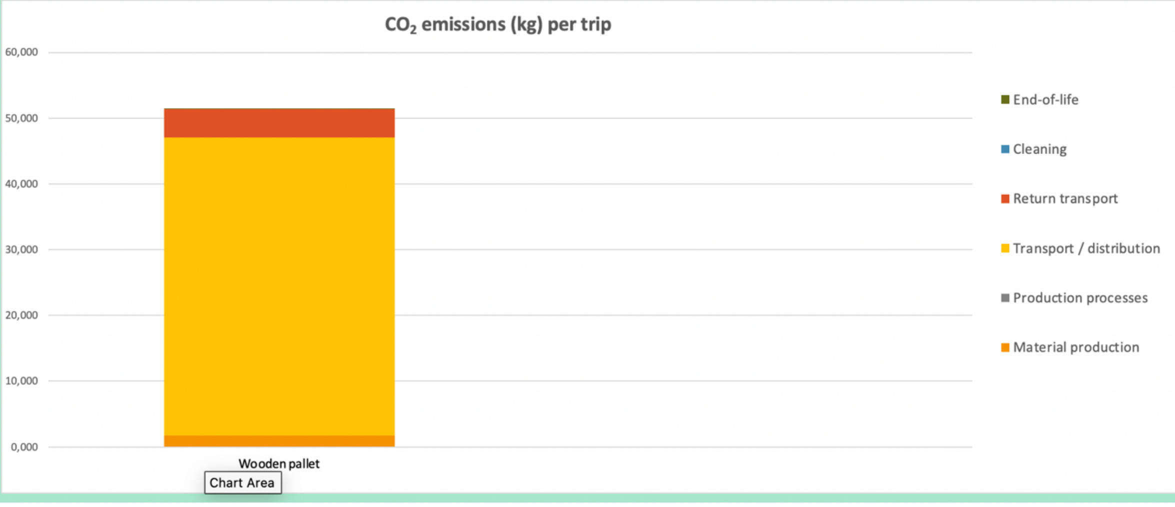


Wooden pallet new tool

RESULTS

	Packaging name	Total CO_2 emissions (kg)	Extra CO_2 emissions (%)	Material production	Production processes	Transport / distribution	Return transport	Cleaning	End-of-life
Reusable packaging	Wooden pallet	51,417	-	1,701	0,000	45,351	4,325	0,000	0,040
Single use packaging #2	Single use packaging #2	0,000	-100%	0,000	0,000	0,000	-	-	0,000
Single use packaging #3	Single use packaging #3	0,000	-100%	0,000	0,000	0,000	-	-	0,000

Help



9.7. Appendix G: extended calculation per step per scenario.

Scenario 1.

Surrounding volume:

Units: mm*mm*mm = m^3

l*b*h = 100*80*80 = 0,00064 .

Efficiency factors:

Units: $(unitless) = \frac{\text{number}}{\text{m3/m3}} * \frac{\text{number}}{\frac{\text{m3}}{\text{m3}}}$

$$\text{T4: } \varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{360}{0{,}045/0{,}00064} * \frac{896}{\frac{46}{0{,}045}} = 4{,}488$$

$$\text{T5: : } \varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{360}{0{,}045/0{,}00064} * \frac{896}{\frac{46}{0{,}045}} = 4{,}488$$

$$\text{T6: : } \varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{100}{0{,}016/0{,}00064} * \frac{36}{\frac{2{,}6}{0{,}016}} = 0{,}886$$

$$\text{T8: : } \varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{15.000}{46/0{,}00064} * 1 = 0{,}209$$

$$\text{T9: } \varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{360}{0{,}045/0{,}00064} * \frac{896}{\frac{46}{0{,}045}} = 4{,}488$$

$$\text{T11: } \varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{15.000}{46/0{,}00064} * 1 = 0{,}209$$

Weight factor:

Units: $(unitless) = \frac{kg}{number*kg}$

T4: $wf = \frac{GVW-AFL}{load} = \frac{19.300}{322560*2,9E-6}$ = 2,063

T5: $wf = \frac{GVW-AFL}{load} = \frac{19.300}{322560*2,9E-6}$ = 2,063

T6: $wf = \frac{GVW-AFL}{load} = \frac{1000}{3600*2,9E-6}$ = 9,579

T8: $wf = \frac{GVW-AFL}{load} = \frac{19.300}{15.000*2,9E-6}$ = 44,368

T9: $wf = \frac{GVW-AFL}{load} = \frac{19.300}{322560*2,9E-6}$ = 2,063

T11: $wf = \frac{GVW-AFL}{load} = \frac{19.300}{15.000*2,9E-6}$ = 44,368

Final factor:

Units: $(unitless) = \frac{(unitless)}{number*(unitless)}$

Units: $(unitless) = (unitless) * number * (unitless)$

T4: $\varphi f = \frac{4,488}{(4+1)*2,063}$ = 0,435

T5: $\varphi f = \frac{4,488}{(4+1)*2,063}$ = 0,435

T6: $\varphi f = 0,886 * (1 + 1) * 9,579$ = 16,976

T8: $\varphi f = 0,209 * (4 + 1) * 44,368$ = 46,297

T9: $\varphi f = \frac{4,488}{(4+1)*2,063}$ = 0,435

T11: $\varphi f = 0,209 * (4 + 1) * 44,368$ = 46,297

Scenario 2.

Surrounding volume:

Units: mm*mm*mm = m^3

T4: $V1 = \ l * b * h = 0{,}6 * 0{,}4 * 0{,}32 = 0{,}0768\ m3$

Efficiency factors:

Units: $(unitless) = \frac{\text{number}}{\text{m3/m3}} * \frac{\text{number}}{\frac{\text{m3}}{\text{m3}}}$

T1 (nested): $\varphi t1 = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{8.100}{\frac{100}{0{,}0768}} * 1 = 6{,}221$

T1 (unnested): $\varphi t2 = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{1323}{\frac{100}{0{,}0768}} * 1 = 0{,}821$

T4 (nested): $\varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{2400}{\frac{46}{0{,}0768}} * 1 = 4{,}007$

T4 (unnested): $\varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{504}{\frac{46}{0{,}0768}} * 1 = 0{,}841$

T6: $\varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{300}{\frac{46}{0{,}0768}} * 1 = 0{,}501$

Weight factor:

Units: $(unitless) = \frac{kg}{number * kg}$

T1 (nested): $wf1 = \frac{GVW-AFL}{load}$ = $\frac{19.300}{8.100*2{,}6}$ = 0,916.

T1 (unnested): $wf2 = \frac{GVW-AFL}{load}$= $\frac{19.300}{1.323*2{,}6}$ = 5,611.

T4 (nested): $wf1 = \frac{GVW-AFL}{load}$= $\frac{19.300}{2.400*2{,}6}$ = 3,103.

T4 (unnested): $wf2 = \frac{GVW-AFL}{load}$= $\frac{19.300}{504*2{,}6}$ = 14,728.

T6: $wf1 = \frac{GVW-AFL}{load}$= $\frac{19.300}{300*2{,}6}$ = 24,744.

T8 (nested): $wf1 = \frac{GVW-AFL}{load}$= $\frac{19.300}{1.200*2{,}6}$ = 6,186.

T8 (unnested): $wf2 = \frac{GVW-AFL}{load}$= $\frac{19.300}{504*2{,}6}$ = 14,728.

T11: $wf1 = \frac{GVW-AFL}{load}$= $\frac{19.300}{360*2{,}6}$ = 20,620.

Final factor:

Units: $(unitless) = \frac{(unitless)}{number*(unitless)}$

Units: $(unitless) = (unitless) * \ number * (unitless)$

T1 (nested): $\varphi f1 = \frac{6,221}{(6+1)*0,916}$ = 0,435.

T1 (unnested): $\varphi f2 = \ 0,821 * (1 + 1) * 5,611$ = 9,214

T4 (nested): $\varphi f1 = \frac{6,221}{(6+1)*0,916}$ = 0,435.

T4 (unnested): $\varphi f = \ 0,841 * (1 + 1) * 14,728 = 24,787$

T6: $\varphi f = \ 0,501 * (1 + 1) * 24,744 = 24,787$

T8 (nested): $\varphi f1 = \frac{2,003}{(2+1)*6,186}$ = 0,108.

T8 (unnested): $\varphi f = \ 0,841 * (1 + 1) * 14,728 = 24,787$

T11: $\varphi f = \ 0,601 * (1 + 1) * 20,620 = 24,78$

Scenario 3.

Cabka pallet:

V_1:

Units: mm*mm*mm = m^3

$$V1 = \ l * b * h = 1 * 1,2 * 0,165 = 0,198\ m3$$

Efficiency factors:

Units: $(unitless) = \ \frac{\text{number}}{\text{m3/m3}} * \frac{\text{number}}{\frac{\text{m3}}{\text{m3}}}$

T1: $\varphi t = \ \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{300}{\frac{81,63}{0,198}} * 1 = 0,728$

T4: $\varphi t = \ \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{40}{\frac{81,63}{0,198}} * 1 = 0,097$

T6: $\varphi t = \ \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{40}{\frac{81,63}{0,198}} * 1 = 0,979$

T8: $\varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{300}{\frac{81{,}63}{0{,}198}} * 1 = 0{,}728$

T11: $\varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{300}{\frac{81{,}63}{0{,}198}} * 1 = 0{,}728$

Weight factors:
Units: $(unitless) = \frac{kg}{number*kg}$

T1: $wf = \frac{GVW-AFL}{load} = \frac{19.300}{300*13} = 4{,}949.$

T4: $wf = \frac{GVW-AFL}{load} = \frac{19.300}{40*13} = 37{,}115.$

T6: $wf = \frac{GVW-AFL}{load} = \frac{19.300}{40*13} = 37{,}115.$

T8: $wf = \frac{GVW-AFL}{load} = \frac{19.300}{300*13} = 4{,}949.$

T11: $wf = \frac{GVW-AFL}{load} = \frac{19.300}{300*13} = 4{,}949.$

Final factors:

Units: $(unitless) = (unitless) * \ number * (unitless)$

T1: $\varphi f = 0{,}728 * (1+1) * 4{,}949 = 7{,}202.$

T4: $\varphi f = 0{,}097 * (10+1) * 37{,}115 = 39{,}612.$

T6: $\varphi f = 0{,}097 * (10+1) * 37{,}115 = 39{,}612.$

T8: $\varphi f = 0{,}728 * (1+1) * 4{,}949 = 7{,}202.$

T11: $\varphi f = 0{,}728 * (1+1) * 4{,}949 = 7{,}202.$

Wooden pallet:

V_1:

Units: mm*mm*mm = m^3

$$V1 = \ l * b * h = 0{,}8 * 1{,}2 * 0{,}15 = 0{,}144 \, m3$$

Efficiency factors:

Units: $(unitless) = \frac{\text{number}}{\text{m3/m3}} * \frac{\text{number}}{\frac{\text{m3}}{\text{m3}}}$

T1: $\varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{300}{\frac{81,63}{0,144}} * 1 = 0,529$

T4: $\varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{40}{\frac{81,63}{0,144}} * 1 = 0,071$

T6: $\varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{40}{\frac{81,63}{0,144}} * 1 = 0,071$

T8: $\varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{300}{\frac{81,63}{0,144}} * 1 = 0,529$

T11: $\varphi t = \frac{\text{U}}{\text{V2/V1}} * \frac{\text{Ubox}}{\frac{\text{Vt}}{\text{V2}}} = \frac{300}{\frac{81,63}{0,144}} * 1 = 0,529$

Weight factors:

Units: $(unitless) = \frac{kg}{number * kg}$

T1: $wf = \frac{GVW-AFL}{load}$ = $\frac{19.300}{300*25}$ = 2,573.

T4: $wf = \frac{GVW-AFL}{load}$ = $\frac{19.300}{40*25}$ = 19,300.

T6: $wf = \frac{GVW-AFL}{load}$ = $\frac{19.300}{40*25}$ = 19,300.

T8: $wf = \frac{GVW-AFL}{load}$ = $\frac{19.300}{300*25}$ = 2,573.

T11: $wf = \frac{GVW-AFL}{load}$ = $\frac{19.300}{300*25}$ = 2,573.

Final factors:

Units: $(unitless) = (unitless) * \ number * (unitless)$

T1: $\varphi f = 0,529 * (1 + 1) * 2,573$ = 2,724.

T4: $\varphi f = 0,071 * (10 + 1) * 19,300$ = 20,428.

T6: $\varphi f = 0,071 * (10 + 1) * 19,300$ = 20,428.

T8: $\varphi f = 0,529 * (1 + 1) * 2,573$ = 2,724.

T11: $\varphi f = 0,529 * (1 + 1) * 2,573$ = 2,724.