3D Printing and Conventional Manufacturing: A Comparative LCC and LCA Analysis in After Sales Service for Gas Hobs

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Master Thesis IEM

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Executive Summary

ATAG Benelux is a leading supplier of various kitchen appliances and is part of the Chinese multinational; Hisense group. ATAG produces expensive, technological, and high-quality kitchen appliances for its customers. Because of these characteristics, ATAG guarantees their customer ten years of after-sales service (ASS) in which ATAG delivers service parts. However, for one of their products, i.e. the Fusion Volcano (FV) wok burner, ATAG will decide to stop selling the burner due to an introduction of a re-design of the FV wok burner in the market. This means that several agreements between the supplier and ATAG will change when it comes to delivering service parts of the FV wok burner during the ASS period, i.e. ten years of service.

Background

Both the production technique additive manufacturing (AM) and conventional manufacturing (CM) have a positive result for ATAG during the ASS period. However, ATAG is not familiar with the impact of AM and CM concerning life cycle costing (LCC) and life cycle assessment (LCA) in ASS. The goal of this research is to construct models that can determine the impact of the use of AM and CM during the ASS period through an LCC analysis and an LCA. In this research, we performed a case study for the service parts of the FV wok burner, i.e. the wok head, roast head and burner cup. With the use of the LCA and LCC models where we assess the costs and carbon dioxide footprints, respectively, we can answer the main research question:

> *Under which condition should ATAG use Additive Manufacturing and Conventional Manufacturing to decrease Life Cycle Cost and environmental impact of service parts during the After Sales Service period?*

Within this research, we analyzed six alternatives for ATAG that determine the costs and CO2 emissions of the demanded service parts of the FV wok burner during the ASS period. In alternative 1 (i.e. MOQ + CM), we look at how much it cost when we place orders at the supplier with an MOQ of 50 using CM production processes. The amount to order is based on a demand forecast. This alternative gives ATAG insight into how much it costs to cover 10 years of service after the redesign is introduced in the market. The second alternative, i.e. outsource + MOQ + AM, is related to outsourcing the FV wok burner components using AM production process. In this alternative, ATAG buys the FV service parts via a 3D print outsource manufacturer. In alternative 3a (i.e. repair + MOQ + CM) we repair a small portion of failed conventional FV wok burner components and where the rest of the demand is filled by placing an order at the supplier where CM production processes are used. In alternative 3b (i.e. repair + outsource + MOQ + AM) we again repair a small portion of the failed conventional FV wok burner components and where the rest of the demand is filled by placing an order at the 3D print outsource manufacturer. In both alternative 3a (i.e. repair + MOQ + CM) and alternative 3b (i.e. repair + outsource + MOQ + AM) repair takes place within ATAG itself. In alternative 4a (i.e. invest in a small AM machine), we look at the possibility of investing in a small new 3D printing machine. In alternative 4b (i.e. invest in a large AM machine), we look at the possibility of investing in a production wide AM machine.

Approach

For the construction of the LCC models, several cost factors were identified. Additionally, existing life cycle cost models in the literature were reviewed. The cost factors are separated into four phases namely, design, production, use, and recycling phase. Within this research, we did not consider the cost factors during the design phase since these costs were already

amortized during 2010 and 2018. After determining the relevant cost factors, the models are constructed specifically to the six alternatives. Further, the costs are calculated per component and then merged in each alternative. Thus, we get the costs of all three FV wok burner components for a period of 10 years of service. The LCC over time was measured using the Net Present Value (NPV), where the sum of all relevant costs created during the 10 years of service is taken into account, i.e. the cost during the production, use, and recycling phase for each component in all six alternatives.

For the construction of the LCA models, a cradle to gate assessment was executed. Next to that, we included a part of the disposal phase in our analysis. When producing with AM production techniques, single-piece or small-batch production are used and leaves us with little or no parts at the end of the life cycle and leads to less waste (e.g. less raw material used, less used energy for production, et cetera). Thus, the disposal phase becomes the "gate" within the LCA analysis. The LCA models are constructed in GaBi Software using flow charts in which the relevant processes were determined in each alternative. The impact category we considered is the Global Warming Potential (GWP) where all emissions that contribute to global warming are converted to kg CO_2-equivalents in each alternative.

Results

After computing the life cycle cost in each alternative, it can be concluded that alternative 1 (i.e. MOQ + CM), and 3a (i.e. repair + MOQ + CM) are the most cost-efficient alternatives with a cost of 11.058,78 € and 9.604,49 €, respectively. This means that CM turns out to be more cost-efficient compared to AM. However, when it comes to the LCA analysis alternative 1 (i.e. MOQ + CM) has a negative impact on global warming. Alternative 3a (i.e. repair + MOQ + CM) and 3b (i.e. repair + outsource + MOQ + AM) are the most environmentally friendly alternatives with a total of 208 and 183 kg CO_2-eq. emissions compared to the rest of the alternatives.

From the sensitivity analysis (SA), two aspects turned out to be sensitive towards the outcome of both the LCC and LCA models, i.e. changing the MOQ's in alternatives 1 (MOQ + CM) and 3a (i.e. repair + MOQ + CM) and changing the repair proportions in alternatives 3a (i.e. repair + MOQ + CM) and 3b (i.e. repair + outsource + MOQ + AM). Both aspects had a significant impact on the life cycle cost and the carbon dioxide footprint. The most important conclusion based on changing the repair proportions is that the cost-saving potential of CM increases in case ATAG decides to repair more components than order with MOQ/outsource the FV wok burner components (i.e. alternatives 3a and 3b). Regarding changing the MOQ values in alternatives 1 (i.e. MOQ + CM) and 3a (i.e. repair + MOQ + CM), we can conclude that:

- Changing the MOQ from 50 to 100 or 150 results in more costs and CO_2 emissions.
- Implementing a Last Time Buy (LTB) analysis, leads to higher use of electricity, fuel for transport and raw materials, which means more release of carbon dioxide footprints and more unnecessary excessive stock in the warehouse in Duiven. However, in case ATAG finds itself in an extreme LTB situation AM starts becoming interesting. If the MOQ parameter in alternative 1 is set to 475 (or higher), the cost increases to 46.213 € and the footprint increases to 1131 kg CO_2 eq. emissions. As a consequence, investing in alternative 3b (i.e. repair + outsource + MOQ + AM) becomes interesting for ATAG since the costs and footprint in this alternative is lower, i.e. 46.146 € and 183 kg CO_2 eq. emissions, respectively. Further, if we change the MOQ parameter in alternative 3a to 460 (or higher) it is also best to switch to AM,

List of Abbreviations

AM Additive Manufacturing

ASS After Sales Service

CM Conventional Manufacturing

FV Fusion Volcano

GWP Global Warming Potential

LCA Life Cycle Assessment

LCC Life Cycle Costing

LTB Last Time Buy

MOQ Minimum Order Quantity

MRP Material Requirement Planning

NPV Net Present Value

SA Sensitivity Analysis

SS Stainless Steel

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Preface

In front of you lies the result of my graduation project at ATAG Benelux about the topic: "3D Printing and Conventional Manufacturing: A Comparative LCC and LCA analysis in After Sales Service for gas hobs". This thesis completes my Master Program Industrial Engineering and Management, specialisation track: Production and Logistics Management, at the University of Twente.

First, I want to thank my supervisor at ATAG Benelux: Jan van Os for his support, feedback and guidance throughout my research period. I appreciate the time you've spent mentoring me during my thesis project. Also, great thanks to my colleagues within the purchasing department, especially Mariska Kleinhaarhuis and Jan Straalman for the information/data and insights provided. Additionally, I want to thank the people within the research and development department. During my graduation period, I worked with great pleasure at ATAG Benelux. Furthermore, I felt very welcome since my first workday in Duiven.

Next, I want to thank my supervisors from the University of Twente. I was not able to write this thesis without the help and guidance of Matthieu van der Heijden. Thank you for the support and feedback during my research project. I admire your dedication to my research project. Because of your continuous involvement, I managed to navigate the research project critically. I also want to thank my second supervisor Devrim Yazan for his feedback and opinions concerning my research. Your feedback and suggestions were of great help. Thank you both very much for this. I also want to thank Rob Basten from the Eindhoven University of Technology. Thank you for your feedback, helpful meetings and discussions on my thesis.

Finally, I am very grateful for the support and prayers of my family and friends. Even though some of you are 5000 miles away from me, you still manage to uphold me. Hope to see you again soon!

Shantal Kartoidjojo

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1 Introduction

This report is written for a master's graduation thesis project at the University of Twente in cooperation with ATAG Benelux in Duiven, Netherlands. In this research, we make a comparative LCC and LCA analysis in After Sales Service. This means that we determine the environmental impact through Life Cycle Assessment (LCA) and the total life cycle cost through Life Cycle Costing (LCC) using Additive Manufacturing (AM) and Conventional Manufacturing (CM) related production processes. The case study we used for both the LCA and LCC analysis is the Fusion Volcano (Fusion Volcano (FV)) wok burner of ATAG Benelux.

1.1 ATAG Benelux

The graduation thesis is performed in Duiven, where ATAG Benelux's head office is located. ATAG Benelux is a leading supplier of various kitchen appliances and is part of the Chinese multinational; Hisense group. ATAG Benelux is originally a Dutch company and sells kitchen appliances known under the brands ATAG, Pelgrim, ETNA. Besides these three Dutch brands the company also sells products under the brands ASKO (laundry) and Hisense (TV & Cooling). Further, there are two branches namely, ATAG Netherlands which is located in Duiven near Arnhem and ATAG Belgium which is located in Denderhoutem. In Figure 1 an overview of the organizational structure is provided. From now on, we address ATAG Benelux as ATAG in the rest of this research.

ATAG sells a collection of hobs, microwaves, ovens, (combi-) steam ovens, extractor hoods, refrigerators and freezers, dishwashers, and coffee machines. In addition, ATAG delivers different types of after-sales services to their customer. These after-sales services range from delivering service parts to consumers, to technician visits at the consumer's location in case of a problem.

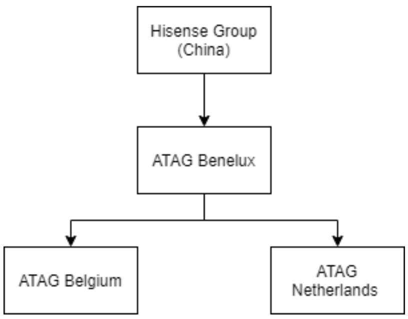


Figure 1: Organizational structure.

1.2 Case study: Fusion Volcano wok burner

One of the kitchen appliances that was assigned a case study for this project is the FV wok burner. The FV wok burner comes in a complete gas hob. There are different types of gas hobs where the FV wok burner is built-in. In Appendix B an overview is given of the different types of gas hobs. However, there are two variants of the FV wok burner in the gas hob namely, the European and the Chinese variant. The Chinese variant is more complex than the European variant. In Figure 2 a gas hob and an exploded view of the FV wok burner (80 cm) is given (European variant). The difference between the two variants is that the roast head of the European variant is made out of aluminium and the roast head of the Chinese variant is made out of brass. In this case study, only the European variant is analyzed.

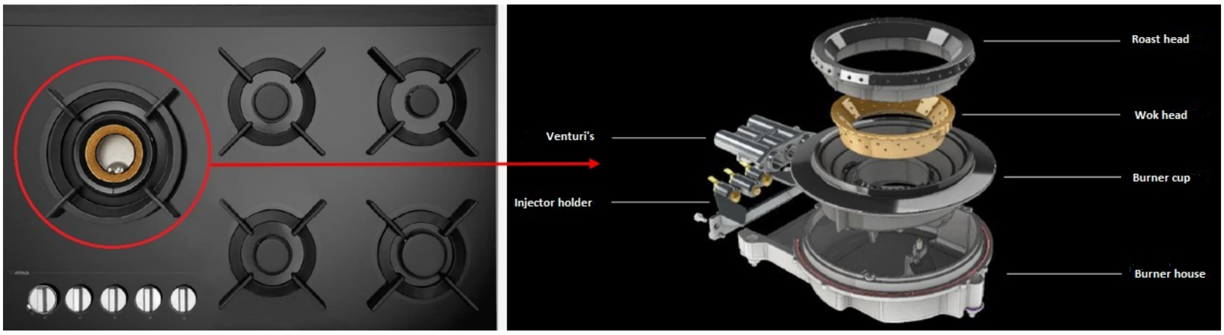


Figure 2: Fusion Volcano wok burner (left gas hob, right exploded view Fusion Volcano wok burner).

The roast head and the burner cup are made of aluminium and produced in Malaysia. From Malaysia, some components are sent to Germany for coating and some directly to Moerwijk in the Netherlands where they are stored. After the components are coated in Germany they are transported to Moerwijk as well. From Moerwijk, the components are sent to Slovenia where the assembly takes place. The wok head is made of brass and produced in Turkey. Afterwards, it is transported directly to Slovenia. The wok head, roast head and burner cup are ordered from Slovenia and afterwards, it is transported to ATAG.

1.3 Problem description

When a product is introduced in the market it goes through different stages. The four main phases are the introduction-, growth-, maturity-, and decline phase. If we look at the sales of the gas hobs where the FV wok burner is built-in in Figure X, notice that the sales started declining since 2017. As a result, the introduction of the new gas law and regulations of the government in 2016. By 2050, all Dutch homes must be sustainable and CO_2-neutral. Moving to sustainable energy sources in the next 30 years is a big operation because 89% of Dutch homes use natural gas for heating and cooking. To make this less stressful for the government many people took initiatives themselves by switching from buying gas hobs to buying induction cookers. Therefore the sales/service gas hobs ordered by consumers decreased as well.

Usually, when a product reaches the decline phase, ATAG decides to stop selling the product (Schoenmaker, 2021). Before the sales stop, ATAG Benelux decides to place a final order of the product that covers ten years of service and put it in stock in the warehouse of Duiven. However, when it comes to the gas hobs where the FV wok burner is built-in, this is a slightly different case. Currently, ATAG is working on a re-design of the FV wok burner. A prototype of the re-design can be found in Figure X.

—Confidential—

To introduce the new FV wok burner in the market, the sales of the "old" FV wok burner will stop. If ATAG decides to keep selling the "old" FV wok burner while introducing the new FV wok burner in the market, it financially will hinder the sale of the new FV wok burner. Thus, it will only take longer to introduce the redesign in the market. Another reason why ATAG will stop selling the "old" FV wok is because of the declining numbers of sales as shown in Figure X. However, the moment when ATAG decides to stop selling the FV wok burner components does not necessarily mean that the production of the FV wok burner in Slovenia, Malaysia, and Turkey will stop. The moulds will still be available and whenever ATAG needs a component of the FV wok burner during the ten years of service, production can start again but under certain circumstances such as the MOQ that is demanded from the Slovenia.

—Confidential—

As soon as ATAG decides to stop selling the FV wok burner an inventory is made to determine how many parts are needed to cover at least ten years of service for the FV wok burner (Walter, 2021). Based on this inventory a (final) order is placed and stocked in the warehouse of Duiven. However, besides placing a (final) order, ATAG did not investigate if other options could be more cost-efficient and environmentally friendly to cover the ten years of service for the FV wok burner.

1.4 Problem approach

Currently, ATAG is looking at options to 3D print service parts. 3D printing or AM is building an object by adding material layer-by-layer, based on a CAD drawing. According to van Os, 3D printing can guarantee that production takes place in small quantities and ensures the availability of components (van Os, 2021; Zijm, Knofhuis & van der Heijden, 2018). Next to that decentral production can take place around the globe and reduces CO2 footprint (van Os, 2021; Zijm, Knofhuis & van der Heijden, 2018). If at a certain point in time AM can meet these requirements, are AM processes interesting for ATAG to use for the manufacturing of service parts, and to what extent? First, a short description of previous research is explained below, and then the problem is formulated.

1.4.1 Previous research related to 3D printing at ATAG

Since the use of AM has an impact on a lot of areas, we specified our research. In the past, two projects were conducted at ATAG regarding 3D printing. This is briefly explained below.

A minor research project (Brugman, Goossens & Eppingbroek, 2020) about 3D printing of service parts within ATAG was performed. This research aimed to gain insight into the potential of 3D printing to minimize the stock of service parts and to advise on the steps to be taken towards the realization of 3D printing within ATAG. This research suggested, among others, that future research is needed on categorizing the current stock in the following product groups: metal, electronics, glass, plastics, and composite products. This indicates which product groups can be 3D printed. Afterwards, the product group should meet the following criteria: material (plastic or metal), size (maximum size available printer), and drawing (drawing available, if scanning is done), since this could influence which kitchen appliance can be 3D printed in the future.

Another minor research project (Baneii et al., 2020) focused on 3D printing of the Fusion Volcano wok burner. This study focused on the impact of 3D printing of the Fusion Volcano wok burner as an alternative to normal production at ATAG. The results were that the turnaround times are considerably shorter with 3D printing of the FV wok burner, potentially reduced to one week. In addition, the processes are less complex from a logistical point of view because production can be done locally. On the other hand, costs will increase significantly if the choice is made to switch to 3D printing. This research suggests, among others, that future research is needed on the LCC since a more detailed LCC can give ATAG a better indication to print a prototype.

This master research study has a connection with the above-described research since the 3D printing technical details and the production process are used for the LCC and LCA models. In the research of Baneii et al. (2020), they investigated how the roast head (see Figure 2), the wok head, and the burner cup can be 3D printed. The venturi's, injector holder, and burner holder are not considered as service components since the chance that these components will fail/break is very small (van Os, 2021). Therefore, the focus of this research is on the roast head, the wok head, and the burner cup. Instead of mentioning the burner cup, wok, and roast head separately, we mention them as "components of the FV wok burner" or "FV wok burner components" in the rest of this research.

The main difference between the mentioned previous research and this study is that a detailed LCC and LCA is conducted for different alternatives based on additive and conventional manufacturing production processes for the FV wok burner components.

1.5 Research question

The goal of this research is to construct models to assess the impact of the use of Additive Manufacturing and Conventional Manufacturing during the After Sales Service (ASS) period, through a Life Cycle Cost analysis and a Life Cycle Assessment of service parts of the FV wok burner at ATAG. Thus, based on the problem definition and the research goal, the main research question of this project is as follows:

> *Under which condition should ATAG use Additive Manufacturing and Conventional Manufacturing to decrease Life Cycle Cost and environmental impact of service parts during the After Sales Service period?"*

1.6 Research design

This thesis consists of several chapters. In Chapter 1 an introduction is given of the company, the problem, the case description, the goal, and the scope. In the following chapters, several topics are discussed, each with its sub-questions. These are explained below.

1.6.1 Chapter 2: Current situation

In this chapter, the current situation at ATAG is analyzed. Thus, the cost variables used when producing through CM and AM are determined. Next to that, the processes for producing the FV wok burner with AM and CM are determined. Furthermore, which conditions does ATAG use for CM and which for AM. Therefore, we have formulated the following question:

- *Which CM and AM input variables and processes are used to determine the LCC /LCA at ATAG, currently?*

To answer this research question it is important to understand the current LCC and LCA method used by ATAG, Benelux. This question is answered based on the following sub-questions:

- How does the ASS look like at ATAG, currently?
- Which CM production steps are used to produce the FV wok burner?
- Which AM production steps are used to produce the FV wok burner?
- Does ATAG use an LCC for the FV wok burner? If yes, how does it work?
- Does ATAG use an LCA for the FV wok burner? If yes, how does it work?
- Which alternatives are considered besides placing a (final) order?

Thus, the first step is to define the ASS period at ATAG at the moment. Next, the production process, i.e. AM and CM, of the FV wok burner are determined. Afterwards, we determine the definition of LCC and LCA as it is at ATAG. Finally, we look at which alternatives there exist for ATAG, besides placing a final order during the ASS period. Thus, these alternatives are used as the base for the LCC and LCA analysis.

1.6.2 Chapter 3: Literature study

In this chapter, a literature study is performed where we determine the LCA cost factors and LCA environmental impact indicators that are used in general, and relevant for the alternatives determined in the previous chapter. The following questions are discussed in this chapter:

- What is LCC and how is it used during the ASS period?
- Which cost factors exist in the literature?
- What is LCA and how is it used during the ASS period?
- Which LCA methods exist in the literature?

1.6.3 Chapter 4: Construction of the LCC model specific to ATAG

After finding the LCC cost factors in the literature, we construct the LCC model specific to ATAG. Thus, we identify which costs incur when producing the FV wok burner with the relevant alternatives and how the LCC model is constructed. In this chapter, we answer the following question:

- *Which cost factors are important to perform a LCC analysis when producing the FV wok burner with the chosen alternatives?*

During this research, we are only interested in the cost factors that are necessary during the ASS period for the service parts of the FV wok burner. We do this by retrieving information from expert opinions at ATAG and literature. Further, the goal of the LCC model is to see what the total costs are and under which conditions the FV wok burner are produced. Thus, the following questions are answered:

- Which cost elements are used to construct the LCC model?
- How is the LCC model formulated to assess the impact of the alternatives during the ASS period?

After gathering all variables of interest in Chapter 4 we can construct a model with all relevant parameters on the situation of ATAG. The LCC model is constructed in Excel for each alternative. The models describe the difference between the alternatives in terms of cost. The necessary data required for the model is based on existing data within ATAG. Furthermore, data is retrieved through interviews, literature, expert opinions, and other available information sources such as internet websites.

1.6.4 Chapter 5: Construction of the LCA model specific to ATAG

In this chapter, based on the information found in Chapter 3, we identify the environmental impact indicators which are important when producing the FV wok burner with AM and CM and how to construct the LCA model. We answer the following question:

- *Which environmental impact indicators are important for the LCA when producing the FV wok burner with AM and CM and how can a model that assesses the impact of AM and CM on the LCA at ATAG be constructed?*

Many studies identify environmental impact indicators to determine the LCA in the case of AM and CM. During this research, however, we are only interested in the environmental impact indicators that affect the environment during the ASS period of the service parts. We do this by discussing the environmental impact indicators of LCA based on expert opinions at ATAG. Further, the goal of the model is to see what the environmental impacts are for the FV wok burner. Thus, the following questions are answered:

- Which method is used to construct the LCA model?
- Which boundaries and processes are included in the LCA?
- Which AM and CM variables/materials are used as input in each process for the LCA?

The LCA model is constructed in the GaBi Software for each production method, i.e. AM and CM. In this software, it is possible to make a dashboard and to show how much impact, e.g. global warming or ozone layer depletion has on the environment when using AM and CM related processes during the ASS period. So, the LCA models describe the difference between CM and AM in terms of indicators. The necessary data required for the models are based on existing data from databases, literature, expert opinions, and other available information sources such as internet websites.

1.6.5 Chapter 6: Analysis of the models

At last, we analyze the models where we evaluate the potential of AM and CM processes. Thus, the following question is answered:

- *Under which condition can ATAG use AM and CM, to decrease Life Cycle Cost and environmental impact of service parts during the ASS phase?*

In this chapter, the results of the LCC and LCA models are analyzed where the following questions are answered:

- What are the results of the constructed LCC model?
- What are the results of the constructed LCA model?

1.6.6 Chapter 7: Conclusions and Recommendations

- *What are the conclusions and what are the recommendations?*

The final chapter concludes the results. Furthermore, recommendations are given on future research areas.

2 Current situation

In this chapter, we start with a short introduction of how the ASS at ATAG works in Section 2.1. Afterwards, we describe how the conventional manufacturing and additive manufacturing process works for the FV wok burner in Sections 2.2 and 2.3, respectively. Then we describe which cost factors are used by Thales to determine the cost of their systems during the entire life cycle in Section 2.4. Hereafter, we describe to what extend ATAG applies a LCA analysis in Section 2.5. Based on the information retrieved we will determine six alternatives in Section 2.6. Finally, we will close this chapter with a conclusion in Section 2.7. All information is obtained through interviews, online databases and an internal document used by ATAG (ATAG Benelux, 2010).

2.1 After sales service at ATAG

Service at ATAG is of high importance. Consumers pay a high price for kitchen appliances and at the same time, they expect good after-sales service. ATAG offers three types of warranty service, namely a 2-year warranty service, a 5-year warranty service and, an 8-year warranty service. The more devices a consumer buys the longer the warranty period.

When a consumer is entitled to an 8-year warranty, it does not mean that ATAG keeps a component in stock for 8 years for that consumer. ATAG commits the consumer whenever a component fails during the warranty period (Schoenmaker, 2021). The commitment is that it can either be repaired or replaced. In some cases, the consumer receives a new device when the component is not in stock and if the consumer has to wait for a long time to replace the broken component.

During ASS for the FV wok, several problems can occur. It is possible that when the outer ring (roast head) is switched on, the flame does not start or only after some time skips from the inner ring (wok). Without a pan on the wok, this can occur and is a property of this burner. With a pan, the flame should skip within 3 seconds. If this does not happen, the roast head is replaced with a new one. Next to that, the wok burner sometimes goes out by itself in a low flame setting which is solved by installing a new brass wok burner head. Another problem that occurs is when switching on the outer ring (especially in a cold situation) there is no flame coming out of some burner ports. This is easily resolved by placing a pan on the wok or leaving the burner on for 30 seconds. If this does not happen, the burner head is replaced (Gal, 2021; Straalman, 2021; van Os, 2021).

When one of the three components of the FV wok burner fails, ATAG usually provides the consumer with a new component. Thus, the component is sent to the consumer immediately upon failure. Afterwards, the consumer can replace the component himself. On a high setting, a higher flame of the simmer burner can be seen on the front (thermocouple and spark plug side) in Figure 3. After the inspection, it was concluded that this failure was caused by how the gas was injected from the rear, creating swirls with associated pressure differences. This is inherent in the design of the burner and does not require the use of a service engineer. Thus, the new service part is sent to the consumer via post, which he can replace themself.

Figure 3: Strange flame at the front of the FV wok burner.

If we look at the (FV) wok burner, it does not break. Consumers usually want a new burner cup, wok, or roast head due to the faded aesthetic look. This means that these service parts just get dirty or the colour fades after several years of using it. Another reason is, that the consumer wants to replace a component due to e.g. a scratch on the roast head (since it is lacquered). It can be concluded that based on the aesthetics, the service components of the FV wok burner are replaced or repaired (Straalman, 2021).

2.2 Conventional manufacturing process

As mentioned earlier in some cases a component needs to be replaced. Now, when the service part is not in stock in the warehouse in Duiven, it is ordered from the production company in Slovenia. The exact amount that is needed is ordered from Slovenia once every week. This means that there is no Minimum Order Quantity (MOQ) required for placing an order for service parts because they are supplied from stock in Slovenia. However, when there is no stock in Slovenia, service parts are automatically filled from the assembly line. Thus, if the assembly line in Slovenia is out of stock, a new batch is produced and ordered from Malaysia and Turkey. The assembly line in Slovenia buys components from the company X (Turkey) and Y (Malaysia). When ordering a part from Malaysia and Turkey a MOQ is required. The MOQ for the roast head and burner cup is 1000 pieces, and the MOQ for the wok head is 2500 pieces which take up to 2 months before the components arrive in Slovenia to be assembled and processed. Afterwards, service is filled from the assembly line again. For service no MOQ is required.

The main production steps for the roast head and the burner cup (both made of aluminium) are casting, machining, transport, and packing. The main production steps for the wok head (made out of brass) is hot pressing, machining, transportation, and packaging. In Appendix A a detailed overview of the CM production process for the FV wok burner is given.

2.3 Additive manufacturing process

Additive manufacturing (AM) is quite new within ATAG when it comes to printing components that are made of certain metals. At the moment, ATAG uses 3D printing systems/printers that are suitable for plastics and aluminium components. However, there is little to no knowledge about which material and AM process to use to print the FV wok burner components. Therefore, we invited an external member from the company Bender Additive Manufacturing B.V. located in the Netherlands, who is an official distributor of EOS GmbH (one of the biggestAM companies globally). During his presentation, it became clear which production steps are used during AM for the FV wok burner. There are several advantages and disadvantages regarding CM and AM production processes. When a product has a highly complex design, CM becomes more expensive. On the other hand, when products are manufactured in large volumes, CM is an ideal production technique since costs are low. AM has a strong cost advantage for complex components and small to mid-size series production (EOS, 2021b).

2.3.1 AM production technique

In previous research by Baneii et al. (2020) several metal 3d printing techniques were analyzed and among them, the Laser Beam Powder Bed Fusion technique was chosen. This technique is also known as Direct Metal Laser Melting. It is a Laser Powder Bed Fusion technology and stands for one of the world's most advanced and reliable technologies in metal 3D printing (EOS, 2021a). The selection of the 3D printing technique was based on the metal type Stainless Steel (SS) 316L (Baneii et al., 2020). SS 316L is the second most widely used stainless steel and is known for its very favourable resistance to corrosion and excellent resistance to high temperatures. Thus, the Direct Metal Laser Melting 3D printing technique is used in this research and the material type SS 316L.

2.4 Life Cyle Costing at ATAG

At this moment in time, ATAG does not use a LCC model to analyse the costs of the FV wok burner during the ASS period. However, when ATAG orders a component from Slovenia, a margin of 4% and 20% is added to the purchase price. The 4% margin includes the following costs:

1. *Transport costs from Slovenia to Duiven.* Per week 4 to 5 trucks arrive, where half of the trucks are filled with spare parts (i.e. spare parts from different kitchen appliances). Within ATAG it is difficult to determine the percentage or cost amount that contains service parts of the FV wok burner in one truck. Next to that, not every truck contains service parts for the FV wok burner. Therefore, the transportation cost is included in the 4% margin (Kleinhaarhuis, 2021).
2. *Customs costs.* These are the costs that arise when the components go through the harbour in Rotterdam. Again, these costs are also included in the 4% margin.

Thus, in the 4% margin, both the transportation cost from Slovenia to Duiven and the customs cost are included. This margin is added on top of the purchase price of the FV wok burner components. Afterwards, a margin of 20% is added to this amount which includes the following costs:

1. *Cost for entry in Duiven.* Entry cost occurs when unloading the goods from the truck that arrives in Duiven and placing it on the racks in the service warehouse. Unloading happens with personnel and sometimes a truck loader forklift. Next to that, paperwork for transport is checked, and service parts that arrive in Duiven must be registered in the SAP system which requires labour. These costs are also categorized under the entry cost.
2. *Cost for storage.* This is the cost of storing a service component. A warehouse costs money. The amount of service parts that are stored at the warehouse in Duiven is very low because service parts are directly filled from the production line or stock in Slovenia (Straalman, 2021). The holding cost at ATAG is determined as inventory service cost + storage space cost + inventory risk (Schoenmaker, 2021; Walter, 2021).
3. *Cost for removal.* Removal cost is the cost when a service part is removed from the racks of the warehouse and send to the consumer (handling cost). This also includes registering

when a product leaves the warehouse. Next to that packaging and shipping cost is also included. Service parts are packed in a box with bubble wrap and labelled (Gal, 2021; Kleinhaarhuis, 2021). Consumer packages are shipped with DHL or postnl. All these costs are categorized under the removal cost.

2.5 Life Cycle Assessment at ATAG

Again, ATAG does not use a LCA model to analyse the environmental impact of producing the FV wok burner during the ASS period, nor do they know how to perform an LCA. ATAG wants to make a start for the LCA analysis by finding ways to reduce the CO_2 footprint of the FV wok burner components. A small amount of data is known when it comes to how the FV wok burner components are produced with CM production processes in Malaysia and Turkey. The same goes for AM production processes for the FV wok burner since this process is quite new within the company. Thus, most of the data we need to retrieve for the LCA is retrieved from online databases.

2.6 Alternatives

As mentioned in Section 1.3, ATAG will decide to stop selling the FV wok burner at the beginning of the year 2023, i.e. after the re-design is introduced in the market. The moment ATAG decides to stop selling the FV wok burner components does not necessarily mean that the production of the FV wok burner in Slovenia, Malaysia and Turkey will stop. The moulds and services will still be available at the suppliers and whenever ATAG needs a new component of the FV wok burner during the ten years of service, production can start again but under certain circumstances such as the MOQ that is demanded.

Before the sales of a certain component stop, ATAG usually makes a forecast to decide how many parts are needed to cover ten years of service. ATAG uses a limit of 10 years because the max warranty that ATAG provides is 8 years. The amount left over after production stops is usually sold within 2 years. Thus, the first step is to make a demand forecast to determine how many parts we need for the next ten years of service. The demand forecast is based on historical data of the FV wok burner service components. The FV wok burner was introduced on the market in 2013. Data regarding how many parts were used during the ASS period was not properly registered in the SAP system until 2018. Further, there is no available data in 2017 due to a stock migration from Duiven (in the Netherlands) to Slovenia (Kleinhaarhuis, 2021). The amount of FV wok burner service components ordered from Slovenia between 2018, and 2021, is shown in Table 1. Notice that these numbers are equal to the number of broken service components registered by the consumers (Hilderink, 2021).

	2018	*2019*	*2020*	*2021*
Wok head	28	23	23	22
Roast head	27	23	20	26
Burner cup	0	15	0	0
Total	*55*	*61*	*43*	*48*

Table 1: Number of service components ordered from Slovenia from 2018 until 2021.

The number of service components is used to forecast the demand during the ten years of service. Afterwards, this amount is used to determine the cost in all six alternatives for each component. With the help of experts within ATAG (van Os, 2021; Versteeg, 2021; van Vliet, 2021), we determined to investigate 6 alternatives. Each alternative is analyzed based on an LCA and LCC analysis. The chosen alternatives are explained in detail below.

2.6.1 Alternative 1: MOQ + CM

The order quantity and the purchase price will change the moment ATAG decides to stop the production of the FV wok burner. Instead of ordering components per part, ATAG has to place orders with an MOQ and with an increased purchase price. However, these agreements, i.e. the expected MOQ and the price increase percentage, have not yet been established with the supplier. Nevertheless, ATAG assumes that the supplier will charge an MOQ of 50 and a purchase price increase of 50% for each FV wok burner component (van Os, 2021). Slovenia produces the FV wok burner for ATAG and ASKO. ATAG sells the FV wok burner only in the Benelux (Netherlands and Belgium), and ASKO sells the FV wok burner worldwide (Russia, Asia, Oceania, Africa and South America). If Slovenia demands an MOQ of more than 50, e.g. an MOQ of 150 pieces per component, then agreements will be made to divide this MOQ under ASKO and ATAG. In this way, both customers can still fulfil the MOQ of Slovenia. Taking an MOQ of 50 is again a risk since we do not know what agreements will take place in the future. So, in this alternative we calculate how much it cost ATAG to place orders with an MOQ of 50 for the next ten years of service, i.e. starting from 2023. In this alternative, CM production processes are applied. The material type remains the same, i.e. aluminium for both the roast- and wok head and brass for the wok head.

2.6.2 Alternative 2: outsource + MOQ + AM

Outsourcing the FV wok burner components with AM production techniques is more beneficial because this technique secures the supply of low-volume parts and materials (Baneii et al., 2020). Thus, the trade-off here was that production can be delayed until demand occurs (make-to-order), which means there will be no/less excess inventory. The disadvantage is, for example, higher production costs per unit of product. However, these costs were not determined. Therefore, we explore how much it cost to produce the FV wok burner via an external 3D printing service provider. The external supplier we choose is located in the UK in Europe. Most of the service components that are replaced are from the Netherlands. Therefore, it is efficient for ATAG to produce the FV wk burner components via an external service provider based in Europe. Further, the FV wok burner components are ordered with an MOQ. Incorporating an MOQ is explained in more detail in Section 4.3.

2.6.3 Alternative 3

As mentioned in Section 2.1, the components of the FV wok burner are replaced upon failure. The broken parts are repaired or used for scrap. Usually, a broken aluminium component, i.e. the roast head or burner cup, cannot be repaired because the flame does not burn properly and must be replaced with a new one. When it comes to a broken brass component, i.e. the wok head, only cleaning/blasting (which is called “repair” within ATAG) is needed to re-use the part again. There is no specific data established within ATAG of how many parts of the FV wok burner are repaired over the past years. Therefore, we cannot estimate how many components we must repair for the ten years of service. However, the brass components have a higher chance of being repaired than the aluminium components because brass is more robust than aluminium. With the help of expert opinions (Hilderink, 2021; van Os, 2021; Versteeg, 2021), we assumed how many parts we must repair. We have estimated that 25% of the forecasted amount of aluminium components are used for repair and that 40% of the forecasted amount of brass components are used for repair. This means that refurbished items cover demand for

25% and 40% for the aluminium (i.e. the roast head and burner cup) and brass component (i.e. wok head) of the FV wok burner, respectively. Thus, 75% of the time demand is not full-filled for the roast head and burner cup, and 60% of the time demand is not full-filled for the wok head. Thus, we combine alternatives 1 and 2 with this alternative to fulfil the rest of the demand. In this alternative, we make a distinction between two sub alternatives, namely:

- **Alternative 3a: repair + MOQ + CM.** In this sub alternative we repair 25% of the broken roast heads and burner cups, and place orders with an MOQ of 50 (combination with alternative 1: MOQ + CM) for 75% of service demand for the roast heads and burner cups. Further, we repair 40% of the broken wok heads, and the rest of the demand, i.e. 60% of wok heads, is ordered from Slovenia with an MOQ of 50 as well (combination with alternative 1: MOQ + CM). This alternative is related to CM production processes.
- **Alternative 3b: repair + outsource + MOQ + AM.** In this sub alternative we repair 25% of the broken roast heads and burner cups, and outsource the rest of the demand at a 3D printing manufacturer using an MOQ, i.e. 75% of the roast heads and burner cups. Further, we repair 40% of the broken wok heads every year and outsource the rest of the demand each year, i.e. 60% of service demand for the wok head. This alternative is related to AM production processes.

2.6.4 Alternative 4

As mentioned in Section 1.4, ATAG is looking at options to 3D print service parts. Baneii et al. (2020) concluded that when production volumes are increasing each year, the investment of in-house AM capacity may be more attractive than outsourcing. Thus, we look at how much it costs ATAG to produce the FV wok burner with AM. The idea behind this alternative is to place a 3D printing machine in Slovenia because Slovenia can use the AM machine to print the Chinese variant of the FV wok burner (sold by Pelgrim) or other (service) components as well, e.g. components of the gas hob. Thus, when the machine is used optimally, certain costs factors decrease, e.g. the downtime cost. If the AM machine is placed in Duiven then there is a risk that the machine does not operate optimally because the AM machine will only be used for limited-service components, whereas in Slovenia, the AM machine is used for several purposes such as printing for services components and production. In this alternative, we look at several different types of machines based on the specifications determined in previous research by Baneii et al. (2020). For this research, we assumed to invest in the 3D print machine produced and sold by EOS GmbH in Germany (2021a) because most 3D print manufacturers use the AM machines that are made by EOS GmbH and next to that ten Pas (2021) also mentioned that these machines are highly recommended for printing gas hob components. In Appendix F the machine selection is determined. Two machine types were appropriate to print the FV wok burner, namely the M290 machine and the M400-4 machine. Therefore, this alternative is divided into two sub alternatives:

- **Alternative 4a: invest in a small AM machine.** In this sub alternative, we invest in a small 3D print machine, i.e. the M290 machine. Furthermore, we determine the cost to print the FV wok burner components in Slovenia.
- **Alternative 4b: invest in a large AM machine.** In this sub alternative, we invest in a 3D print machine that is four times more productive than the machine in alternative 4a, i.e. the M400-4 machine. Furthermore, we also determine the cost to print the FV wok burner components in Slovenia.

2.7 Conclusion

We determined six alternatives where both CM and AM production processes are applied. In the first alternative, we look at how much it costs in terms of LCC when we place orders with an MOQ of 50. Orders with an MOQ of 50 are placed whenever we need demand in a specific year. Demand during the ten years of service is based on a demand forecast which is explained in Section 4.1. Furthermore, the moment to decide when to place an order is determined with a simple Material Requirement Planning (MRP) calculation. The MRP calculation ensures that materials to be supplied in a production process are delivered on time and in the correct numbers. Thus, alternative 1 (i.e. MOQ + CM) provides ATAG insight on how much it costs to cover ten years of service after the redesign is introduced in the market with an MOQ of 50. The second alternative is related to outsourcing. In this alternative, we determine how much it will cost ATAG to outsource the FV wok burner. The third alternative is divided into two sub alternatives where we repair broken service components in combination with placing an order at the supplier (i.e. alternative 3a: repair + MOQ + CM) and outsourcing (i.e. alternative 3b: repair + outsource + MOQ + AM). The fourth alternative is also divided into two sub alternatives where we look at the possibility of investing in two different 3D printing machines.

3 Literature study

In this chapter, we perform a literature study towards an LCC analysis based on the six alternatives to develop a broader view concerning relevant cost factors that might occur during the ASS period. Further, ATAG does not perform an LCA analysis on the FV wok burner. Since no information is available within ATAG regarding an LCA analysis we perform a literature study on how an LCA analysis works and how it can be implemented in the six alternatives in this chapter. In this chapter, several topics are discussed. First, we give a short background about after-sales service in Section 3.1. Next, we explain how a LCC analysis works based on literature in Section 3.2. In Section 3.3 we explain how a LCA analysis works and construct the LCA model based on literature. Finally, we conclude this chapter in Section 3.4.

3.1 Background after-sales service

In today's businesses, after-sales service is becoming more and more attractive when it comes to customers satisfaction (Tevhide et al., 2017; Esmaeili et al., 2021). Furthermore, manufacturing companies recognize their after-sales services as a relevant source of revenue, profit and competitive advantage (Saccani et al., 2007; Cohen et al., 2006). 30% of the profit margin comes from the after-sales service and 10% from the initial sales (Murthy et al., 2004). One way to provide after-sales service is in the form of a warranty. In this case, the manufacturer repairs or replaces the product within a certain amount of time (Murthy et al., 2004).

Spare part availability plays an important role when performing repair activities. In some cases, spare parts are produced using the same manufacturing technique. In other cases, when a product is no longer being produced, it becomes more challenging to supply spare parts (Esmaeili et al., 2021). Therefore, we introduced six alternatives (see Section 2.6) in this research to bridge these challenges.

3.2 Life cycle cost analysis

Life Cycle Costing (LCC) is described by Ellram and Siferd (1998) as follows:

> *The aim of a LCC analysis is to look beyond the purchase price of a product by determining what it costs the organization to maintain a product throughout its use, maintain and break down the life cycle.*

To perform a LCC analysis several frameworks are described in literature such as the framework by Ellram (1993a), Greene & Shaw (1990) and Coorens (2001). Each of these authors distinguishes eight steps when performing a LCC analysis. Detailed information on each step is given in Appendix C.

As mentioned before, life-cycle costs are all the costs associated with the product for its entire life cycle. A product life cycle consists of four phases, namely: the design/development, production, use, and recycling/disposal phase (Fixon, 2004; Ellram, 1993b; Ellram & Siferd, 1998; Coorens, 2001). In each of these phases, several activities take place to which a cost factor is attached. Further, Dhillon (2010) also describes six general LCC models and five specific LCC models. In this research, we construct an LCC model based on the LCC cost factors determined by Dhillon (2010), Fixon (2004), Ellram (1993b), Ellram & Siferd (1998), Coorens (2001). The cost factors described in each of the (necessary) models are categorized under four phases, namely: design/development, production, use, and recycling/disposal.

The cost of the design/development phase consists of the following cost factors:

- Costs that are related to product engineering.
- Costs that are related to prototyping.
- Costs that are related to test and evaluation.
- Costs that are related to R&D for tooling.

The cost of the production phase consists of the following cost factors:

- Cost for manufacturing the product with AM or CM.
- Cost for quality control.
- Cost for industrial engineering and operations analysis.
- Procurement cost. These are the costs that a company pays for the quantity ordered from a supplier such as costs per unit of a product, the contracted cost of a product, or the service charged by the supplier.
- Administration cost. This is divided into the following costs:
    1. Planning costs which are the costs of finding a suitable supplier or other pre-contract costs.
    2. Contracting and legal costs. These costs refer to all contracting and legal costs associated with outsourcing the product or service.
    3. Coordinating and communicating costs. These are the costs from administration, travel and other coordinating expenses with the supplier(s) due to design specifications, change in design, and change in demand.
    4. Quality control and inventory costs. These costs do not always incur but if quality control or inventory holdings are needed they are covered here.

The cost of the use phase consists of the following cost factors:

- Costs that occur for operating personnel.
- Asset costs. Assets are purchased to serve in long term and for a fixed period. Several costs occur when buying an asset based on a life cycle costing model. The three main costs are the acquisition costs (such as costs for installing the machine), operations costs (such as costs for space and energy), and life support costs (such as costs for maintenance and repair).
- Costs for storing service product (inventory cost). Inventory cost is the cost for storing the components.
- Transportation and handling cost for product.
- Downtime cost.
- Labour cost for maintenance.
- Energy cost.
- Repair cost. when a product fails, two types of costs incur, namely fixed and variable costs. Fixed costs are usually all the costs related to fixing the malfunction. These costs are, e.g. labour costs, the costs of ordering parts or sending an inoperative product to the manufacturer for service. Furthermore, fixed costs occur regardless of the duration of product downtime. Variable costs are out of pocket expenses. These are, e.g. expenses to pay for idle workers and production time lost until repairs are complete. Next to that, variable costs change according to the duration of product downtime.

The cost of the recycling/disposal phase consists of the following cost factors:

- Costs that occur when disassembling a product.
- Disposal cost. Disposal cost is the cost when too many parts are ordered as well as the cost for resale of excess inventory. This means that the company has to liquidate the unnecessary parts if possible. These excessive parts are used for scrap.

When we look at the LCC model according to literature as described in Section 3.2, we see that some cost factors are merged in the 20% margin of ATAG. These cost factors are mainly a result of costs during the after-sales period: transportation and handling cost, labour cost, and storage cost (20% margin).

The cost factors that are not included in the literature models but which are considered as important within ATAG are the costs of transportation, customs from Slovenia to Duiven and the costs of repair of spare parts. Within ATAG, it may be preferable to repair expensive parts instead of replacing them with new ones (i.e. in alternatives 3a and 3b).

3.2.1 Method of economic evaluation

Inflation

ATAG expects that during the ten years of service inflation can occur in the purchase price from the supplier in Slovenia. In previous years it was shown, that price inflation is much more common than general price deflation (Sullivan et al., 2014). General price inflation is defined as an increase in the average price that is paid for goods and services bringing about a reduction in the purchasing power of the monetary unit. Furthermore, inflation can affect the economic comparison of alternatives (Sullivan et al., 2014).

When it comes to AM, the opposite happens, i.e. deflation. This means that, as for price changes in the future, we are more likely to see price decreases in the coming years. AM is still a relatively new technology. We will see that investment in a new 3D printing machine will increase the rate of build with larger build platforms and more automated processing. This may not happen for the next 2 to 4 years, but with the increased competition prices are likely to drop rather than increase in the future (Wennington, 2021). Since there is no specific data to calculate the deflation rate for alternatives 2 (i.e. outsource + MOQ + AM), 3b (i.e. repair + outsource + MOQ + AM), 4a (i.e. invest in small AM machine), and 4b (i.e. invest in large AM machine), we leave this out of scope. However, we do consider a price reduction for alternatives 2 and 3b which is further explained in Appendix I.

Net Present Value

Now that the cost factors that occur during the product life cycle in each of the four phases are clear we now have to determine how to measure the LCC over time. LCC method calculates both present and future value of discounted cash flow. Regarding the time value of money and opportunity cost calculation, we use the Net Present Value (NPV) as the basic tool for comparison of the money values in the different times. The equation is as follows (Spickova, & Myskova, 2015):

$$NPV = \sum_{t=1}^{t=10} \frac{C_t}{(1+r)^t}$$

where:

- NPV is the Net Present Value of a product Life Cycle Costs.
- C_t is the sum of all relevant costs created in period t. In this case, C_t refers to the costs that occur during the design, production, use, and recycling phase-in period t.

- r is the discount rate. The discount rate that ATAG uses is 10% (Alofs, 2021; Kleinhaarhuis, 2021; Noorel, 2021) which is used to calculate the NPV for all the alternatives.
- t is the monitored period in years which is ten years of service.

Based on the NPV calculation we can recommend which of the six alternatives is most cost-efficient.

3.3 Life cycle assessment

According to ISO 14040.2, LCA is defined as:

> *Life cycle assessment (LCA) determines the environmental impacts of products, processes or services, through production, usage, and disposal. So, it is an instrument to support environmental policy (making).*

Another definition in the literature that was found in the paper by Rebitzer et al. (2004) is that LCA is a methodological framework for estimating and assessing the environmental impacts attributable to the life cycle of a product. In the Paris Climate Agreement 195 countries, including Slovenia, Malaysia and Turkey, have agreed to limit the increase in the average global temperature to well below 2 degrees Celsius by 2050, and if possible 1.5 degrees Celsius. This attention to the consequences of global warming led to more awareness. The main greenhouse gas is carbon dioxide (CO_2). The FV wok burner components are produced in Malaysia and Turkey and assembled in Slovenia. Turkey, Malaysia, and Slovenia contribute 1,03%, 0,74%, and 0,04% of CO_2 emission to the world (IEA, 2018). In terms of electricity consumption Turkey, Malaysia and Slovenia are on the 22^{nd}, 27^{th}, and 81^{st} place with a total consumption of 1,07%, 0,63%, and 0,06% respectively (IEA, 2018). To decrease greenhouse gases and to fulfil the plans of the Paris Agreement (UN, 2021), we perform an LCA with a focus on the environmental global warming potential (GWP) in the industry sector.

In literature, several papers discuss the topic of a LCA. All the papers contain four methodological steps and therefore, there is no specific reason to make a distinction between the papers that discuss this topic. Thus, a random but detailed and logical paper was chosen, i.e. the paper by UNEP (2005). The four methodological phases discussed in this paper are (1) Goal and scope definition, (2) Life Cycle Inventory Analysis, (3) Life Cycle Impact Assessment, and (4) Life Cycle Interpretation. Detailed information on each phase is explained in Appendix D. Next, we explain how each step is performed based on our case study.

3.3.1 Goal and Scope Definition

If we look at the CM production process in Appendix A, which is related to alternatives 1 (i.e. MOQ + CM) and 3a (i.e. repair + MOQ + CM) , notice that several steps take place. However, we could not retrieve any information regarding the CM production process steps due to confidentiality and political reasons. Therefore, certain assumptions are made.

To make these assumptions more clear, we defined the system boundary. The system boundary defines which processes are included in or excluded from the system, i.e. the LCA. There are four main options to define the system boundaries (UNEP, 2012). These are as follows:

- **Gate-to-gate LCA**. Gate-to-gate LCA is a partial LCA that only includes the processes from the production phase. Thus, we use gate-to-gate to determine the environmental impacts of a single production step or process.

- **Cradle-to-gate LCA**. Cradle-to-gate LCA includes all processes from the raw material extraction through the production phase (gate of the factory). So, cradle-to-gate is an assessment of a partial product life cycle from the moment it is produced ("cradle") to the moment it enters the store "grave"). Thus, the use and disposal/recycling phase of the product are omitted in this case. Cradle-to-gate is used to determine the environmental impact of the production of a product.
- **Cradle-to-grave LCA**. Cradle-to-grave LCA assesses a product from a linear perspective, including all phases of the product life cycle. It is the full Life Cycle Assessment from the design phase ("cradle") to the use phase and disposal phase "grave"). So, from raw materials until after the consumer is done with the product and enters the waste stream.
- **Cradle-to-cradle LCA**. Cradle-to-cradle or closed-loop production LCA only assesses a product from a closed-loop recycling perspective. The end-of-life disposal step for the product is a recycling process step. So, cradle-to-cradle is a closed-loop Life Cycle Assessment from the design phase ("cradle") to the recycling phase ("grave"). We use this variant to minimize the environmental impact of products by employing sustainable production, operation and disposal practices. Further, social responsibility is incorporated into product development (Ecomii, 2021).

In this research, we used the cradle-to-gate variant of the LCA to calculate the environmental GWP. Cradle-to-Gate only assesses a product until it leaves the factory gates before we ship the product to the retailer and consumer. This means that the use and disposal phases are not included in this. Cradle-to-gate analysis can significantly reduce the complexity of an LCA and thus create insights faster, especially about internal processes. Next to that, due to time limitations and data availability, not the whole LCA i.e. cradle-to-grave, can be executed. However, when it comes to producing the FV wok burner components with AM processes, the disposal phase may have more value because single-piece or small-batch production will leave us with little or no parts at the end of the life cycle, which leads to less waste (e.g. less raw material used, less used energy for production, et cetera). Thus, we will add a small part of the disposal phase within the LCA of both CM and AM and call this the cradle-to-gate + small part of disposal LCA. Next to that, the disposal phase is also taken into account in the LCC analysis. Thus, to prevent unequal comparison of the LCA and LCC analysis, the disposal phase is also added in the LCA analysis. When it comes to the AM related alternatives little to no parts of the FV wok burner will be disposed at the end of the life cycle. However, when it comes to the CM related alternatives we dispose a larger amount of FV wok burner components due to the large MOQ. So, after the product leaves the factory gates and is disposed, we can assume that the amount of FV wok burner left over at the end of the life cycle is used as scrap in the exploitation process (see Figure 4).

Thus, the system boundary to calculate and compare the environmental impact of the CM and AM materials used concludes the process of cradle-to-gate + disposal. Further, the life span of the FV wok burner is set to ten years. In Figure 4 a general overview for the six alternatives of the system boundary and life cycle stages is given.

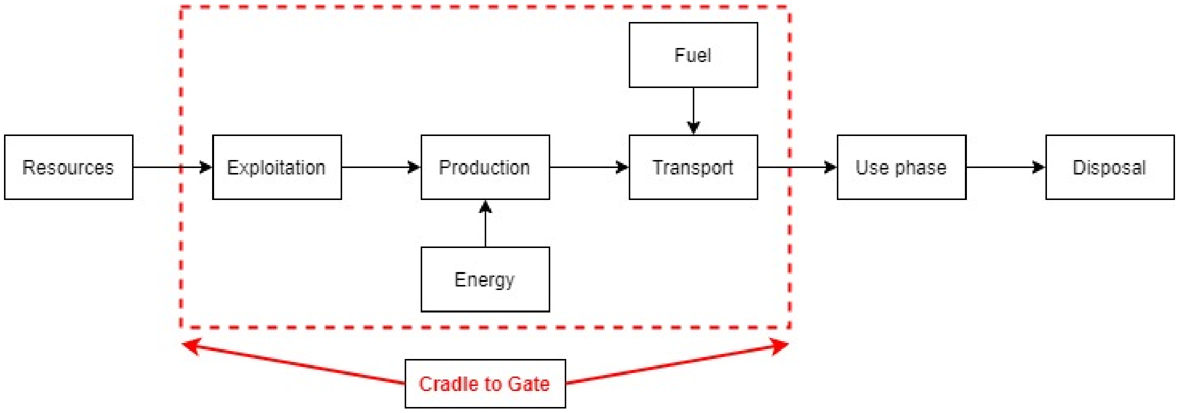


Figure 4: System boundary and life cycle stages.

3.3.2 Life Cycle Inventory

In this phase, we collect data and calculate procedures that are the most work-intensive and time-consuming of all phases in an LCA. It includes collecting quantitative and qualitative data for every unit process in the system. Further, we use the GaBi Education Software for calculations. For certain data such as from where the AM materials are extracted, we use the GaBi Ecoinvent database which is the biggest data source available when performing an LCA (Saade et al., 2019).

3.3.3 Impact Assessment

Different methods are used to perform a Life Cycle Impact Assessment (LCIA). In this research, we want to focus on the environmental GWP. The LCIA methods available to measure the climate change impact in the GaBi Education Software are TRACI, CML2001, and ReCiPe.

All three methods are problem-oriented approaches (midpoint). This means that flows are classified as belonging to environmental impact categories to which they contribute to the problem-oriented approach. Calculating the midpoint indicators are mathematical equations that convert (emitted or consumed) substances into a contribution to a specific impact category, e.g. converting amounts of emitted greenhouse gases into Global Warming Potential (Saade et al., 2019). For example, let's say we have 1.3 kg CO (carbon dioxide) and 6 kg CH_4 (methane). Both CO and CH_4 contribute to the GWP. Therefore, during this classification step, CO and CH_4 are classified as a contributor to the GWP impact category. According to, e.g. the CML 2001 method, CH_4 has a characterization factor of 28 which means that CML has determined that CH_4 contributes 28 times more than CO_2 to the GWP. The 6 kg of CH_4-emissions in this example contribute 150 kg CO_2-equivalents to the total GWP. The 1.3 kg CO-emissions in this example contribute 10.3 kg CO_2-equivalents to the total GWP. The results of the Life Cycle Inventory are converted into reference units using characterization factors. We only consider the GWP. The reference substance for the impact category GWP is CO_2 and the reference unit is defined as "kg CO_2-equivalent". All emissions that contribute to global warming are converted to kg CO_2-equivalents according to the relevant characterization factor.

Above, we gave an example using the CML 2001 method. As mentioned before, there are two other methods available in the GaBi software, i.e. TRACI and ReCiPe. The LCIA output of all three methods has slightly different values. However, there was no extensive manual on how to perform the TRACI or ReCiPe LCIA approach step by step. Therefore, we will continue with the CML 2001 approach in this research.

3.3.4 Interpretation

In the interpretation phase, we connect the Life-Cycle Inventory and the Life Cycle Impact Assessment to conclude the decision and give recommendations by the goal and scope of definition of this study. The CO_2-emission is chosen to compare the six alternatives because this is one of the main pillars to adapt the climate change.

The price of the machines and materials required for AM (alternative 2: outsource + MOQ, alternative 3b: repair + outsource + MOQ, alternative 4a: invest in a small AM machine, and alternative 4b: invest in a large AM machine) are relatively high compared to the machine and material price in the case of CM. However, when we look at the LCA models, the environmental impact can be lower than the CM related alternatives (alternative 1: MOQ + CM, and alternative 3a: repair + MOQ + CM) because of decentral production locations. This means that the CO_2-emissions are less than the CM related alternatives. So, in the end, production by AM related alternatives is not necessarily more expensive and environmentally friendly than CM related alternatives. Especially if one outsources the production (alternative 2: outsource + MOQ + AM, and alternative 3b: repair + outsource + MOQ + AM), preventing high investment costs because of the purchasing of new AM machines.

3.4 Conclusion

Concerning LCC of the different alternatives where AM and CM processes are applied we have to take care of the input parameters. As stated in Section 3.2, the cost of the design/development phase consists of several cost factors. However, the FV wok burner was designed and developed by ATAG in 2010 and introduced in the market in 2013. The total project for developing and designing the FV wok burner cost around €250.000 (ATAG, 2010). This amount has already been depreciated within a period of 5 years. So, from 2013 until 2018 there was a surcharge on top of the cost price of the FV wok burner. After that, it was already paid off. Therefore, the cost factors that take place during this phase can be neglected in every alternative. Further, in this research, we perform a cradle-to-gate LCA because it can significantly reduce the complexity of an LCA and thus create insights faster, especially about internal processes.

4 Construction of the LCC models

In this chapter the construction of the LCC models are determined. First, the forecast model is described in Section 4.1. Afterwards, we can move on to the LCC construction of the six alternatives. In Section 4.2 the LCC model of alternative 1, i.e. MOQ + CM, is constructed. In Section 4.3 the LCC model for alternative 2, i.e. outsource + MOQ + AM, is constructed. In Section 4.4 we construct the third and fourth LCC model, i.e. repair failed service components in combination with outsourcing and placing orders with an MOQ. In Section 4.5 the last two LCC models are constructed, i.e. invest in two different 3D printing machines. Finally, this chapter is closed with a conclusion in Section 4.6.

4.1 Forecast model

The first step is to determine how many components ATAG needs during the ten years of service. The numbers are derived from historical data as shown in Table 1 in Section 2.6. We used the data from 2018 until 2021 to forecast ten years of service. Data before 2018, i.e. 2013 until 2017, were not stable because the use of service components was not properly registered in the SAP system (van Os, 2021). The question is which forecasting technique is the most suitable to construct a forecast of ten years ahead with three years of known data. There are three basic types of forecasting techniques, namely: qualitative techniques, time series and projections analysis, and causal models (Chambers et al., 1971). Qualitative techniques use qualitative data (such as expert opinions) and may or may not consider the past. Time series and projections analysis focus entirely on patterns and pattern changes and thus rely on historical data. Causal models use highly refined and specific information about relationships between system elements and are powerful enough to take special events formally into account. Here, the past is also important to causal models. In our case, time series and projection analysis are the most suitable since we want to use historical data to forecast ten years. There are three steps involved when conducting a time series forecast, i.e.:

- Step 1: Select an appropriate underlying model of the demand pattern through time.
- Step 2: Select the values for the parameters inherent in the model.
- Step 3: Use the model (selected in Step 1) and the parameter values (chosen in Step 2) to forecast the future demands.

There are five general types of time series and projection analyses models, i.e. moving average, exponential smoothing, Box-Jenkins, X-11, and Trend projections. Since we want to forecast ten years, the forecast accuracy for the moving average, exponential smoothing, Box-Jenkins, X-11 technique are insufficient (Chambers et al., 1971). On the other hand, the trend projection technique gives us a good accuracy when we want to forecast two years & up ahead (Chambers et al., 1971). This technique fits a trend line to a mathematical equation and then projects it into the future through this equation. The result of this forecast calculation is given in Appendix G. To measure the forecast accuracy we used the mean square error (MSE) technique. In Table 2 the MSE is 27,75. We were not able to find a good value for the MSE to say whether the forecast accuracy is biased or not. However, the lower the MSE the better the forecast. In this case, the MSE seems to be a reasonable value and so we can say that our forecast is reasonable.

					Total	MSE
Actual demand x_t	55	61	43	48		
Forecast $\hat{x}_t$	58	54	50	46		
Error or deviation $e_t = x_t - \hat{x}_t$	-3	7	-7	2		
Squared deviation e_t^2	9	49	49	4	111	27,75

Table 2: Forecast accuracy using mean square error (MSE) technique.

Next, we explain how each alternative works. We only provide the crucial formulas for one component, i.e. the wok head in each alternative explained below. The formulas are applied in the same way for the roast head and burner cup by changing the index. The complete formulas are given in the relevant appendices.

4.2 Life cycle cost of alternative 1: MOQ + CM

In this alternative, we performed an LCC analysis based on placing orders with an MOQ of 50. The costs that occur during this alternative are mainly procurement cost, disposal cost, and an additional marginal cost. ATAG does not use a safety stock for the FV wok burner. If a component is not in stock in the service warehouse, usually the component is removed from a complete set of a gas hob (see Appendix B for the different types of gas hobs from where the FV wok burner components can be removed). In the meantime, ATAG orders a new component from Slovenia and arrives in Duiven within a week. Thus, having a safety stock level within ATAG for the FV wok burner does not have any impact on the availability of the FV wok burner components. Thus, to determine when to order we applied a simple Material Requirements Planning (MRP). The MRP system is a planning and decision-making tool used in the production process which analyses the need to order goods based on a forecast analysis. As soon as the inventory level is below zero an order is placed. We assumed to place the order at the beginning of the year. Therefore, we also ordered a batch of 50 pieces in the first year to fulfil the forecast demand in year 1 (i.e. January 2023).

4.2.1 Cost factors during the production phase

The main activities that appear during this phase are manufacturing of the product, quality control, the cost for operations analysis. As mentioned before, production and assembly take place in Malaysia, Turkey, and Slovenia. The production and assembly costs are included in the purchase price that Slovenia charges. ATAG only pays the procurement price when placing an order. Thus, in this phase, we only considered the procurement price which is defined as the price that ATAG pays to place an order for the FV wok burner components. The procurement price is calculated as:

$$ProcurementCost_{WH}(t) = Total_{WH}(t) * PurchasePrice_{WH}(t)$$

Where $Total_{WH}(t)$ is the number of wok heads that we order in year t. We will provide an example of how this is determined in Table 3. The row "Forecast in year t" is the forecasted amount determined in Section 4.1. We assumed to place an order of 50 at the beginning of year 1. So, 31 parts are left at the end of year 1. In year 2, we need a demand of 17 pieces of the wok head. Because there are 31 pieces left at the end of year 1, we do not have to place a separate order. Instead, we use the leftover from year 1. Notice that in year 3, the stock is not enough and therefore we place a new order. In Table 3 the numbers that are underlined and in bold are the number of wok heads we order in year t, i.e. $Total_{WH}(t)$.

Year	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**
t	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Forecast in year t	19	17	15	13	11	9	7	6	4	2
Orders in year t	**50**	0	**50**	0	0	0	0	0	**50**	0
Amount left over by the end of year t	31	14	49	36	25	16	9	3	49	47

Table 3: Calculation of how much to order in year t for the wok head.

Further, the $PurchasePrice_{WH}(t)$ is the price that the supplier in Slovenia charges. In this price, costs such as the transport from Malaysia/Turkey to Slovenia, raw material, production cost, energy and other costs are included. However, the cost for transporting the goods from Slovenia to Duiven, and storing the goods in Duiven is not included in this purchase price. These costs are calculated in the 4 % and 20% margin which is explained next.

4.2.2 Cost factors during use phase

The activities that take place during this phase are the transportation and handling of the FV wok burner components from Slovenia to Duiven, storing the components in the warehouse, and sending a service component to the consumer. So, the costs involved during this phase are the transportation and handling cost, storage cost, removal cost, and labour cost. These costs are calculated in the 4% and 20% margin and added on top of the procurement price as mentioned in Section 3.2. We used these percentages in the rest of the LCC models as well. Each year ATAG makes an analysis of the inflow (all of the income that is brought to ATAG) and outflow (includes any debts, liabilities, and operating costs) of all the goods. Based on these inflows and outflows, the 4% and 20% margin is determined. We decided to use the same percentage due to the following reasons:

- In alternatives 1 (i.e. MOQ + CM), 3a (i.e. repair + MOQ + CM), 4a (i.e. invest in a small AM machine) and 4b (i.e. invest in a large AM machine), the components are produced in Slovenia. Slovenia charges a standard purchase price for ATAG. In this purchase price, the cost for production, transport from Malaysia or Turkey, labour, and other costs are involved. Thus, when ATAG places an order in Slovenia, they pay the purchase price. The cost for transporting the goods from Slovenia to Duiven has to be covered by ATAG itself. However, when we place an order, they usually arrive in a full truckload in DUiven. Per week 4 to 5 trucks arrive, where half of the trucks are loaded with spare parts (i.e. spare parts from different kitchen appliances). One truck contains about 1% or 2% service parts of the FV wok burner. Next to that, when a container goes through the port of Rotterdam, customs costs are involved and the amount of customs is dependent on the value of the goods in the truck. In practice, the orders for the FV wok burner differs every week and if we had to determine the transportation and customs in a percentage or value in euro, this percentage (or value in euro) would be different every week. Thus, we have to calculate the total volume of the FV wok burner components in each truck every week (note that the truck size also differs from time to time depending on the number of goods to transport to Duiven). This calculation can be very complex especially if we have to determine the cost for the next ten years of service. Further, the data we worked with is indicated in years and not weeks. Thus, we decided to adhere to these percentages in alternatives 1 (i.e. MOQ + CM), 3a (i.e. repair + MOQ + CM), 4a (i.e. invest in a small AM machine) and 4b (i.e. invest in a large AM machine).

- In alternatives 2 (i.e. outsource + MOQ + AM) and 3b (repair + outsource + MOQ + AM), the FV wok burner components are produced at an outsource manufacturer. The outsource manufacturer charges a transportation cost of 40 € per batch to ship the items from the outsource manufacturer to Duiven. However, customs costs are not involved and are covered by ATAG. Again the customs cost are dependent on the value of goods loaded in a truck. This is also complex to determine since we work with data per year, and the amount of customs to pay is uncertain. Next to that, in the future, ATAG might choose a different outsource manufacturer that charges a different shipping cost. Thus, for the sake of simplicity, we also adhered to the 4% margin in alternatives 2 (i.e. outsource + MOQ + AM) and 3b (repair + outsource + MOQ + AM).
- When it comes to the 20% margin, we also have the same problem as explained in the first bullet. If we had to determine a percentage, then we have to take into account how many people unload the goods from the truck, how much space is needed for the FV wok components, how long it takes to move the components in the warehouse et cetera. All these factors should be determined every time a truck with the FV wok burner arrives in Duiven. Again this is a complex process, and thus we decided to use the 20% margin for storage, removal, and entry cost in each alternative.

First, ATAG adds a margin of 4% on top of the procurement price. Afterwards, ATAG adds a 20% margin on this amount. The additional margin of 4% that ATAG adds on the procurement price is calculated as:

$$\begin{aligned} \textit{Cost with additional 4\% margin}_{WH}(t) = &\Big(\textit{ProcurementCost}_{WH}(t) \times 4\%\Big) \\ &+ \textit{ProcurementCost}_{WH}(t) \end{aligned}$$

Where t is the service year. On top of this 4% margin ATAG adds a 20% margin, which is calculated as:

$$\begin{aligned} \textit{Cost with additional 20\% margin}_{WH}(t) = &\Big(\textit{Cost with additional 4\% margin}_{WH}(t) \times 20\%\Big) \\ &+ \textit{Cost with additional 4\% margin}_{WH}(t) \end{aligned}$$

4.2.3 Cost factors during the disposal phase

Since the orders are placed with an MOQ, it is expected that there are parts left at the end of the ten years of service where a disposal cost incurs. Within ATAG, the disposal costs are the costs that too many components are ordered and sent for scrap. The scrap yield is calculated as:

$$\textit{Scrap yield}_{WH} = N_{WH} \times \textit{scrap price}_{WH} \times \textit{component weight}_{WH}$$

Where N_{WH} is the number of wok heads leftover by the end of year 10. As you can see in Table 3, there are 47 pieces left at the end of year 10 and is disposed. Thus, the disposal cost is technically speaking, the amount we ordered in the last year, i.e. year 10, minus the scrap yield.

4.2.4 NPV alternative 1: MOQ + CM

The cash flow, i.e. the costs of alternative 1 (i.e MOQ + CM), is determined by subtracting the total cash outflow by the total cash inflow. The total outflow in year t is the sum of the *Cost with additional 20% margin*$_{WH}(t)$, the *Cost with additional 20% margin*$_{RH}(t)$, and

Cost with additional 20% margin$_{BC}(t)$. This total inflow is based on the scrap yield and is determined as:

$$Cash\ inflow(t = 10) = Scrap\ yield_{WH} + Scrap\ yield_{RH} + Scrap\ yield_{BC}$$

The cash flow in year t (C_t) is resolved by subtracting the cash inflow by the cash outflow. Afterwards, we determined the NPV as:

$$NPV = \sum_{t=1}^{t=10} \frac{C_t}{(1+r)^t}$$

where r is a discount rate of 10% (Alofs, 2021; Kleinhaarhuis, 2021; Noorel, 2021). The complete formulas and results of the LCC calculation of this alternative are given in Appendix H and Table X, respectively.

4.3 Life cylce cost of alternative 2: outsource + MOQ + AM

A few benefits of implementing outsourced processes within a company's supply chain are cost savings on maintenance, increased quality, no high investments in machines (Manda et al., 2018). On the other hand, the risks are that there is loss of core knowledge, the cost can increase over the product life cycle period, and there can be low morale for the customer, i.e. the company that decides to outsource.

Within Europe, there are not many suppliers that can produce the FV wok burner with the material type SS 316L. Many suppliers think that 3D printing machines for specific metal printing do not exist. However, we found one supplier based in the UK that can print the FV wok burner with the material type SS 316L. So, in this alternative, data is mostly based on the information we have retrieved via the supplier in the UK. Next to that, uncertainty might occur in this alternative when it comes to calculating the outsource costs since every (possible) 3D printing manufacturer establishes different prices for their outsource service.

4.3.1 Cost factors during the production phase

During production at the outsource company several activities take place. We will only describe the activities the outsource manufacturer uses and the related costs. First, the material, i.e. SS 316L, is placed in the machine. Afterwards, the component can be printed. Next to that, heat treatment and post-processing steps take place. Heat treatment is a stress relief cycle at a high temperature in a furnace. The post-processing step is when the part is removed from the printer through an Electrical Discharge Machining (EDM) and where the holes of the FV burner components are built to tight tolerances through a Computer Numerical Control (CNC) machine. During each of these activities, a cost incurs, namely: print cost, material cost, heat treatment cost, and post-processing cost.

The roast head and the burner cup are coated with a layer of paint in Germany. However, when ATAG decides to 3D print the FV wok burner components, it is not clear whether the burner cup and roast head need a layer of paint due to a different type of material used for printing, i.e. stainless steel 316L. Next to that, when it comes to 3D printing the surface of the FV wok burner will be smoother and thus requires a different type of painting, and even an extra process step before the layer of paint goes on the component, i.e. making the surface rough so that the paint is applied a little better to the surface. Currently, the painting process happens in Germany. We are not certain whether this company has the right paint and tools to perform this process. Next to that, the wok head is also made out of the same material and we do not know whether this component also needs a layer of paint or not. Many factors are uncertain, and if we have to implement the painting process in all six alternatives, we are not able to make an equal comparison of this process between the alternatives. Thus, the cost of painting is neglected in each alternative.

Production takes place in batches of 9 for the wok and roast heads and 4 for the burner cups (Wennington, 2021). The outsource manufacturer uses an MOQ for AM production techniques because the production price is cheaper in comparison to producing per piece. Producing the burner cup per piece cost 3423 € and producing the burner cup per batch, i.e. per 4 pieces, cost 5979 € which is 1495 € per piece (Wennington, 2021). However, if look at the last service year we do not want to order another batch if we only need a few pieces. In year 9 we need 2 pieces of the wok head, and in year 10 also 2 pieces of the wok head. If we decide to produce these pieces separate the cost would be 3053 € for all 4 pieces. If we decide to produce the wok head in a batch of 9 the cost is €2207 which is more cost-efficient for ATAG. Thus, 5 pieces will be left at the end of the life cycle and will have to be disposed. The same holds for the roast head. So, the price and MRP calculation are based on producing the FV wok burner components in batches of 9 or 4 since this is more cost-efficient than producing the components per unit. So, the outsource purchase price is determined as:

$$\begin{aligned} OutsourcePurchasePrice_{WH}(t) = &\ material\ cost_{WH}(t) + print\ cost_{WH}(t) \\ &+ heat\ treatment\ cost_{WH}(t) + post\ processing\ cost_{WH}(t) \\ &+ transportation\ cost_{WH}(t) \end{aligned}$$

The procurement price is calculated as:

$$ProcurementCost_{WH}(t) = TotalBatches_{WH}(t) * OutsourcePurchasePrice_{WH}(t)$$

Where $TotalBatches_{WH}$ is the number of wok head batches that is outsourced in year t. This is calculated the same way as described in Section 4.2.1. However, here we work with batches of 9 for the wok and roast head and 4 for the burner cup. Further, the $OutsourcePurchasePrice_{WH}(t)$ is the price that the outsource company charges. However, the customs cost and the cost for storing the goods in Duiven are not included in this purchase price. These are calculated in the 4% and 20% margin and by ATAG.

4.3.2 Cost factors during use phase

The cost during the use phase is the cost that occurs when shipping the 3D printed components from the outsource manufacturer to Duiven, storing the components, and removing the components to send them to the consumer. These costs are calculated in the 4% and 20% margin and added on top of the procurement price as mentioned in Section 3.2. The cost with an additional 4% margin and 20% margin is calculated the same way as in alternative 1, i.e. MOQ + CM (see Appendix I).

4.3.3 Cost factors during the disposal phase

In this alternative little to no disposal takes place. If we look at the results of the MRP calculation, we have 5 pieces of the wok head, 5 pieces of the roast head and 0 pieces of the burner cup left at the end of the life cycle which we have to dispose. Here, the disposal cost is also calculated the same way as in alternative 1, i.e. MOQ + CM (see Appendix I).

4.3.4 NPV alternative 2: outsource + MOQ + AM

Next to all the costs mentioned in the phases above, we found the administration cost (which occurs in the production phase) in the literature. This cost factor was already included in the product price offered by the 3D print supplier. Therefore, we do not make a separate analysis for this.

To determine the cash flow of alternative 2 (i.e. outsource + MOQ + AM), the total cash outflow is subtracted by the total inflow. The total cash outflow in year t is the sum of the $\textit{Cost with additional 20\% margin}_{WH}(t)$, $\textit{Cost with additional 20\% margin}_{RH}(t)$, and $\textit{Cost with additional 20\% margin}_{BC}(t)$. This inflow is based on the scrap yield and is determined as:

$$\textit{Cash inflow}(t = 10) = \textit{Scrap yield}_{WH} + \textit{Scrap yield}_{RH} + \textit{Scrap yield}_{BC}$$

The cash flow in year t (C_t) is determined by subtracting the cash inflow by the cash outflow. Afterwards we determined the NPV with a discount rate of 10% (Alofs, 2021; Kleinhaarhuis, 2021; Noorel, 2021). The complete formulas and results of the LCC calculation of this alternative are given in Appendix I and Table 18 (in Appendix I), respectively.

4.4 Life cycle cost of alternatives 3a & 3b: Repair + MOQ + CM & repair + outsource + MOQ + AM

Most of the complaints from consumers refer to the aesthetic appeal of the FV wok burner. There are two ways to solve this within ATAG. The first way is to blast the component to give it a shine, and the second way is to clean the component with a soap-based cleanse. However, the latter option can be done at home by the consumer and is left out of scope. The first option takes place at ATAG in Duiven in a blasting booth or a blast cabin (Herngreen, 2021). In this alternative, we have two sub alternatives. In the first sub alternative, we repair 25% of the broken roast heads and burner cups and place orders with an MOQ of 50 for 75% of service demand for the roast heads and burner cups. Further, we repair 40% of the broken wok heads, and the rest of the demand, i.e. 60% of wok heads, is ordered from Slovenia.

In the second sub alternative, we repair 25% of the broken roast heads and burner cups, and outsource the rest of the demand, i.e. 75% of the roast heads and burner cups. Further, we repair 40% of the broken wok heads every year and outsource the rest of the demand each year, i.e. 60% of service demand for the wok head. Note that the percentages are taken from the forecasted amount explained in Section 4.1.

4.4.1 Cost factors during the production phase

In alternatives 3a (i.e. repair + MOQ + CM) and 3b, production takes place by CM and AM production processes, respectively. The production costs are determined the same way as the costs determined in alternatives 1 (i.e. MOQ + CM) and 2 (i.e. outsource + MOQ + AM) (see Sections 4.2 and 4.3, respectively). Thus, in this phase, we mainly consider the cost when producing the FV wok burner components.

4.4.2 Cost factors during use phase

The use phase is the cost when the consumer has to ship the broken component to Duiven and when Duiven has to send the new component to the consumer. These are called the return and shipping costs. The shipping cost is included in the 20% margin that ATAG adds on top of the procurement price. On the other hand, the return cost is reimbursed by ATAG and is not included in the margin of 20%. Therefore, this is calculated separately in the LCC (see Appendix J). Further, we also consider the cost that incurs when shipping the 3D printed components from the outsource manufacturer and Slovenia to Duiven. This cost is included in the 4% margin and is taken into account in this phase.

4.4.3 Cost factors during repair phase

The cost that occurs during this phase is the cost of repairing the failed component. The repair activity that takes place is blasting which happens with a blasting machine. Next to that, the machine works with a compressor. Based on the compressor's power we can calculate the electricity cost. Thus, the electricity is calculated as:

$$\begin{aligned} \textit{Electricity cost}_{WH} = \; & \textit{Compressor power (in kW)}\times \\ & \textit{number of operating hours for blasting per year}_{WH}\times \\ & \textit{cost of electricity (expressed in euros per kWh)} \end{aligned}$$

When we blast a component, corundum is used. The amount of abrasive that is used is based on the number of times a repair takes place. On average 15 kilograms of normal corundum is needed to blast a component of the FV wok burner. Thus, the abrasive cost is calculated as:

$$\textit{Abrasive Cost}_{WH} = \textit{\# of repairs}_{WH} \times (\textit{15 kg of normal corundum}) \times \text{€}2{,}40$$

Further, labour is also needed to repair a component (see Appendix J). The total cost for repair is the sum of all the costs that incur for repairing one component, i.e.:

$$\textit{Repair Cost}_{WH} = \textit{Electricity cost}_{WH} + \textit{Labour cost}_{WH} + \textit{Abrasive cost}_{WH} + \textit{Return cost}_{WH}$$

As mentioned before, ATAG adds a 4%, and 20% margin on the procurement price. In this alternative, these percentages are added whenever we repair components, place orders in Slovenia, and when we outsource. The 4%, and 20% for ordering from Slovenia (alternative 1: MOQ + CM), and outsourcing (i.e. alternative 2), is calculated the same way as explained in Appendix H, and I. However, the 4%, and 20% for repair are calculated slightly differently. Here, the 4% margin is calculated as:

$$\begin{aligned} \textit{Cost with additional 4\% margin}_{WH}(t) = \; & \Big(\textit{Repair cost}_{WH}(t) \times 4\%\Big) \\ & + \textit{Repair cost}_{WH}(t) \end{aligned}$$

On top of this 4% margin ATAG adds a 20% margin, which is calculated as:

$$\begin{aligned} \textit{Cost with additional 20\% margin}_{WH}(t) = \; & \Big(\textit{Cost with additional 4\% margin}_{WH}(t) \times 20\%\Big) \\ & + \textit{Cost with additional 4\% margin}_{WH}(t) \end{aligned}$$

4.4.4 Cost factors during disposal phase

The cost involved during this phase is the disposal cost, and only incurs when we order components from Slovenia with an MOQ and or when we outsource. This is the same as the costs explained in the disposal phase of alternatives 1 and 2 (see Sections 4.2 and 4.3, respectively).

4.4.5 NPV alternatives 3a & 3b

To determine the cash flow of alternatives 3a (i.e. repair + MOQ + CM) and 3b (i.e. repair + outsource + MOQ + AM), the total cash outflow is subtracted by the total inflow. The total cash outflow in year t for alternative 3a is determined as:

$$\begin{aligned} \textit{Cash outflow}(t) = \; & \Big(\textit{Repair}_{WH}(t) + \textit{Orders with MOQ}_{WH}(t)\Big) \\ & + \Big(\textit{Repair}_{RH}(t) + \textit{Orders with MOQ}_{RH}(t)\Big) \\ & + \Big(\textit{Repair}(t)_{BC} + \textit{Orders with MOQ}_{BC}(t)\Big) \end{aligned}$$

The total cash outflow in year t for alternative 3b is determined as:

$$\begin{aligned} Cash\ outflow(t) = &\Big(Repair_{WH}(t) + outsource_{WH}(t)\Big) \\ &+ \Big(Repair_{RH}(t) + outsource_{RH}(t)\Big) \\ &+ \Big(Repair(t)_{BC} + outsource_{BC}(t)\Big) \end{aligned}$$

Further, we have a cash inflow only at the end of year 10. This inflow in alternative 3a is determined as:

$$\begin{aligned} Cash\ inflow(t = 10) = &\ Scrap\ yield\ from\ orders\ with\ MOQ_{WH} \\ &+ Scrap\ yield\ from\ orders\ with\ MOQ_{RH} \\ &+ Scrap\ yield\ from\ orders\ with\ MOQ_{BC} \end{aligned}$$

The inflow in alternative 3b is determined as:

$$\begin{aligned} Cash\ inflow(t = 10) = &\ Scrap\ yield\ from\ outsource_{WH} \\ &+ Scrap\ yield\ from\ outsource_{RH} \\ &+ Scrap\ yield\ from\ outsource_{BC} \end{aligned}$$

The cash flow in year t (C_t) is resolved by subtracting the cash inflow by the cash outflow. Afterwards we determined the NPV with a discount rate of 10% (Alofs, 2021; Kleinhaarhuis, 2021; Noorel, 2021). The complete formulas and results of the LCC calculation of this alternative are given in Appendix J and Table X, Y, 21, and 22.

4.5 Life cycle cost of alternatives 4a & 4b: invest in small AM machine & invest in large AM machine

Investing in an industrial 3D printer is useful when the scale, size, and quantity of products to be manufactured are large enough (Manda et al., 2018). The cost of an industrial 3D printer is very high and demands a lot of technical knowledge and skilled labour to efficiently operate and handle the machine. Investing in an industrial 3D printer makes sense if the company management is fully committed to the 3D printing technology and wants to implement it factory-wide. In this alternative, the costs are divided into two parts, namely the costs for investing in a 3D printing machine and the costs for printing the FV wok burner components.

4.5.1 Cost factors during the production phase

In this phase, we considered the costs that incur when buying a 3D printing machine and the costs for 3D printing the FV wok burner itself. First, Slovenia should look for a suitable machine. We assumed to invest in the 3D print machine of EOS GmbH in Germany since a good amount of data was publicly addressed and could be used as input to calculate certain cost factors. Further, the machines that were chosen are suitable for large manufacturers. When we install the machine in Slovenia, the three main costs that incur are the acquisition cost, operation cost, and the repair and maintenance cost (Fixson, 2004). Each of these costs is divided into sub-activities. The calculation and explanation of these costs are provided in Appendix K. Now, if we sum up the cost for the first part, i.e. the costs related to buying and installing the 3D printing machine, the cost is too high, i.e. around 1 million for alternative 4a (i.e. invest in a small AM machine) and around 2 million for alternative 4b (i.e. invest in a large AM machine), and it would not make any sense to consider this alternative. However, we assumed that Slovenia will use the machine for other purposes as well. Thus, we only added a small percentage of the costs of the first part into our calculation, i.e. $\frac{\textit{Production capacity of machine X}}{\textit{\#of FV wok burner components to produce in year t}} \times 100\%$. The total cost related to investing in a new 3D printing machine is defined as follows:

Total machine cost(t)= Acquisition cost(t)+ Operation cost(t) + Repair & Maintenance cost(t)

The cost of the first part for both machines is determined as:

$$\textit{Total machine cost FV wok burner (t)} = \textit{Total machine cost(t)} \times \frac{\textit{Production capacity of machine X}}{\textit{\#of FV wok burner components to produce in year t}}$$

Where *Production capacity of machine X* is referred to the production capacity of machine M290 and M400-4 (see Appendix K), and *#of FV wok burner components to produce in year t* is referred to the forecasted amount determined in Appendix G.

Further, we have the costs related to printing the FV wok components themselves. For this, we found eight steps in the literature to determine the cost for printing which is explained in Appendix E. To calculate the costs in each step, certain steps are merged. Step 1 (make CAD model) and step 2 (conversion from CAD to STL) are merged, since converting a CAD file to an STL file only takes a few minutes. Furthermore, there are no specific costs incurred in step 2. The same holds for steps 3 (transfer to AM machine) and 4 (machine setup). Again transferring an STL file to an AM machine takes only a few minutes. Thus, this step is merged with step 4, i.e. machine setup. After merging the steps, we categorized the cost parameters under the four phases as described in Section 3.2. These costs are categorized just like in the outsource alternative (see Section 4.3), i.e. heat treatment cost, removal/post-processing cost, material cost. Next to that, labour cost is also included since certain AM production steps require some labour. Thus, the cost related to printing is calculated as:

$$\begin{aligned}\textit{Cost related to printing}_{WH}(t) &= \textit{material cost}_{WH}(t) + \textit{print cost}_{WH}(t)\\ &+ \textit{heat treatment cost}_{WH}(t) + \textit{post processing cost}_{WH}(t)\end{aligned}$$

4.5.2 Cost factors during use phase

The activities that take place during this phase are the transportation and handling of the FV wok burner components from Slovenia to Duiven, storing the components, and sending the components to the consumer. Again the margin of 4% and 20% (transportation and handling cost, storage cost, removal cost, and labour cost) that ATAG adds on top of the procurement price is the only relevant cost in this phase.

The cost with additional 4% margin is determined as:

$$\begin{aligned}\textit{Cost with additional 4\% margin}_{WH}(t) &= \Big(\textit{Cost related to printing}_{WH}(t) \times 4\%\Big)\\ &+ \textit{Cost related to printing}_{WH}(t)\end{aligned}$$

On top of this 4% margin ATAG adds a 20% margin, which is calculated as:

$$\begin{aligned}\textit{Cost with additional 20\% margin}_{WH}(t) &= \Big(\textit{Cost with additional 4\% margin}_{WH}(t) \times 20\%\Big)\\ &+ \textit{Cost with additional 4\% margin}_{WH}(t)\end{aligned}$$

4.5.3 Cost factors during the disposal phase

Whenever ATAG needs a new component, they order the parts from Slovenia without any required MOQ at the moment. We assumed that this is also the case when Slovenia decides to 3D print the FV wok burner for ATAG. This means that we do not have any disposal cost since we can order the amount in the desired quantity from Slovenia at any time.

4.5.4 NPV alternatives 4a & 4b

In this alternative, we do not have a cash inflow since we will not have any disposal. Thus, the cash flow of alternatives 4a (i.e. invest in a small AM machine) and 4b (i.e. invest in a large AM machine) in year t is determined as:

$$\begin{aligned} \textit{Cash flow}(t) = & \textit{ Total machine cost FV wok burner (t)} \\ & + +\textit{Cost with additional 20\% margin}_{WH}(t) \\ & + \textit{Cost with additional 20\% margin}_{RH}(t) \\ & + \textit{Cost with additional 20\% margin}_{BC}(t) \end{aligned}$$

Afterwards we determined the NPV with a discount rate of 10% (Alofs, 2021; Kleinhaarhuis, 2021; Noorel, 2021). The complete formulas and results of the LCC calculation of this alternative is given in Appendix K and Tables 23, 24, 25, and 26 (in Appendix K).

4.6 Conclusion

In this chapter, we constructed six alternatives each with its LCC model. These LCC models can determine the NPV for a period of ten years. Additionally, the models determine how much ATAG should invest during a service period of ten years for the FV wok burner. Through, these models we can recommend whether the AM (alternative 2: outsource + MOQ, alternative 3b: repair + outsource + MOQ, alternative 4a: invest in a small AM machine, and alternative 4b: invest in a large AM machine) or CM (alternative 1: MOQ, and alternative 3a: repair + MOQ) models are more relevant for ATAG when it comes to financial feasibility. The total life cycle of a component is divided into three phases each with its cost factors taken into account. The LCC models were validated using experts from different relevant department within ATAG (Alofs, 2021; Kleinhaarhuis, 2021; Noorel, 2021; Versteeg, 2021; van Os, 2021). With their feedback, we have verified the working of the model.

5 Construction of the LCA models

In this chapter, the construction of the LCA models are determined. Process flows of each of the six alternatives based on the cradle-to-gate + disposal LCA are determined as well. Furthermore, we use the problem-oriented approach using the CML2001 method. Next to that, all emissions that contribute to global warming are converted to kg CO_2-equivalents. First, we determine the input variables for the LCA, which is explained in Section 5.1.1. In Section 5.2 the LCA model for alternative 1, i.e. MOQ + CM, is constructed. In Section 5.3 the LCA model for alternative 2, i.e. outsource + AM, is constructed. In Section 5.4 we construct the third LCA model, i.e. repair + MOQ + CM. In section 5.5 we construct the LCA model of alternative 3b (i.e. repair + outsource + MOQ + AM). In Section 5.6 the last two LCA modes are constructed, i.e. invest in two different types of 3D printing machines. Finally, this chapter is closed with a conclusion in Section 5.7.

5.1 Life Cycle Inventory

Certain material extraction processes from Slovenia and Turkey are not available. Therefore, we have to use either literature, online databases, or assumptions. This may differ per alternative described in Section 2.6. Next to that, we were not able to retrieve data for all the CM production processes given in Appendix A. Thus, we made a couple of assumptions because of a lack of information in the literature:

- The painting process is neglected in all six alternatives. So, transport to Germany and (un)packaging in Germany is neglected as well. Thus, for transport of the roast head and burner cup, we consider the following route: Malaysia → Rotterdam → Moerdijk → Slovenia → Duiven. For transport of the wok head, we considered the following route: Turkey → Slovenia → Duiven.
- The process steps such as cleaning, internal transport, and packaging in Malaysia and Turkey are neglected (see Figure X in Appendix A). No data was found/available for these processes. Next to that, these processes have little to no impact on the LCA.

For the alternatives that are related to 3D printing the following assumptions are made:

- The painting process is neglected. If ATAG decides to 3D print the FV wok burner components it is not yet clear whether a layer of paint on each component is necessary with the new material type, i.e. SS 316L.
- For the material type SS 316L we used stainless steel 316. Further, we adjusted the weight of SS316 in such a way that it is at least the same weight as SS 316L.

5.1.1 Input LCA

For the LCA, we used the forecasted number of components determined in each LCC models as input for the LCA models (see Table 27 in Appendix L). This way, we can calculate the total amount of emissions to the air. Furthermore, based on Table 27 in Appendix L, we can determine the number of kilograms of material we need and the travel distance. The data collected is presented in Table 4. The values are represented for a period of ten years of service. For example, the weight of one conventional manufactured wok head is 0,32 kg. In alternative 1 (i.e. MOQ + CM), we produce 150 pieces of the wok head which means we need 150 times 0,32 kg equals 48 kg of brass. However, this is not exactly the input for the LCA models because when producing with, e.g. CM processes oftentimes we need more, e.g. kilograms of material. Gabi has a scaling function that determines the exact amount of material we need as input based on available literature. These values are provided in Table 4. The mass is calculated in the same way for all the other components in each alternative.

Another aspect we have to consider is the travel distance per boat. In alternative 1 (i.e. MOQ + CM), orders are placed with an MOQ of 50 from Slovenia. We expect to place four orders for the roast head and burner cup, i.e. (150+50=) 200 pieces during the whole lifetime, i.e. ten years of service (see Table 27 in Appendix L). In other words, Slovenia has to make sure there is enough in stock in their warehouse by placing an order from Malaysia. In alternatives 1 and 3a, the roast head and burner cup are shipped per boat from Malaysia to the port of Rotterdam that lasts 15000 km (see Table 28 in Appendix L). Slovenia and Malaysia work with different requirements and conditions. Thus, not because ATAG places orders in batches of 50 in Slovenia means that Slovenia has to place the same amount of orders in Malaysia since Furthermore, in practice, it is always the case that in a boat there is a load of several products and not just a load of 200 pieces of components. Therefore, we assumed that only one boat transport movement would be necessary over ten years of service since 200 pieces (i.e. 2 to 3 carton boxes) is only a fraction of a total ship. The amount of fuel that is used for the ship is scaled according to the weight of the number of FV wok burner components transported in GaBi. Thus, the fuel used for a whole ship is not taken into account, only a small portion of it. The same holds for alternative 3a (i.e. repair + MOQ + CM) for the roast head and burner cup.

The third aspect we considered is the travel distance by truck (see one before the last column in Table 4). This distance is based on the total amount of travel movements during ten years of service (see the last column in Table 4). The wok head is made in Turkey and transported directly to Slovenia with a travel distance of 1690 km per shipment (see Table 28 in Appendix L). Whenever ATAG places an order it is shipped from Slovenia to Duiven which last 1200 km per load. Since we have to place 3 orders for the wok head in alternative 1 (i.e. MOQ + CM) during the ten years of service, $\frac{150}{\textit{MOQ of 50}} = \textit{3 orders}$, we have 3 transport movements meaning we have to travel a total distance of $(1680 + 1200) \times 3 = 8670$ km.

On the other hand, the roast head in alternatives 1 and 3a is transported by truck through several locations. Here we also made a few assumptions. Whenever the boat arrives at the port of Rotterdam the components are transported to Moerdijk where they are stored. This movement lasts a distance of 130 km per shipment. When Slovenia needs a batch it is shipped from Moerdijk to Slovenia with a travel distance of 1280 km per shipment and when ATAG places an order the components are shipped from Slovenia to Duiven with a travel distance of 1200 km per shipment. When an order is placed we take into account the transportation from Rotterdam to Moerdijk. So, e.g. for the roast head in alternative 1 (i.e. MOQ + CM), we have three transport movements during the whole life cycle. It takes a total of $(130 + 1280 + 1200) \times 3 = 7830$ km travel distance to transport 150 pieces of roast heads (or 20,7 kg of roast heads) during the ten years of service (see Table 4).

In alternative 3a (i.e. repair + MOQ + CM), partly repair takes place. Here, the consumer has to send the broken component to Duiven, and when the component is repaired it is sent to the consumer which lasts 50 km in total. Repair of, e.g. the wok head in alternative 3a takes place 36 times during ten years of service. Thus, the total travel distance that takes place is $50 \times 36 = 1800$ km (see Table 4).

For the outsource alternatives, i.e. alternatives 2 and 3b, we assumed to use the location of the outsource manufacturer we found in the UK. In both alternatives, the components are transported directly by truck from the UK to Duiven which lasts a travel distance of 620 km per shipment. Since we have to place orders in batches of 9 for the wok and roast head and batches of 4 for the burner cup, we assumed that whenever a batch is ordered a transport movement takes place. Thus, the amount to travel during the ten years of service for, e.g. the wok head in alternative 2 (i.e. outsource + MOQ + AM) is a total of $620 \times 12 = 7440$ km. The same way the travel distance is determined for the other components.

In alternatives 4a & 4b, we assumed that orders are placed without an MOQ. So, we assumed that each component is shipped separately and therefore, a transport movement takes place during every order (see Table 4).

Alternative	*Component*	*Material*	*Mass (kg)*	*Travel distance by truck (km)*	*Transport movements*
1 (MOQ + CM)	Wok head	Brass	55,2	8670	3
	Roast head	Aluminium	20,7	7830	3
	Burner cup	Aluminium	26,4	2610	1
2 (outsource + MOQ + AM)	Wok head	SS 316	37,8	7440	12
	Roast head	SS 316	43,2	7440	12
	Burner cup	SS 316	29	3100	5
3a (repair + MOQ + CM)	Wok head (MOQ)	Brass	36,8	5780	2
	Roast head (MOQ)	Aluminium	13,8	5220	2
	Burner cup (MOQ)	Aluminium	26,4	2610	1
	Wok head (repair)	Brass	11,5	1800	36
	Roast head (repair)	Aluminium	2,5	1050	21
	Burner cup (repair)	Aluminium	0	0	0
3b (repair + outsource + MOQ + AM)	Wok head (outsource + MOQ)	SS 316	22,3	4960	8
	Roast head (outsource + MOQ)	SS 316	36	6200	10
	Burner cup (outsource + MOQ)	SS 316	29	3100	5
	Wok head (repair)	Brass	11,5	1800	36
	Roast head (repair)	Aluminium	2,52	1050	21
	Burner cup (repair)	Aluminium	0	0	0
4a & 4b (invest in 2 different machines)	Wok head	SS 316	31,9	123600	103
	Roast head	SS 316	37,1	123600	103
	Burner cup	SS 316	27,4	24000	20

Table 4: Input data LCA.

5.2 Life cycle assessment of alternative 1: MOQ + CM

After determining the input data, we can construct flow charts in Gabi. In Figure 5 a detailed flow chart of the impact assessment of the wok head in alternative 1 (i.e. MOQ + CM) is provided along with its data of the input and output flows of fixed parameters in Table 5. First, we need to forge (or die-cast) the wok head (or roast head/burner cup) with electricity, thermal energy and brass (or aluminium). Afterwards, the components are machined where holes are drilled each component with the precise tolerance. For this electricity is needed as well. Data for forging and machining the brass component (i.e. CM process of the wok head) could not be found and was therefore approximated for the aluminium type of components. For the wok head, an extra step occurs which is blasting the component. In this process step, we need electricity and abrasive material as input. Afterwards, the wok heads are transported from Turkey to Slovenia to Duiven per truck, and the burner cup and roast heads are transported from Malaysia to Moerdijk to Slovenia to Duiven.

Since we are doing a cradle to gate LCA, we assumed that the usage of the component does not contribute to any environmental impact, consume any power or release any emissions. Then we assumed that after the use phase, which has no environmental impact, the components are thrown away. For this step, we integrated a waste flow where the brass component from the use phase is considered as input, and brass scrap (or aluminium scrap) is considered as output in our use/disposal process. This means that we can model a circular material flow within the component life cycle by connecting the output flow of the use/disposal phase with the brass (or aluminium) production process. Thus, brass scrap (or aluminium scrap) is used in production to produce a new component. In Appendix M in Figure 11, and 12 detailed flow charts of the impact assessment of the roast head and the burner cup in alternative 1 (i.e. MOQ + CM) is provided.

5.3 Life cycle assessment of alternative 2: outsource + MOQ + AM

When outsourcing the FV wok components several steps are involved. In this alternative, we only worked with the process steps that were mentioned by the outsource manufacturer in the UK. First, we need to print the components and, for this process step, we need SS 316 and electricity. We get as output steel parts. Afterwards, the components are going through a heat treatment process where again electricity is used. As output, we get steep parts that are processed. Next, we need to post-process the components where we also need some electricity. Then the components are shipped from the UK to Duiven. Here, we assumed that the usage of the 3D printed component does not contribute to any environmental impact, consume any power or release any emissions. After the use phase, we assumed that the components are thrown away. To model this we integrated a waste flow, where we use as input steel components from the use phase and as output SS 316 in our use/disposal process. Thus, we can model a circular material flow within the component life cycle by connecting the output flow of the use/disposal phase with the SS 316 production process. Thus, SS 316 is used in production to produce a new component. In Appendix N in Figure 13, 14, and 15 detailed flow charts of the impact assessment of the wok head, roast head and the burner cup in alternative 2 (i.e. outsource + MOQ + AM) is provided. The related data set for the input and output flows of fixed parameters of the wok head, roast head and burner cup is given in Appendix N in Table 30.

5.4 Life cycle assessment of alternative 3a: repair + MOQ + CM

In this alternative, we made two separate flow charts for repair and orders with MOQ to determine the total amount of emissions to air. For the repair, we only considered blasting (see Section 2.6.3). Here, the components arrive in the warehouse of Duiven first. Afterwards, the components are repaired in a blast machine using silica sand and electricity. After the components are repaired they are sent to the consumer again. In Appendix O in Figure 17, 19, and 21 detailed flow charts of the impact assessment for the repair of the wok head, roast head and the burner cup is provided. The related data set for the input and output flows of fixed parameters of the wok head, roast head and burner cup is given in Appendix O in Table 32.

The process flows for orders with an MOQ is the same as described in Section 5.2. However, the input and output flow of the fixed parameters are different which is given in Appendix O in Table 31. The related flow charts of the impact assessment of the wok head, roast head and the burner cup in alternative 3a (i.e. repair + MOQ + CM) is given in Appendix O in Figure 16, 18, and 20.

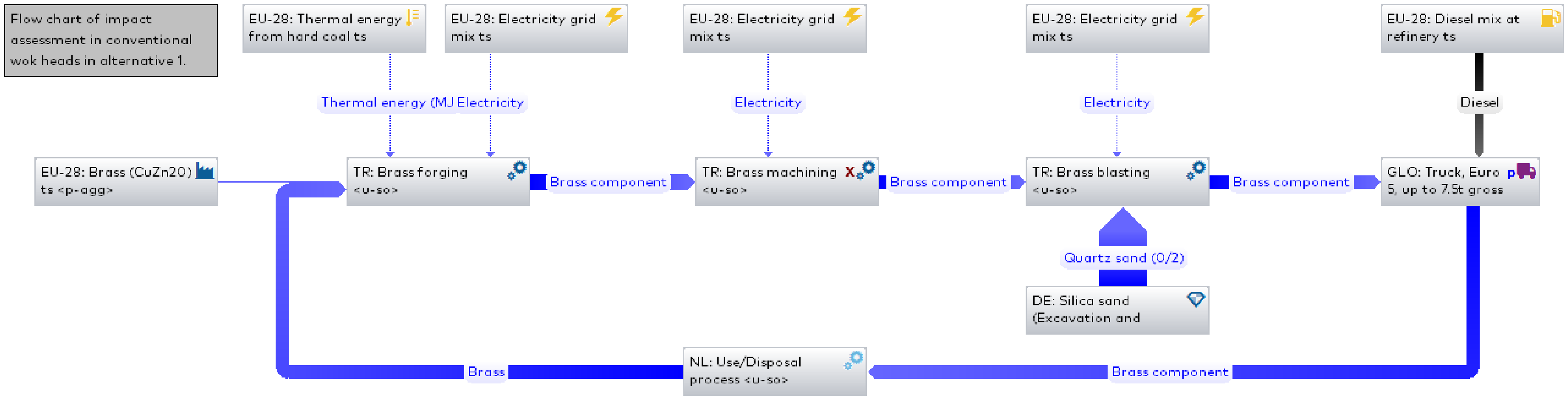


Figure 5: Flow chart of impact assessment in conventional wok heads in alternative 1 (i.e. MOQ + CM).

Component	*Process*	*Input*				*Output*			
		Parameter flow	*Quantities*	*Amount*	*Units*	*Parameter flow*	*Quantities*	*Amount*	*Units*
Wok head	TR: Brass forging	Brass [Metals]	Mass	55,20	kg	Brass component [Metal parts]	Mass	52,80	kg
		Electricity [Electric power]	Energy (net calorific value)	184,50	MJ				
		Thermal energy (MJ) [Thermal energy]	Energy (net calorific value)	100,20	MJ				
	TR: Brass machining	Brass component [Metal parts]	Mass	52,80	kg	Brass component [Metal parts]	Mass	48,00	kg
		Electricity [Electric power]	Energy (net calorific value)	15,30	MJ				
	TR: Brass blasting	Brass component [Metal parts]	Mass	48,00	kg	Brass component [Metal parts]	Mass	48,00	kg
		Electricity [Electric power]	Energy (net calorific value)	18,00	MJ				
		Quartz sand (0/2) [Minerals]	Mass	150,00	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Brass component [Metal parts]	Mass	48,00	kg	Brass component [Metal parts]	Mass	48,00	kg
		Diesel [Refinery products]	Mass	32,09	kg				
	NL: Use/Disposal process	Brass component [Metal parts]	Mass	48,00	kg	Brass [Metals]	Mass	48,00	kg

Table 5: Input and output flows of fixed parameters in alternative 1 (i.e. MOQ + CM).

5.5 Life cycle assessment of alternative 3b: repair + outsource + MOQ + AM

In this alternative, we again made two separate flow charts for repair and orders with MOQ. The flow charts for repair is the same as explained in Section 5.4. In this alternative, all the components that are returned to the warehouse in Duiven during the ASS period are conventional. The 3D printed items will less likely be returned since they are more robust than the conventional components (Wennington, 2021). Thus, conventional components that cannot be repaired are outsourced. In Appendix P in Figure 23, 25, and 27 detailed flow charts of the impact assessment for the repair of the wok head, roast head and the burner cup is provided. The related data set for the input and output flows of fixed parameters of the wok head, roast head and burner cup is given in Appendix P in Table 34.

The process flows for outsourcing is the same as described in Section 5.3. However, the input and output flow of the fixed parameters are different which is given in Appendix P in Table 33. The related flow charts of the impact assessment of the wok head, roast head and the burner cup are given in Appendix P in Figure 22, 24, and 26.

5.6 Life cycle assessment of alternatives 4a & 4b: invest in two different 3D printing machines

In alternatives 4a & 4b, the components are printed in Slovenia. Several steps are involved when 3D printing a part. These are given in Appendix E. However, we did not take all the steps into account since they do not have any impact on the LCA. The steps we left out are making the CAD model, transforming the CAD model into an STL file, transferring a file to AM machine, and machine setup. So, steps such as the print process, heat treatment process, post-processing are all taken into account. Next to that, after the items are printed, they are shipped from Slovenia to Duiven. The components are printed with the material type SS 316. In Appendix Q in Figure 28, 29, and 30 detailed flow charts of the impact assessment of the wok head, roast head and the burner cup are provided. The related data set for the input and output flows of fixed parameters of the wok head, roast head and burner cup is given in Appendix Q in Table 35.

5.7 Conclusion

In this chapter, we constructed six LCA models for each alternative. These models can determine the number of emissions to air in kg CO_2-equivalents for a period of ten years. Additionally, the models give ATAG insight into which of the alternatives are more environmentally friendly and has less impact on global warming. Through, these models we can see whether the AM (alternative 2: outsource + MOQ, alternative 3b: repair + outsource + MOQ, alternative 4a: invest in a small AM machine, and alternative 4b: invest in a large AM machine) or CM (alternative 1: MOQ, and alternative 3a: repair + MOQ) models are more relevant for ATAG when it comes to global warming. In the literature, there are no specific models related to the FV wok burner components to relate to. However, with the help and feedback of colleagues, we have verified the working of the LCA models.

6 Analysis of the models

In this chapter, we analyse the LCC and LCA models to evaluate the potential of Conventional Manufacturing (CM) or Additive Manufacturing (AM). The LCC models are constructed in such a way as to choose the most cost-efficient alternative. The LCA models are constructed in such a way to identify the alternative with the lowest CO_2-emission associated with the cradle to gate process of the FV wok burner components. In Section 6.1, we present the result of the LCC and LCA models. Furthermore, we determine the cost structure, so it becomes clear to identify the main cost differences. In Section 6.2 we will do a thorough sensitivity analysis of the LCC and LCA models. Finally, this chapter is closed with a conclusion in Section 6.3.

6.1 LCC and LCA model analysis

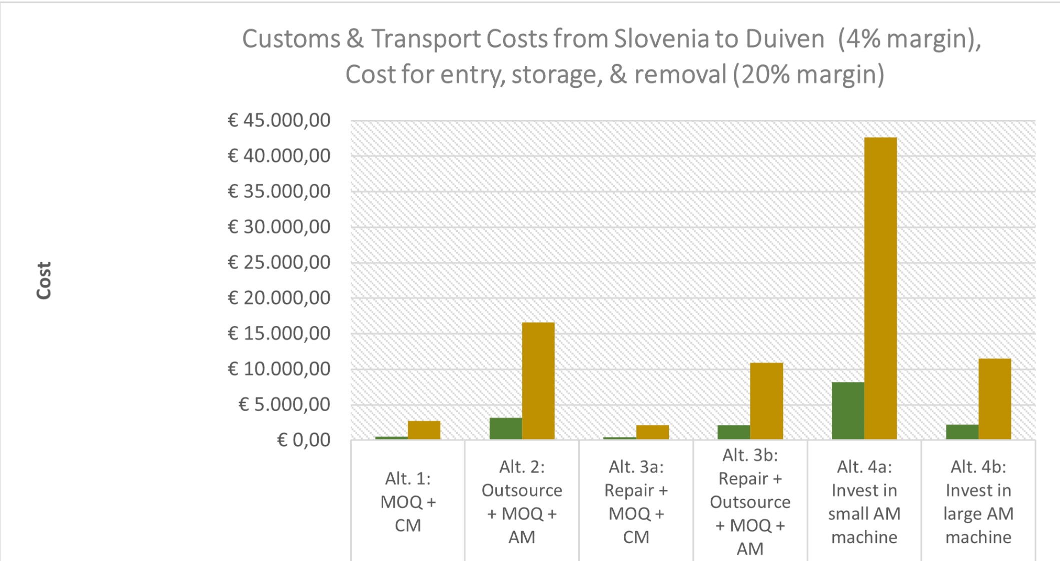
Out of each of the processes of the LCA models in, e.g. Figure 5 we calculated the amount of GWP in kg CO_2-equivalents using the CML2001 calculation method available in the Gabi Software. In Table 6, we placed the NPV's and the total amount of kg CO_2-equivalents of all six alternatives next to each other to make a comparison. Investing in a small AM machine, i.e. alternative 4a seems to have the largest NPV during the ASS period with a cost of 183.411.19 €. The main reason for such a high cost is the high acquisition cost of the 3D printing machine. The same holds for alternative 4b (i.e. invest in a large AM machine). Further, both of these alternatives contribute the most to global warming with a total of 2580 kg CO_2-eq. emissions to air. The assumption here was that the 3D printed FV wok burner components are ordered from Slovenia per piece. So, there are more transport movements during the ASS period as opposed to the other alternatives where components are delivered to ATAG in batches/MOQ's. Now, if we compare these two alternatives to alternative 2 (i.e. outsource + MOQ + AM), it seems that outsourcing is a better option than investing in a small AM machine (alternative 4a). Next to that, we have less CO_2 emissions when we outsource. For outsourcing, we have fewer transport movements due to ordering with an MOQ instead of ordering per piece as in alternatives 4a & 4b. If we compare alternative 2 with alternative 4b, alternative 4b is a better option in terms of cost. In alternative 4b, the assumption was to use the AM machine for other purposes. Next to that, this machine can produce much more components compared to the AM machine used in alternative 4a. Thus, the costs, i.e. repair-, maintenance-, operation-, and acquisition cost, are scaled depending on the amount of FV wok burner components that are printed on the machine in alternative 4a. Scaling the costs according to the machine maximum volume production ensures that the costs are lower than the costs in alternative 2.

The most efficient alternative to investing in is alternative 3a (i.e. repair + MOQ + CM) with a cost of 9.604,49 € (see Table 6). However, when it comes to the amount of emissions in this alternative it is the second most environmentally friendly alternative with a total of 208 kg CO_2-eq. emissions to air. This amount is lower than alternatives 4a & 4b because the components are ordered in batches of 50 which means there are fewer transport movements during the ASS period. The first most environmentally friendly alternative is alternative 3b (i.e. repair + outsource + MOQ + AM), with a total of emissions to air of 183 kg CO_2-eq.

Alternative	***NPV***	***CML2001 - Jan. 2016, GWP- emissions to air in kg CO_2 eq.***
Alt. 1: MOQ + CM	€ 11.058,78	312
Alt. 2: Outsource + MOQ + AM	€ 71.091,38	255
Alt. 3a: Repair + MOQ + CM	€ 9.604,49	208
Alt. 3b: Repair + Outsource + MOQ + AM	€ 46.145,81	183
Alt. 4a: Invest in small AM machine	€ 183.411,19	2580
Alt. 4b: Invest in large AM machine	€ 51.786,36	2580

Table 6: LCC and LCA results of all six alternatives.

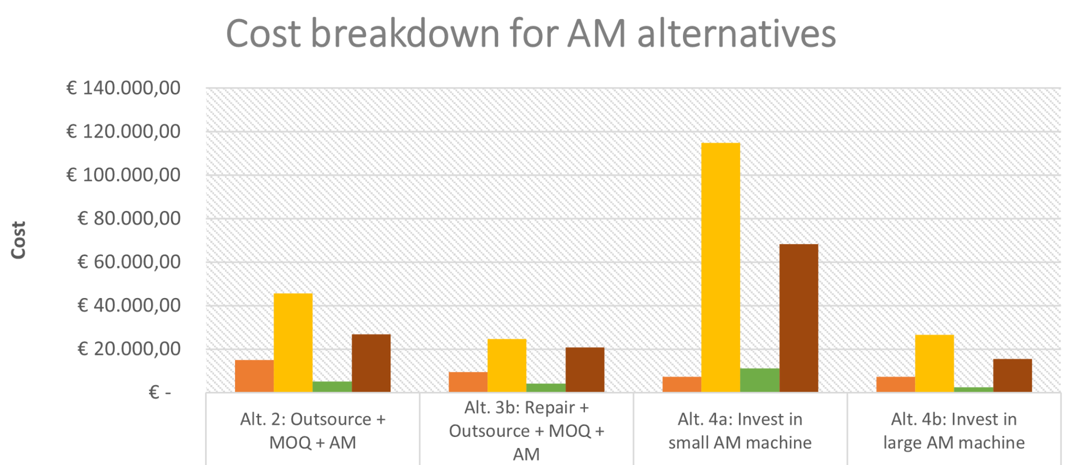
The cost factors that are common in all the six alternatives are the customs & transport costs (margin of 4%) and the cost for entry, storage, & removal (margin of 20%). In Figure 6 an overview of these cost factors is given. Alternative 4a (i.e. invest in a small AM machine) covers the highest customs and transport cost as well as the highest cost for entry, storage, and removal cost. These margins are added on top of the production cost. Thus, the cost of producing with AM are the cause of such high numbers. So, the costs for material-, print-, heat treatment-, and post-processing costs are high expenses which are explained later in this section. From this figure, alternatives 1 and 3a are the most cost-efficient when it comes to customs & transport costs, and the cost for entry, storage, & removal. This is because the purchase price from the supplier in Slovenia is lower than the purchase price of, e.g. the outsource manufacturer. Furthermore, the customs & transport costs (margin of 4%) and the cost for entry, storage, & removal (margin of 20%) follow the same pattern in the figure because the 20% margin is always added on top of the 4% margin.



	Alt. 1: MOQ + CM	Alt. 2: Outsource + MOQ + AM	Alt. 3a: Repair + MOQ + CM	Alt. 3b: Repair + Outsource + MOQ + AM	Alt. 4a: Invest in small AM machine	Alt. 4b: Invest in large AM machine
Customs and Transport Costs	€ 517,55	€ 3.184,95	€ 410,14	€ 2.098,70	€ 8.194,68	€ 2.208,62
Cost for entry, storage, and removal	€ 2.691,25	€ 16.561,75	€ 2.132,75	€ 10.913,23	€ 42.612,35	€ 11.484,83

Figure 6: Customs & Transport Costs from Slovenia to Duiven (4% margin), and cost for entry, storage, & removal (20% margin).

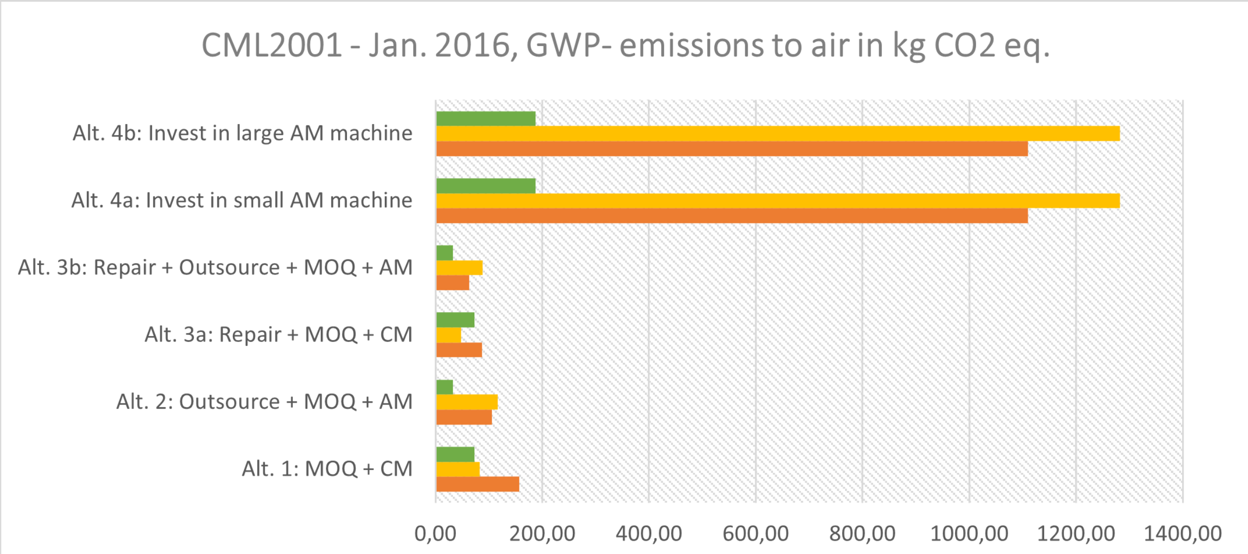
Since the CM alternatives, i.e. alternatives 1 and 3a, seem to be the most cost-efficient, we will now analyze the cost factors for the AM alternatives, i.e. alternatives 2, 3b, 4a, & 4b. The cost factors that are common in all these four alternatives are the material-, print-, heat treatment-, and post-processing cost. In Figure 7 an overview of these cost factors is given. Notice that the print cost covers the majority of the four cost factors. Printing takes several days and therefore increases the cost of electricity by many folds. Heat treatment cost is a cost factor that is the lowest. This treatment is a stress relief cycle at a high temperature in a furnace. Depending on the material, this is at a different temperature duration but improves material properties post-build. During the heat treatment process, the component is heated, without letting it reach its melting stage, and then the metal is cooled down in a controlled way to select the desired mechanical properties. The process itself does not take as long as the printing process and therefore uses less electricity.



	Alt. 2: Outsource + MOQ + AM	Alt. 3b: Repair + Outsource + MOQ + AM	Alt. 4a: Invest in small AM machine	Alt. 4b: Invest in large AM machine
Material cost	€ 14.876,17	€ 9.451,62	€ 7.230,75	€ 7.230,75
Print cost	€ 45.717,88	€ 24.642,66	€ 114.889,52	€ 26.610,63
Heat treatment cost	€ 5.072,97	€ 4.023,39	€ 11.070,00	€ 2.510,00
Post processing cost	€ 26.824,27	€ 20.652,85	€ 68.286,79	€ 15.474,16

Figure 7: Cost breakdown for Additive Manufacturing alternatives: 2, 3b, 4a, & 4b.

In Figure 8 the amount of carbon dioxide used per component per alternative is provided. Alternatives 4a (i.e. invest in a small AM machine) and 4b contribute the most to global warming because of the high number of transport movements during the ASS period. In Figure 9 this is more clear. The processes in each alternative are categorized under electricity, transport, raw material, repair and rest (i.e. disposal, thermal energy, and abrasive material) as shown in Figure 9. Notice that transport consumes the largest carbon dioxide in all six alternatives except transport for the burner cup in alternatives 1 and 3a because in both of these scenarios only one batch of 50 pieces is transported during the ASS period, which means that we have fewer CO_2 footprints. In alternatives 4a and 4b, transport consumes the most CO_2 emissions, as the FV wok burner components are transported per piece instead of per batch/MOQ. Further, the weight of each component transported is scaled to the amount of fuel used in a truck. The second-largest category that has a negative impact on global warming is electricity.



	Alt. 1: MOQ + CM	Alt. 2: Outsource + MOQ + AM	Alt. 3a: Repair + MOQ + CM	Alt. 3b: Repair + Outsource + MOQ + AM	Alt. 4a: Invest in small AM machine	Alt. 4b: Invest in large AM machine
Burner cup	72,60	32,30	72,60	32,30	188,00	188,00
Roast head	82,60	117,00	48,39	88,09	1282,55	1282,55
Wok head	157,00	106,00	87,09	62,89	1109,89	1109,89

Figure 8: Carbon Dioxide of each alternative per component.

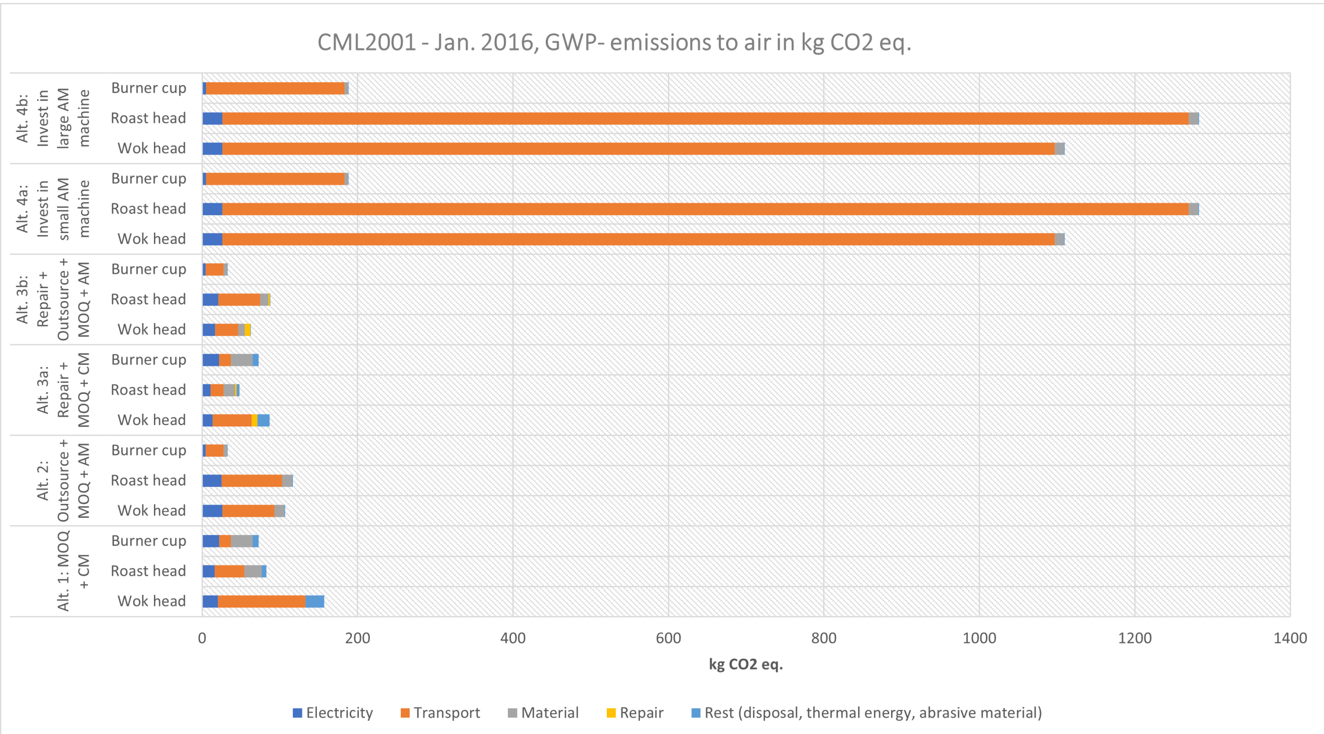


Figure 9: Carbon Dioxide of the materials used in each alternative per component.

6.2 Sensitivity analysis

In this subsection, we performed a sensitivity analysis (SA) to investigate the relations between uncertain cost factors of the LCC and LCA models. Regarding the LCC models, there are in total two factors that are subjected to uncertainty, namely:

- MOQ in alternatives 1 (i.e. MOQ + CM) and 3a (i.e. repair + MOQ + CM). In both alternatives, we used an MOQ of 50, which was an uncertain factor since no agreements have yet been made with the supplier in Slovenia. Thus, we analyzed this aspect for MOQ values of 100 and 150 for each component. Next to that, we will also implement a simple Last Time Buy (Last Time Buy (LTB)) analysis. In an extreme case, the supplier of Slovenia would also decide to stop producing the FV wok burner component and demand the MOQ used for production in the last order, which is an MOQ of 1000 for the roast head and burner cup, and an MOQ of 2500 for the wok head. These are the MOQ's that the suppliers in Turkey and Malaysia use for production, and therefore, we will also do a SA based on this given MOQ (Baneii et al., 2020). This way we analyze when production with AM becomes interesting for ATAG. Incorporating a LTB analysis in alternatives 2, 3b and 4a & 4b would not be practical because the service of the 3D print (outsource) manufacturer will always be available to produce the components per piece or small batches.
- Repair and orders with MOQ of 50/outsource proportions in alternatives 3a (i.e. repair + MOQ + CM) and 3b (i.e. repair + outsource + MOQ + AM). In alternative 3a (and 3b), we used the following proportions: 60% orders from Slovenia (outsource) and 40% repair for the wok heads, 75% orders from Slovenia (outsource), and 25% repair for the burner cups and roast heads. This proportion was uncertain and determined by expert opinions. However, we still want to know if there is at least a 5% deviation from the proportions. Therefore, we analyze this aspect with the following proportions: 35% and 45% for the wok heads, and 20% and 30% repair for the roast heads and burner cups. Thus, we place orders in Slovenia (outsource) 65% and 55% of the time for the wok heads and 80% and 70% of the time for the burner cups and roast heads. Next, to these proportions, we will also analyze what will happen if we decide to repair all the components in alternatives 3a and 3b. Both alternatives have the same repair process, and in both alternatives, only conventional components are repaired.

After the factors in the LCC model are changed we will be able to perform the SA for the LCA models since we will need the output of the LCC models for the LCA models. To be specific, we will need the number of components to produce during the ten years of service for the specific LCA models.

6.2.1 SA - MOQ of 100

Concerning the SA we varied one factor at a time while assuming all other input cost factors are fixed. The results of changing the MOQ value for alternatives 1 and 3a from 50 to 100 are given in Table 7. The NPV for both alternatives 1 and 3a has increased with 3565,38 € and 1685,77 €, respectively, compared to the NPV shown in Table 6. Further, the number of carbon dioxide emissions has also increased with 86 kg CO_2-eq and 39 kg CO_2-eq for alternatives 1 and 3a, respectively. If we had to choose between alternatives 1 and 3a in terms of cost and CO_2 emissions, alternative 3a (i.e. repair + MOQ + CM) would be the best choice. However, if we compare this with the rest of the alternatives then alternative 3b would be a better option in terms of sustainability.

Alternative	***NPV***	***CML2001 - Jan. 2016, GWP- emissions to air in kg CO_2 eq.***
Alt. 1: MOQ + CM	€ 14.624,16	398
Alt. 2: Outsource + MOQ + AM	€ 71.091,38	255
Alt. 3a: Repair + MOQ + CM	€ 11.290,26	247
Alt. 3b: Repair + Outsource + MOQ + AM	€ 46.145,81	183
Alt. 4a: Invest in small AM machine	€ 183.411,19	2580
Alt. 4b: Invest in large AM machine	€ 51.786,36	2580

Table 7: LCC and LCA output with the change of MOQ to 100 in alternatives 1 and 3a.

6.2.2 SA - MOQ of 150

Changing the MOQ value for alternatives 1 and 3a from 50 to 150, we retrieved the NPV's and total amount of emissions in Table 8. The NPV for both alternatives 1 (i.e. MOQ + CM) and 3a (i.e. repair + MOQ + CM) has increased with 3575,08 € and 6544,03 €, respectively, compared to the NPV given in Table 6. Further, the amount of carbon dioxide emission has also increased by 45 kg CO_2-eq. and 159 kg CO_2-eq. for alternatives 1 and 3a sequentially. These amounts are higher compared to the SA of changing the MOQ to 100 because the amount of, e.g. burner cup components we need is not more than 20 components during the 10 years of service. Demanding an MOQ of 150 results in more waste at the end of the life cycle and therefore higher costs and CO_2 emissions. Thus, an MOQ of 100 would be more efficient compared to an MOQ of 150. Again, if we compare alternatives 1 and 3a with the rest of the alternatives then alternative 3b would be a better option in terms of sustainability.

Alternative	***NPV***	***CML2001 - Jan. 2016, GWP- emissions to air in kg CO_2 eq.***
Alt. 1: MOQ + CM	€ 14.633,86	357
Alt. 2: Outsource + MOQ + AM	€ 71.091,38	255
Alt. 3a: Repair + MOQ + CM	€ 16.148,52	367
Alt. 3b: Repair + Outsource + MOQ + AM	€ 46.145,81	183
Alt. 4a: Invest in small AM machine	€ 183.411,19	2580
Alt. 4b: Invest in large AM machine	€ 51.786,36	2580

Table 8: LCC and LCA output with the change of MOQ to 150 in alternatives 1 and 3a.

6.2.3 SA - Last Time Buy

Incorporating a LTB analysis in alternatives 1 and 3a gives us the NPV's and total amount of emissions in Table 9. As we can see is that both the cost and CO_2 emissions have increased drastically in alternatives 1 and 3a. High MOQ's result in higher use of electricity, fuel for transport and raw materials. As a consequence, we have more carbon dioxide footprints and unnecessary excessive stock in the warehouse in Duiven. Further, at the end of the life cycle, a large amount of stock will be leftover and has to be thrown away. In case ATAG has to face this extreme scenario, it would be best to switch to 3D printing. Notice that alternative 3b is the best option to consider in terms of cost and sustainability.

Alternative	***NPV***	***CML2001 - Jan. 2016, GWP- emissions to air in kg CO_2 eq.***
Alt. 1: MOQ + CM	€ 178.018,86	3200
Alt. 2: Outsource + MOQ + AM	€ 71.091,38	255
Alt. 3a: Repair + MOQ + CM	€ 179.533,52	3210
Alt. 3b: Repair + Outsource + MOQ + AM	€ 46.145,81	183
Alt. 4a: Invest in small AM machine	€ 183.411,19	2580
Alt. 4b: Invest in large AM machine	€ 51.786,36	2580

Table 9: LCC and LCA output with Last Time Buy analysis in alternatives 1 and 3a.

In case ATAG ends up in an LTB situation, we analyzed which MOQ in alternatives 1 and 3a is valid to switch to AM. In other words, we look at the point at which a change to the contrary occurs, i.e. alternatives 2 (outsource + MOQ + AM), 3b (i.e. repair + outsource + MOQ + AM), and 4b (invest in a large AM machine). Notice, we did not take 4a (i.e. invest in a small AM machine) into account. The MOQ maximum in this alternative is 1000 and 2500 and these MOQ's resulted in a cost lower than alternative 4a. So, there is no need to make a comparison of the turning point with alternative 4a. First, we look at the MOQ turning point of alternatives 1 (i.e. MOQ + CM) and 3a (i.e. repair + MOQ + CM) compared to alternative 2. The turning point in alternative 1 is between 730 and 730 (see Table 10). So, if we had to switch to AM, i.e. alternative 2, then the MOQ in alternative 1 should be a minimum of 735 for each component, i.e. the wok head, roast head, and burner cup. In other words, alternative 1 is more cost-efficient than alternative 2 if the MOQ in alternative 1 is less than or equal to an MOQ of 730. The turning point in alternative 3a is between 715 and 720 meaning that if we had to switch to AM, i.e. alternative 2, the MOQ in alternative 3a should be a minimum of 720 for each component. When it comes to the amount of emission to air, the AM alternative, i.e. alternative 2, is more sustainable regardless. So, if we 3D print the FV wok burner components, we release 255 kg CO_2 eq. emissions to air during the 10 years of service and if we produce the FV wok burner components with CM, we release 1737 CO_2 eq. emissions (alternative 1 with MOQ 730) to air or 1710 CO_2 eq. emissions (alternative 3a with MOQ 715) to air during the 10 years of service. Thus, switching to 3D printing, i.e. alternative 2, is a more efficient option in terms of costs and sustainability when ATAG is forced in an (extreme) LTB situation.

Alternative	***NPV (LTB)***	*CO_2 (LTB)*	***NPV (MOQ 730)***	*CO_2 (MOQ 730)*	***NPV (MOQ 735)***	*CO_2 (MOQ 735)*
Alt. 1: MOQ + CM	*€ 178.018,86*	*3200*	*€ 70.989,73*	*1737*	*€ 71.475,56*	1749
Alt. 2: Outsource + MOQ + AM	*€ 71.091,38*	*255*				

Alternative	***NPV (LTB)***	*CO_2 (LTB)*	***NPV (MOQ 715)***	*CO_2 (MOQ 715)*	***NPV (MOQ 720)***	*CO_2 (MOQ 720)*
Alt. 3a: Repair + MOQ + CM	*€ 179.533,52*	*3210*	*€ 71.046,91*	*1710*	*€ 71.532,74*	1722
Alt. 2: Outsource + MOQ + AM	*€ 71.091,38*	*255*				

Table 10: Turning point of alternatives 1 and 3a compared to alternative 2.

Now, we will look at the turning point of alternatives 1 and 3a compared to alternative 3b (i.e. repair + outsource + MOQ + AM). The turning point in alternative 1 is between 470 and 475 (see Table 11). Costs are increasing when an MOQ of 475 and above is required in alternative 1 as well as the amount of CO_2 emissions. So, if we had to switch to AM, i.e. alternative 3b, the MOQ in alternative 1 should be a minimum of 475 per component. The turning point in alternative 3a is between 455 and 460. An advantage of an MOQ less than or equal to 455 is that we produce conventionally at a low cost compared to alternative 3b. A disadvantage of an MOQ greater than or equal to 460 is that we produce conventionally at higher costs compared to alternative 3b. So, if we had to switch to alternative 3b, the MOQ in alternative 3a should be greater than or equal to 460. Furthermore, switching to AM, i.e. alternative 3b, is more sustainable compared to alternatives 1 and 3a.

Alternative	***NPV (LTB)***	*CO_2 (LTB)*	***NPV (MOQ 470)***	*CO_2 (MOQ 470)*	***NPV (MOQ 475)***	*CO_2 (MOQ 475)*
Alt. 1: MOQ + CM	*€ 178.018,86*	*3200*	*€ 45.726,76*	*1118*	*€ 46.212,58*	1131,00
Alt. 3b: Repair + Outsource + MOQ + AM	*€ 46.145,81*	*183*				

Alternative	***NPV (LTB)***	*CO_2 (LTB)*	***NPV (MOQ 455)***	*CO_2 (MOQ 455)*	***NPV (MOQ 460)***	*CO_2 (MOQ 460)*
Alt. 3a: Repair + MOQ + CM	*€ 179.533,52*	*3210*	*€ 45.783,93*	*1092*	*€ 46.269,76*	1104
Alt. 3b: Repair + Outsource + MOQ + AM	*€ 46.145,81*	*183*				

Table 11: Turning point of alternatives 1 and 3a compared to alternative 3b.

Lastly, we will look at the turning point of alternatives 1 and 3a compared to alternative 4b (i.e. invest in a large AM machine). The turning point in alternative 1 is between 530 and 535 (see Table 12). So, if we had to switch to AM, i.e. alternative 4b, the MOQ in alternative 1 should be greater than or equal to 535 per component. The turning point in alternative 3a is between 515 and 520 meaning that if we had to switch to alternative 4b then the MOQ in alternative 3a should be a minimum of 520. In other words, alternative 3a would be more cost-efficient than alternative 4b if the MOQ in alternative 3a is less or equal to an MOQ of 515. However, switching to AM, i.e. alternative 4b, is unfortunately not more sustainable compared to alternatives 1 and 3a. So, if we 3D print the FV wok burner components, we release 2580 kg CO_2 eq. emissions to air during the 10 years of service and if we produce the FV wok burner components with CM, we release 1261 CO_2 eq. emissions (alternative 1 with MOQ 530) to air or 1235 CO_2 eq. emissions (alternative 3a with MOQ 515) to air during the 10 years of service. In alternatives 1 and 3a we have one transport movement because we place one last order during the 10 years of service. Next to that, we have more items left at the end of the life cycle. Therefore, we dispose more components which increases the amount of CO_2 emissions.

Alternative	***NPV (LTB)***	*CO_2 (LTB)*	***NPV (MOQ 530)***	*CO_2 (MOQ 530)*	***NPV (MOQ 535)***	*CO_2 (MOQ 535)*
Alt. 1: MOQ + CM	*€ 178.018,86*	*3200*	*€ 51.556,68*	*1261*	*€ 52.042,50*	1274,00
Alt. 4b: Invest in large AM machine	*€ 51.786,36*	*2580*				

Alternative	***NPV (LTB)***	*CO_2 (LTB)*	***NPV (MOQ 515)***	*CO_2 (MOQ 515)*	***NPV (MOQ 520)***	*CO_2 (MOQ 520)*
Alt. 3a: Repair + MOQ + CM	*€ 179.533,52*	*3210*	*€ 51.613,85*	*1235*	*€ 52.099,68*	1247,08
Alt. 4b: Invest in large AM machine	*€ 51.786,36*	*2580*				

Table 12: Turning point of alternatives 1 and 3a compared to alternative 4b.

6.2.4 SA - changing proportions with 5% less

The next factor we performed a sensitivity analysis on is the proportions used in alternatives 3a and 3b. The first proportion we used is 65% order from Slovenia (outsource from the UK) and 35% repair for the wok head, and 80% order from Slovenia (outsource from the UK) and 20% repair for the roast head and burner cup. The results are shown in Table 13. Notice that the NPV for alternative 3a (i.e. repair + MOQ + CM) decreased with 127,96 € compared to the initial values in Table 6. However, the NPV for alternative 3a (i.e. repair + MOQ + CM) increased with 224,37 € compared to the initial values. Further, the carbon dioxide in both alternatives decreased by 2 kg CO_2-eq.

Alternative	***NPV***	***CML2001 - Jan. 2016, GWP- emissions to air in kg CO_2 eq.***
Alt. 1: MOQ + CM	€ 11.058,78	312
Alt. 2: Outsource + MOQ + AM	€ 71.091,38	255
Alt. 3a: Repair + MOQ + CM	€ 9.476,53	206
Alt. 3b: Repair + Outsource + MOQ + AM	€ 46.370,18	181
Alt. 4a: Invest in small AM machine	€ 183.411,19	2580
Alt. 4b: Invest in large AM machine	€ 51.786,36	2580

Table 13: LCA input with the change of proportion: 65% MOQ + CM (or outsource + MOQ + AM) and 35% repair for the wok head, and 80% MOQ + CM (or outsource + MOQ + AM) and 20% repair for the roast head and burner cup.

6.2.5 SA - changing proportions with 5% more

The second proportion we used is 70% order from Slovenia (outsource from the UK) and 30% repair for the roast head and burner cup, and 55% order from Slovenia (outsource from the UK) and 45% repair for the wok head. The results are given in Table 14. Notice that the NPV for alternative 3a (i.e. repair + MOQ + CM) increase with 151,36 €, and the NPV for alternative 3b (i.e. repair + outsource + MOQ + AM) decrease with 2735,47 € compared to the initial values of the NPV and emissions we found in Table 6. The carbon dioxide in alternative 3a (i.e. repair + MOQ + CM) increased by 2 kg CO_2-eq. and alternative 3b (i.e. repair + outsource + MOQ + AM) decreased with 21 kg CO_2-eq. emissions.

Alternative	***NPV***	***CML2001 - Jan. 2016, GWP- emissions to air in kg CO_2 eq.***
Alt. 1: MOQ + CM	€ 11.058,78	312
Alt. 2: Outsource + MOQ + AM	€ 71.091,38	255
Alt. 3a: Repair + MOQ + CM	€ 9.755,85	210
Alt. 3b: Repair + Outsource + MOQ + AM	€ 43.410,34	162
Alt. 4a: Invest in small AM machine	€ 183.411,19	2580
Alt. 4b: Invest in large AM machine	€ 51.786,36	2580

Table 14: LCA input with the change of proportion: 55% MOQ + CM (or outsource + MOQ + AM) and 45% repair for the wok head, and 70% MOQ + CM (or outsource + MOQ + AM) and 30% repair for the roast head and burner cup.

6.2.6 SA - repair all components

Now if we decide to repair all the components during the ASS period in alternatives 3a (i.e. repair + MOQ + CM) and 3b we would get the values in Table 15. Notice that the NPV's and the CO_2 emissions have decreased drastically because there are no costs for long-distance transportation, no production costs, no 3D print costs et cetera. Costs such as cost for abrasive material and labour cost incur when we repair components. These costs are less compared to outsourcing and placing orders in Slovenia.

Alternative	***NPV***	***CML2001 - Jan. 2016, GWP-emissions to air in kg CO_2 eq.***
Alt. 3a: repair + MOQ + CM	€ 5.930,23	76
Alt. 3b: repair + outsource + MOQ	€ 5.930,23	76

Table 15: Repair components in alternatives 3a and 3b.

6.3 Conclusion

Based on the performed analysis, we can conclude that the change in the repair and order/outsource proportions in alternatives 3a and 3b and the MOQ's in alternatives 1 and 3a has a significant impact on the life cycle costs and the carbon dioxide footprint of the FV wok burner components. The most important conclusion based on the analysis is that the cost-saving potential of CM increases in case ATAG decides to repair more components than order them from Slovenia or outsource them. Thus, ATAG has to invest less in outsourcing or placing orders in Slovenia if ATAG increases the proportion to repair components. So, this reduces the production cost and the amount of carbon dioxide footprint.

As mentioned earlier, the right amount of MOQ is not established yet between ATAG and the supplier in Slovenia. If the supplier does not agree with an MOQ of 50 then the second-best option would be a negotiation of an MOQ of 100 since this would result in fewer costs than charging an MOQ of 150. Further, an LTB analysis with an MOQ of 1000 for the roast head and burner cup, and an MOQ of 2500 for the wok head would not be cost-saving for ATAG since the cost and carbon dioxide footprint are exceptionally high. However, decreasing the MOQ in the LTB scenario from 730 downwards leads to cost savings for alternatives 1 (i.e. MOQ + CM) and 3a (i.e. repair + MOQ + CM).

7 Conclusions, discussions and recommendations

This Chapter includes the conclusion, discussions, and recommendations of the research. First, we give the main conclusion of this research in Section 7.1, whereafter we discuss the limitations of the research in Section 7.2. Based on this information, we continue with the recommendations and finally end up with suggestions for further research regarding this project in Section 7.3.

7.1 Conclusion

This research is initiated by ATAG to determine the costs and carbon dioxide footprints of the use of AM and CM processes for the FV wok burner during the ASS period since a redesign of the FV wok burner will be introduced in the market within a year from now. The goal of this research is to construct a model to assess the impact of the use of Additive Manufacturing and Conventional Manufacturing during the After Sales Service (ASS) period, through a Life Cycle Cost analysis and a Life Cycle Assessment of service parts of the FV wok burner at ATAG.

We analyzed six alternatives, where both CM and AM production processes are applied, to determine what ATAG can do to fill demand for the FV wok burner during the ASS. Two alternatives were based on CM processes where orders are placed in Slovenia with an MOQ of 50 i.e. alternatives 1 and 3a. Four alternatives were based on AM processes, where outsourcing (implemented in alternatives 2 and 3b) was an option and printing the FV wok burner components in-house with two different AM machines was another option (implemented in alternatives 4a and 4b). For each alternative, we build separate LCC and LCA models. In each alternative, we also calculated the cost separately for the wok head, roast head and burner cup due to their different material, weight, and shape characteristics. The same holds for the LCA models. For each FV wok burner component, separate flow charts were made to calculate the amount of kg CO_2 eq. emissions.

With the use of the LCA and LCC models to assess the costs and carbon dioxide emissions, we can answer the main research question:

> *Under which condition should ATAG use Additive Manufacturing and Conventional Manufacturing to decrease Life Cycle Cost and environmental impact of service parts during the After Sales Service period?"*

Based on the results of the LCC models, alternative 4a, i.e. investing in a small AM machine, resulted in the highest investment for ATAG. Furthermore, producing the FV wok burner components with AM resulted in high costs due to the long print time. Next to that, this alternative (along with alternative 4b, i.e. invest in a large AM machine) has the highest impact on global warming. In this alternative (along with alternative 4b) parts are ordered per unit which means that the number of transport movements is higher compared to the other alternatives, and therefore leads to more CO_2 emissions.

The two most attractive alternatives for ATAG are alternatives 1, (i.e. MOQ + CM) and 3a (i.e. repair + MOQ + CM) with a cost of 11.058,78 € and 9.604,49 €, respectively. However, the amount of CO_2- emission in alternative 1 (i.e. MOQ + CM) is a slightly higher compared to alternative 3a, i.e. 104 kg CO_2 eq. emissions higher. When it comes to the LCA models, the two most attractive alternatives are alternatives 3a (i.e. repair + MOQ + CM) and 3b (i.e. repair + outsource + MOQ + AM) with 208 kg CO_2 eq. and 183 kg CO_2 eq. emissions, respectively. Alternative 3b has the lowest impact on global warming compared to the rest of the alternatives but is not the most cost-efficient alternative. Further, repairing more service parts during the ASS period also results in lower CO_2-emissions and is, therefore, more environmentally friendly. Thus, if ATAG repair more components than for both CM (i.e. alternative 3a) and AM (i.e. alternative 3b) the costs and CO_2 emissions will reduce to a minimum of 5930 € and 76 kg CO_2 eq. emissions. However, this is not guaranteed because not all components can be repaired during the ASS period. Suppose we change the repair parameter to 99% repair in both alternatives. The cost in alternative 3a becomes 9.822,36 € and in alternative 3b 18.759,53 €, which is twice the investment in alternative 3a. Thus, to decrease the life cycle cost and environmental impact, it is best to invest in CM, i.e. alternative 3a, by changing the repair parameter.

If ATAG is in an exceptional situation, i.e. LTB situation, then both CM and AM are interesting depending on the MOQ. As mentioned before the cheapest AM option is alternative 3b (i.e. repair + outsource + MOQ + AM). We compared this alternative with the CM alternatives, i.e. alternatives 1 (i.e. MOQ + CM) and 3a (i.e. repair + MOQ + CM), to find the turning point. Changing the MOQ parameter in alternative 1 to 475 leads to a cost of 46.213 € and releases 1131 kg CO_2 eq. emissions to air. This cost and amount of emissions are higher than the cost and emissions determined in alternative 3b, i.e. 46.146 € and 183 kg CO_2 eq. emissions. Thus, in this case, ATAG should switch to AM. However, if we change the MOQ parameter to 470 (or lower) in alternative 1 to 470, the costs are decreasing to 45.727 €, which means that this alternative is cheaper compared to alternative 3b. However, the amount of footprint is still higher than alternative 3b. The turning point in terms of emissions would be to choose an MOQ below 50. This MOQ releases fewer emissions to air compared to outsourcing, i.e. alternative 3b. If this would be the case it is best to switch to CM.

In the same way, we determined the turning point analysis between alternatives 3a (i.e. repair + MOQ + CM) and alternative 3b. If we change the MOQ parameter to 460 (or higher) in alternative 3a it is best to switch to AM, i.e. alternative 3b, and if we change the MOQ parameter to 455 (or lower) in alternative 3a it is best to produce the FV wok burner components with CM.

In alternatives 4a (i.e. invest in a small AM machine) and 4b (i.e. invest in a large AM machine), we mentioned that the items are ordered per piece as to how it works currently within ATAG. This resulted in excessive CO_2 emissions (see Figure 9). The amount of CO_2 emissions can reduce drastically if ATAG decides to order the 3D printed parts in batches of 50. In this way, fewer transport movements take place and therefore fewer CO_2 emissions, i.e. 314 kg CO_2 eq. emissions to air are released. However, the cost for producing these items with an MOQ of 50 doubles, i.e. a cost of 363.398 € in alternative 4a and a cost of 107.723 € in alternative 4b, due to the fraction we use to determine the machine cost itself is higher, i.e. we order 350 FV wok burner components while without an MOQ of 50 we order 226 FV wok burner components (see Table 27 in Appendix L). Next to that, we have more components left at the end of the life cycle, i.e. $350 - 226 = 124$ FV wok burner components which also increases storage and disposal cost. Thus, if we switch to AM, it is best to place orders in alternative 4a with an MOQ 2 (which is the maximum that the small machine can produce in a batch) for the wok head and roast head and an MOQ of 1 for the burner cup. This results in a cost of 192.817 € for alternative 4a. If we invest in alternative 4b, it is best to place orders in this alternative with an MOQ 9 (which is the maximum that the large machine can produce in a batch) for the wok head and roast head and an MOQ of 4 for the burner cup and results in a cost of 58.326 €. Next to that, the number of emissions reduces to 1446 kg CO_2 eq. emissions in alternative 4a and 441 kg CO_2 eq. emissions in alternative 4b compared to the initial values we found in Table 6 in Section 6.1.

7.2 Discussion

We used historic data of four years in the forecast model to forecast for 10 years in the future. This was a difficult part to implement within this research since the forecast model does not guarantee that the forecasted values are accurate enough. However, based on the sales pattern of the FV wok burner gas hobs from 2013 until 2021, we could validate that the demand for service components were always around 50 pieces per year.

The MOQ of 50 used in alternatives 1 and 3a was based on an intuitive expectation by experts within ATAG. However, if the supplier in Slovenia does not agree with this MOQ, ATAG must reevaluate the MOQ and agree with Slovenia to fulfil demand during the ASS period. Based on the SA an MOQ of 100 would be the second-best value. If ATAG and the supplier manage to agree with an MOQ of 100, ATAG will still be able to profit from the deal since the costs for both alternatives 1 and 3a will increase with 3565,38 € and 1685,77 €, respectively. Further, the amount of carbon dioxide emission increases with only 86 kg CO_2-eq and 39 kg CO_2-eq for alternatives 1 and 3a, respectively.

The LCC models determined in this research can potentially be used for other service components. However, several (cost) factors in these models will change such as the weight of the component, transport, and the unit purchase price. Next to that, not all alternatives will be relevant for another service component. If we apply the models for a different case study, e.g. a circulation pump which is a component of the dishwasher and made of plastic, we do not have to consider the outsource alternatives since ATAG already has plastic 3D printing machines in their workshop.

Regarding the lack of data issues for the LCA analysis, we chose to use Euro 5 trucks to transport the FV wok burner components in the last two phases of the cradle-to-gate assessment. However, knowing which type of truck and the size of the truck the FV wok burner are transported through the different countries could provide more insight into the environmental impact in the transport phase. In reality, this impact could be less than what we determined.

For outsourcing, we only worked with data from one outsourced manufacturer located in the UK. ATAG can also explore AM outsourcing partners near Duiven. During my final presentation at ATAG, it was suggested to look for outsource partners in China, since they believe that the costs will be cheaper. However, ATAG has to consider the certification process as well. This was out of scope within our research. This way ATAG can identify an outsource manufacturer with the best deal and service. Thus, several aspects should be taken into account if we outsource in Europe or Asia.

7.3 Recommendation

We would recommend assessing the whole LCA from cradle to cradle in future. Next to that, we would also recommend taking each process step as shown in Appendix A. The steps such as the painting process were left out of scope in this research. Painting is known to have harsh chemicals and can have a negative impact on global warming and can therefore also change the amount of CO_2 emissions that we have found within our research. This process was also neglected in the LCC models. We would also recommend taking this into account.

If ATAG considers outsourcing the FV wok burner components, several steps should also be taken into account. Several testing scenarios should take place such as testing whether the FV wok burner fits perfectly within an actual gas hob. Further, the FV wok burner should also be tested on actual gas to see if the material is heat resistant enough and adhere to the requirements in the certification process.

Lastly, I would recommend ATAG to optimize each scenario like finding an outsource partner near Duiven and optimizing batch sizes and ways of transport. The development in the technology of AM processes is increasing due to competition. Furthermore, AM prices may decrease in the next five to 10 years and therefore the cost for outsourcing or 3D printing in-house may decrease as well. Therefore, ATAG should research the right timing to 3D print the FV wok burner components to profit from AM.

References

[1] Aelmans, J. J. M. (2014). Spare parts inventory management by a supplier of a capital good. Eindhoven University of Technology. DOI: https://research.tue.nl/en/studentTheses/spare-parts-inventory-management-by-a-supplier-of-a-capital-good

[2] Alofs, E. (2021). Sales controller at ATAG Benelux. Discussion on Net Present Value and inflation rate.

[3] ATAG Benelux (2010, January 21). Project plan: design Fusion Volcano wok burner. Duiven, Gelderland, Netherlands.

[4] Baneii, S., Spies, T., & Vink, M. (2020). 3D Printen Metaal Fusion Volcano Wok Brander Onderzoeksrapport. Minor ICT Infrastructure & Security Management, Finance and Control at HAN University of Applied Science in Nijmegen

[5] Brugman, D., Goossens, C., & Eppingbroek, B. (2020). Onderzoek naar het 3D-printen van serviceonderdelen binnen ATAG Benelux. Technische Bedrijfskunde Saxion Deventer. Minor Smart Industry at HAN University of Applied Science in Nijmegen.

[6] Chambers, J. C., & Mullick, K. S, & Smith, D. D. (1971). How to Choose the Right Forecasting Technique. Harvard Business Review. 84. 129-138. DOI: https://hbr.org/1971/07/how-to-choose-the-right-forecasting-technique.

[7] Cohen, M., & Agrawal, N., & Agrawal, V. (2006). Winning in the Aftermarket. Harvard Business Review. 84. 129-138.

[8] Coorens, J. J. (2001). Life Cycle Costing. Cost Engineers.

[9] Dhillon, B. S. (2010). Life cycle costing for engineers. Boca Raton: CRC Press.

[10] Ecomii (2021). Cradle-to-Cradle Definition. Retrieved from https://ecomii.com/ecopedia/cradle-to-cradle/.

[11] Ellram, L. M. (1993a). A Framework for Total Cost of Ownership. International Journal of Logistics Management, 4(2), 49-60.

[12] Ellram, L. M. (1993b). Total Cost of Ownership: Elements and Implementation. International Journal of Purchasing and Materials Management, 29: 2-11. DOI: https://doi.org/10.1111/j.1745-493X.1993.tb00013.x.

[13] Ellram, L. M., & Siferd, S. P. (1998). Total cost of ownership: A key concept in strategic cost management decisions. Journal of Business Logistics, 19(1), 55-84.

[14] Embleton, P.R. and Wright, P.C. (1998), "A practical guide to successful outsourcing", Empowerment in Organizations, Vol. 6 No. 3, pp. 94-106. DOI: https://doi.org/10.1108/14634449810210832

[15] EOS (2021a). Metal 3D Printing - The DMLS Technology. Retrieved from: https://www.eos.info/en/industrial-3d-printing/additive-manufacturing-how-it-works/dmls-metal-3d-printing?utm_source=google&utm_medium=cpc&utm_campaign=generic&utm_value=wyn&gclid=CjwKCAjwgviIBhBkEiwA10D2j1OCADGbkY0bWXNX-edBNWP1MeOEQqa4aRhSEpqxJYSj22nvQeHL2xoCbs4QAvD_BwE

[16] EOS (2021b). Online webinar: "From zero to hero - Additive Manufacturing with Metals". Speaker: Fabian Stöver, EOS GmbH.

[17] Esmaeili, N., Teimoury, E., & Pourmohammadi, F. (2021). A scenario-based optimization model for planning and redesigning the sale and after-sales services closed-loop supply chain. RAIRO - Operations Research, 55. DOI: 10.1051/ro/2020131

[18] Fixson, S. K. (2004). Assessing product architecture costing: Product life cycles, allocation rules, and cost models. In ASME 2004 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (pp. 857-868). American Society of Mechanical Engineers.

[19] Gal, L. (2021). Employee customer contact team retail at ATAG Benelux. Discussion on warranty service.

[20] Gibson, I., Rosen, D. W., Stucker, B. (2010). Additive manufacturing technologies: Rapid prototyping to direct digital manufacturing. New York: Springer.

[21] Greene, L. E., & Shaw, B. L. (1990). The steps for successful life cycle cost analysis. In Aerospace and Electronics Conference, 1990. NAECON 1990., Proceedings of the IEEE 1990 National (pp 1209- 1216). IEEE.

[22] Gunnewijk, X. (2021). Manager R & D at ATAG Benelux. Discussion on re-design FV wok burner and new production process.

[23] Herngreen, J. (2021). Model maker at ATAG Benelux. Discussion on 3D printing machines and blasting cabine.

[24] Hilderink, D. (2021). Quality engineer at ATAG Benelux. Discussion on complaints from consumers and repair of failed service components.

[25] IEA (2018). Report extract 2020 Regional focus: Southeast Asia. Retrieved from: https://www.iea.org/reports/electricity-market-report-december-2020/2020-regional-focus-southeast-asia

[26] ISO 14040 (2006). Environmental management — Life cycle assessment — Principles and framework

[27] Kleinhaarhuis, M. (2021). Employee purchasing parts at ATAG Benelux. Several discussion on purchasing service components and after sales service.

[28] Kotabe, M. (1992). Global sourcing strategy: R&D, manufacturing, and marketing interfaces. New York:Quorum.

[29] Kruisselbrink, E. (2021). Manager repair service. Several discussions on repair services and repair logistic.

[30] Manda, Varaprasadarao & Kampurath, Vidhu & Chaitanya, Msrk. (2018). 3D Printing and its Effect on Outsourcing: A Study of the Indian Aircraft Industry. Journal of Aerospace Technology and Management. 10. DOI: 10.5028/jatm.v10.862.

[31] Moore, J. R. (1971). Forecasting and scheduling for past-model replacement parts.Management Science Series B-Application, 18 (4), 200 - 213.

[32] Murthy, D. N. P., Solem, O., & Roren, T. (2004). Product warranty logistics: Issues and challenges. European Journal of Operational Research 156 (1) 110-126. DOI: //doi.org/10.1016/S0377-2217(02)00912-8

[33] Noorel, G. (2021). Financial controller at ATAG Benelux. Discussion on Net Present Value and inflation rate.

[34] Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W. P., Suh, S., Weidema, B.P., Pennington, D.W. (2004). Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications, Environment International. Pages 701-720, ISSN 0160-4120, Retrieved from: https://doi.org/10.1016/j.envint.2003.11.005.

[35] Saade, Marcella & Yahia, Ammar & Amor, Ben. (2019). How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies. Journal of Cleaner Production. 244. 118803. DOI: 10.1016/j.jclepro.2019.118803.

[36] Saccani, N., & Johansson, P., & Perona, M. (2007). Configuring the after-sales service supply chain: A multiple case study. International Journal of Production Economics. 110. 52-69. DOI: 10.1016/j.ijpe.2007.02.009.

[37] Schoenmaker, A. (2021). Senior product manager at ATAG Benelux. Discussion on sales and how a new product goes into production.

[38] Silver, E. A., Pyke, D. F., & Thomas, D. J. (2017). Inventory and production management in supply chains.

[39] Spickova, M., & Myskova, R. (2015). Costs Efficiency Evaluation using Life Cycle Costing as Strategic Method, Procedia Economics and Finance, DOI: https://doi.org/10.1016/S2212-5671(15)01638-X.

[40] Straalman, J. (2021). Buyer at ATAG Benelux. Discussion on purchasing and CM production process of the components of FV wok burner.

[41] Sullivan, W. G., Wicks, E. M., Koelling, C. P., & Sharma, A. (2014). Engineering economy (Sixteenth edition, Global). Pearson.

[42] ten Pas, H. (2021). Sales Manager AM Equipment & Supplies at Bender Additive Manufacturing B.V.. Presentation about EOS and how the FV can be 3D printed and several discusion on machine and material price. Presentation at company ATAG in Duiven on 6^{th} of July 2021.

[43] Tevhide, A. F., Ezgi, A. & Güvenç, Ş. (2017). After-sales services network design of a household appliances manufacturer, Journal of the Operational Research Society, 68:9, 1056-1067. DOI: 10.1057/s41274-016-0142-y

[44] UNEP - United Nations Environment Programme (2005). Life Cycle Approaches: The road from analysis to practice. A publication of: UNEP/ SETAC Life Cycle Initiative. Available at: https://www.lifecycleinitiative.org/starting-life-cycle-thinking/benefits/.

[45] UNEP - United Nations Environment Programme (2012). Greening the Economy through Life Cycle Thinking Ten Years of the UNEP/SETAC Life Cycle Initiative. Available at: http://www.unep.fr/shared/publications/pdf/DTIx1536xPA-GreeningEconomythroughLifeCycleThinking.pdf.

[46] United Nations (UN) (2021). The Paris Agreement. Retrieved from: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[47] van Vliet, J. (2021). Mechanical engineer at ATAG Benelux. Discussion on re-design FV wok burner, alternatives for the FV wok burner, and EOS.

[48] van Os, J. (2021). Innovation manager at ATAG Benelux and main supervisor at ATAG. Several discussions on- and off-line.

[49] Versteeg, J. (2021). Product engineer at ATAG Benelux. Discussion on re-design FV wok burner and repair of failed service components, and alternatives for the FV wok burner.

[50] Walter, M. (2021). Logistics Manager at ATAG Benelux. Discussion on After Sales Service & warehouse stock cost.

[51] Wennington, M. (2021). Business Development Manager at 3T additive manufacturing. Discussion on the amount of pieces that can be printed on certain machines.

[52] Zijm, H., Knofius, N., & van der Heijden, M. (2018). Additive Manufacturing and its impact on the supply chain. In H. Zijm, M. Klumpp, A. Regatierri, & S. Heragu (Eds.), Operations, Logistics and Supply Chain Management (1 ed.). (Lecture Notes in Logistics). Springer. Retrieved from: https://doi.org/10.1007/978-3-319-92447-2_23

Appendices

A Conventional manufacturing production process of the FV wok burner

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B Different types of gas hobs at ATAG

In Figure 10 several gas hobs that ATAG sells can be found. Notice that in the figure there is a mixture of the European and Chinese variant FV wok burner. The wok burner is used in products under the brands ATAG and ASKO. The European wok variant is sold in Europe, Russia, Asia, Oceania, Africa and South America. Outside the Benelux, this is sold under the ASKO brand i.e. the Chinese variant.

Figure 10: Different types of gas hobs with the FV wok burner.

1. Sold by ATAG & ASKO.
2. Sold by ATAG & ASKO.
3. Sold by ATAG & ASKO.
4. Sold by ASKO i.e. the Chinese variant.
5. Sold by ATAG & ASKO.
6. Sold by ATAG & ASKO.
7. Sold by ATAG & ASKO.

C LCC framework

A detailed description of each step is described below:

- **Step 1: Identify the context of the analysis.** Why does the organization want to use an LCC? Determining the context of the analysis is important to determine what result the analysis should yield.
- **Step 2: Determine the purchases for which the analysis is performed.** Since an LCC analysis is very labour-intensive, the analysis is only applied to products where the cost reduction potential is greater than the cost of the modelling.
- **Step 3: Set up an LCC team.** For a LCC analysis, data must often be collected manually from all departments within an organization. For that reason, a LCC team should preferably consist of members of different disciplines. An additional advantage is that in this way all departments are involved in the LCC implementation. It is also important to appoint a project leader who is responsible for steering the project in the right direction, and also the one who makes the assumptions and continues to test underlying formulas for the product's maintainability in the future.
- **Step 4: Identify relevant costs.**
  - Cost identification. To identify all costs, Ellram (1993b) proposes to first identify all activities that describe the entire lifespan of a product. Afterwards, for each activity, we determine which cost elements these activities consist of.
  - Selecting relevant costs. In the LCC analysis, consideration must be made as to which costs are worth investigating because time and resources are limited. A balance has to be found between the exactness and usability of the model versus the cost of modelling.
  - Collecting cost data. In this phase, the actual cost data must be determined. Depending on the existing administrative system, any information must be obtained manually from different functions in the organization.
  - Document. To be able to apply the LCC analysis in the future, one should document from where all the cost information is retrieved from. Furthermore, all assumptions and underlying formulas and algorithms should be recorded so that the analysis is as transparent as possible. In this way, the project leader (see step 3) can review the documentation from time to time and test whether these assumptions are still maintainable (such as salaries, energy prices, et cetera.).
- **Step 5: Verification of the model.** In this phase, the LCC analysis is verified. All data is processed in the model and checked whether the results are logical that follows from the documented information (origin of the data, assumptions, formulas and algorithms). If necessary, one should return to step 4.
- **Step 6: Validate the model.** During the validation of the model, we check whether the results are valid and useful for the purpose for which the model was prepared. Similar to the verification step (step 5). During the validation of the model, it may be necessary to return to step 4. Note the difference between verification and validation: verification is checking the model in itself while validation is the results of the model are compared with reality. The outcome, in reality, could be unknown when they are in the future. The

validation of the model is therefore based on historical data (if any). In the validation phase, a sensitivity analysis can also be performed to see how a change in one of the cost elements affects the outcome.

- **Step 7: Link LCC model to other systems.** According to Ellram (1993a), there are three systems to which LCC is linked: evaluation, education and computer systems.
  - Evaluation systems: During the use of a product, the actual costs are compared with the predetermined costs in the LCC analysis to evaluate the system and personnel performance. This information can be used by management to adjust the maintenance strategy and process control in the right way.
  - Education systems: Staff from different disciplines need to be familiar with the LCC method to be able to deliver relevant information for a LCC analysis and interpret results appropriately.
  - Computer systems: For a broad implementation of LCC, computer systems are a good support to collect relevant LCC data. As long as the registration of a necessary LCC data is not automated, the LCC analysis stays a labour-intensive process because all information is obtained manually. In addition, the accuracy of a LCC analysis is not optimal because cost estimates cannot be based on historical data, but on expert estimates.
- **Step 8: Update, check and manage the model.** With the LCC model, we must regularly check whether the origin of the data, assumptions, formulas and algorithms are still maintainable. In addition, we check whether the LCC model still achieves its objectives.

D LCA framework

For this research, the paper by UNEP (2005) is used, where the LCA contains four methodological phases, namely:

1. **Goal and scope definition**. In the first step, the goal and scope definition should be defined and a description of the process and the context should be established. This includes an exact formulation of what we are going to analyze, and how this analysis is carried out. Furthermore, the system boundaries, i.e. an LCA variant as explained earlier, are chosen and argued.

2. **Life Cycle Inventory Analysis**. A Life-Cycle Inventory is a process of quantifying all the inputs and outputs of (industrial) processes that occur during the life cycle of a product such as energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other processes. The next step is to collect data on each process. This data is retrieved via scientific literature or published data (e.g. databases). The most important processes are selected for further analysis after data is collected on all processes. Since this step is very time-consuming, it is better to reduce the scope of the analysis so that the LCA can be reduced to a more manageable size. However, this can lead to a risk that influences the results. In the last step of a Life Cycle Inventory, data is processed, in which all inputs and outputs have been translated into environmental inputs and outputs.

3. **Life Cycle Impact Assessment**. The result of step 2 is used in this step, the Life Cycle Impact Assessment (LCIA). In the Life Cycle Impact Assessment, the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in step 2 are assessed. These inputs and outputs are classified according to the kind of environmental problem to which they contribute such as acidification, global warming, and human toxicity. In the next step, the characterisation step is determined. Characterization calculates the relative contribution of resources and emissions (inventory) for each type of environmental impact (impact categories) and is expressed as a category indicator. So, the LCIA identifies and evaluates the amount and significance of the potential environmental impacts arising from the LCI, where the inputs and outputs are first assigned to impact categories and their potential impacts quantified according to characterization factors.

4. **Life Cycle Interpretation**. Then this last step, the results of steps 2 & 3 are evaluated. This involves the overall comparison of the environmental problems. This is done via six interpretation processes, namely: (1) consistency check, (2) completeness check, (3) contribution analysis, (4) perturbation analysis, (5) sensitivity and uncertainty analysis, (6) conclusion and recommendations.

E Production steps for Additive Manufacturing

In the paper by Gibson, et al. (2010), the author explained that every AM method involves at least eight process steps. These are as follows:

- **Step 1: Make CAD model.** The first step is to describe the external geometry a CAD modelling software. The output is a 3D solid or surface representation.
- **Step 2: Conversion from CAD to STL.** In this step, the CAD model is converted in an STL file format which is used on an AM machine.
- **Step 3: Transfer to AM machine.** In step 3 the STL file is transferred to the AM machine by manipulating the file to establish the right size, position, and orientation for the building.
- **Step 4: Machine setup.** The next step is to set up the AM machine according to the build parameters. Build parameters are an energy source, layer thickness, timings, et cetera.
- **Step 5: Building process.** During the building process, monitoring is necessary now and then to ensure no errors occurs. Next to that, the building process is an automated process that does not require a lot of supervision.
- **Step 6: Removal process.** After the part is fully printed, it has to be removed from the printing machine. Some AM machines give a sign/alarm when to remove the part to ensure that temperatures are sufficiently low.
- **Step 7: Post processing.** After the part is removed from the machine, most of the time an additional cleaning is required. For example, parts may have supporting structures that have to be removed.
- **Step 8: Application.** In the last step of the AM process, some parts require a painting to give a polished finish. Next to that, some parts have to be assembled with other components to form a final part.

F Machine selection for alternative 4

In previous research, Baneii et al. (2020) certain specifications were mentioned when selecting a machine. However, it is not clear which AM machine is useful to 3D print the FV wok burner. Therefore, a selection of AM machines is made based on two critical aspects, i.e. material and production size. Further, we assumed to invest in the 3D print machine of EOS GmbH in Germany since a good amount of data was publicly addressed and could be used as input to calculate certain cost factors. Further, the machines that are chosen are suitable for large manufacturers. Notice that in Table 16 the 3D printing machines M290, and M400-4 are the most appropriate that can print the FV wok burner.

Specification | Machine type	M100	M290	M300-4	M400	M400-4
Material					
Stainless Steel 316L	✓	✓	x	x	✓
Size					
Production size: 45,6x49,2x127	x	✓	x	x	✓

Table 16: Machine selection for alternative 4.

G Forecast calculation

The forecasted amount is from January 2022 until December 2032. Notice that this is more than ten years of service because demand is not known from November 2021 until the sale of the "old" FV wok burner will stop, i.e. estimated at the beginning of 2023. Until October 2021, the number of components that were used for the wok head was 18, 21 for the roast head, and 0 for the burner cup. For one year, we divided the amount used by 10 months which gives us the average amount per month. We then added the average value of two months (i.e. November and December) on top of the data available until October 2021 to get an estimated value for the whole year of 2021. Furthermore, we correlated the data and made the forecast calculation based on the total amount of the wok head, roast head, and burner cup.

The demand has the following linear trend equation:

$$D_t = a + bt$$

Where D_t is the correlated demand in year t and a and b the intercept and slope, respectively. For future values we want fit the values according to the line. Thus, the forecast model is as follows:

$$\hat{D}_t = \hat{a} + \hat{b}t$$

The values of the parameters $\hat{a}$ and $\hat{b}$ are calculated as follows:

$$\hat{b} = \frac{\sum_{t=1}^{n} tD_t - \left(\frac{n+1}{2}\right)\sum_{t=1}^{n} D_t}{n(n^2-1)/12}$$

$$\hat{a} = \sum_{t=1}^{n} x_t/n - \hat{b}(n+1)/2$$

Where n is the number of periods already known. The forecast horizon is ten years thus, $n = 10$. In Excel, this is done by using the INTERCEPT and SLOPE functions. Further, since we cannot order/produce parts per half or quarter piece we rounded the forecast numbers up to integers. Afterwards, the forecast amount is divided over the wok head, roast head, and burner cup by taking the percentage value. The sum of all the components from 2018 until 2021 is 208. 46% comes from the wok head, 47% from the roast head, and 7% from the burner cup. Thus, these percentages or taken to determine the forecast separate for each component. The forecast result is given in Table 17. For the LCC (and LCA) calculation, we used the demand forecast period from January 2023 until December 2032 for the six alternatives.

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Wok head	28	23	23	22											
Roast head	27	23	20	26											
Burner cup	0	15	0	0											
Total	55	61	43	48											
$\hat{a}$	61,5														
$\hat{b}$	-3,9														
Forecast	58	54	50	46	42	39	35	31	27	23	19	15	11	7	3
Wok head	27	26	24	22	20	19	17	15	13	11	9	7	6	4	2
Roast head	27	26	24	22	20	19	17	15	13	11	9	7	6	4	2
Burner cup	5	4	4	4	4	3	3	3	2	2	2	2	1	1	1

Table 17: Forecast from January 2022 until December 2032.

H LCC calculation of alternative 1: MOQ + CM

The costs that occur during this alternative are mainly procurement cost, disposal cost, and an additional marginal cost. In this alternative, orders are placed with an MOQ throughout the ten years of service. To determine when to order, we applied a simple Material Requirements Planning (MRP). The MRP system is a planning and decision-making tool used in the production process which analyses the need to order goods, based on a forecast analysis. As soon as the inventory level is below 0 an order is placed. It is assumed to place the order at the beginning of the year. Therefore, we also ordered a batch of 50 pieces in the first year to fulfil the forecast demand in year 1 (i.e. January 2023).

Procurement cost

The procurement cost is the cost of the forecasted number of parts that ATAG needs for the next ten years of service multiplied by the purchase price that Slovenia charges. The purchase price is calculated as:

$$ProcurementCost_{WH}(t) = Total_{WH}(t) * PurchasePrice_{WH}(t)$$
$$ProcurementCost_{RH}(t) = Total_{RH}(t) * PurchasePrice_{RH}(t)$$
$$ProcurementCost_{BC}(t) = Total_{BC}(t) * PurchasePrice_{BC}(t)$$

Where $Total_{WH}$ is the number of wok heads that should be ordered in year t and $Total_{RH}$ the number of roast heads that should be ordered in year t and $Total_{BC}$ the number of burner cups that should be ordered in year t. The amount of components that should be ordered is based on the forecast method explained in Section 4.1. Because we assumed a low MOQ, i.e. 50, we also assumed that the purchase price is increased by 50%. The current purchase price and the increased purchase price for each FV wok burner service component are given in Table X.

—Confidential—

Inflation cost

—Confidential—

Additional marginal cost

The additional margin of 4% that ATAG adds on the procurement price is calculated as:

$$Cost\ with\ additional\ 4\%\ margin_{WH}(t) = \Big(ProcurementCost_{WH}(t) \times 4\%\Big) + ProcurementCost_{WH}(t)$$

$$Cost\ with\ additional\ 4\%\ margin_{RH}(t) = \Big(ProcurementCost_{RH}(t) \times 4\%\Big) + ProcurementCost_{RH}(t)$$

$$Cost\ with\ additional\ 4\%\ margin_{BC}(t) = \Big(ProcurementCost_{BC}(t) \times 4\%\Big) + ProcurementCost_{BC}(t)$$

Where t is the service year. On top of this 4% margin ATAG adds a 20% margin, which is calculated as:

$$\begin{aligned} Cost\ with\ additional\ 20\%\ margin_{WH}(t) &= \Big(Cost\ with\ additional\ 4\%\ margin_{WH}(t) \times 20\%\Big) \\ &\quad + Cost\ with\ additional\ 4\%\ margin_{WH}(t) \\ Cost\ with\ additional\ 20\%\ margin_{RH}(t) &= \Big(Cost\ with\ additional\ 4\%\ margin_{RH}(t) \times 20\%\Big) \\ &\quad + Cost\ with\ additional\ 4\%\ margin_{RH}(t) \\ Cost\ with\ additional\ 20\%\ margin_{BC}(t) &= \Big(Cost\ with\ additional\ 4\%\ margin_{BC}(t) \times 20\%\Big) \\ &\quad + Cost\ with\ additional\ 4\%\ margin_{BC}(t) \end{aligned}$$

Disposal cost

Often times it is so that in reality too few or too many items are order. In our case we only know how many items are ordered too few based on a simple MRP calculation. The yield that ATAG can get from scrap is €1,45 for aluminium and €3,70 for brass.[1] The scrap yeild is calculated as:

$$Scrap\ yield_{WH} = N_{WH} \times scrap\ price_{WH} \times component\ weight_{WH}$$

$$Scrap\ yield_{RH} = N_{RH} \times scrap\ price_{RH} \times component\ weight_{RH}$$

$$Scrap\ yield_{BC} = N_{BC} \times scrap\ price_{BC} \times component\ weight_{BC}$$

Where N_k is the number of components of type k, i.e. $k = WH, RH, BC$ that are leftover by the end of year 10. The value of N_k is determined with the MRP calculation. To determine the cash flow of alternative 1 (i.e. MOQ + CM), the total cash outflow is subtracted by the total inflow. Afterwards, the NPV is determined. The results are given in Table X.

[1] https://www.metalimex.nl/prijs-berekenen

I LCC calculation alternative 2: outsource + MOQ + AM

All the data in this alternative is retrieved from an outsource manufacturer, 3T additive manufacturing, based in the UK. Next to that, the orders can only be placed in batches of 9 for the wok, and roast heads and 4 for the burner cups. Here, we also applied a simple MRP calculation to determine when and how much to order. As soon as the inventory level is below or equal to zero an order is placed.

Outsource purchase price

The outsource purchase price is related to the costs of internal production. The outsource purchase price is divided into several costs factors, namely material cost, print cost, heat treatment cost, and post-processing cost. The shipment cost is also based on the amount printed per batch. The transport cost that the supplier in the UK uses is €40,82 per shipment.[2] Thus, the outsource purchase price is calculated as:

$$\begin{aligned} OutsourcePurchasePrice_{WH}(t) = {} & \textit{material cost}_{WH}(t) + \textit{print cost}_{WH}(t) + \textit{heat treatment cost}_{WH}(t) \\ & + \textit{post processing cost}_{WH}(t) + \textit{transportation cost}_{WH}(t) \end{aligned}$$

$$\begin{aligned} OutsourcePurchasePrice_{RH}(t) = {} & \textit{material cost}_{RH}(t) + \textit{print cost}_{RH}(t) + \textit{heat treatment cost}_{RH}(t) \\ & + \textit{post processing cost}_{RH}(t) + \textit{transportation cost}_{RH}(t) \end{aligned}$$

$$\begin{aligned} OutsourcePurchasePrice_{BC}(t) = {} & \textit{material cost}_{BC}(t) + \textit{print cost}_{BC}(t) + \textit{heat treatment cost}_{BC}(t) \\ & + \textit{post processing cost}_{BC}(t) + \textit{transportation cost}_{BC}(t) \end{aligned}$$

The procurement price is calculated as:

$$ProcurementCost_{WH}(t) = TotalBatches_{WH}(t) * OutsourcePurchasePrice_{WH}(t)$$

$$ProcurementCost_{RH}(t) = TotalBatches_{RH}(t) * OutsourcePurchasePrice_{RH}(t)$$

$$ProcurementCost_{BC}(t) = TotalBatches_{WH}(t) * OutsourcePurchasePrice_{BC}(t)$$

Where $TotalBatches_{WH}$ is the number of wok head batches that are outsourced in year t, $TotalBatches_{RH}$ is the number of roast head batches that should be outsourced in year t, and $TotalBatches_{RH}$ is the number of burner cup batches that should be outsourced in year t.

Price reduction

Further, when the outsource company sees component/order values over £100.000 they begin production pricing. That does not necessarily mean the full £100.000 worth of components needs to be delivered at the same time. We can opt for split shipments, but it allows the outsource company to book time appropriately. Thus, depending on the value of the order, the outsource manufacturer could look at a 10-20% reduction. In this case, we took the average, so a price reduction of 15%.

[2] Data retrieved from an outsource manufacturer 3T, additive manufacturing, based in the UK.

Additional marginal cost

As mentioned before, ATAG adds a 4% (and 20%) margin on the procurement price. However, the 3D manufacturing company already incurred a price for transport from the UK to Duiven. Since it is not sure if the margin of 4% will drop in the future, we assume to keep this as it is. So, the 4% margin is calculated as:

$$\begin{aligned} \textit{Cost with additional 4\% margin}_{WH}(t) = &\Big(\textit{ProcurementCost}_{WH}(t) \times 4\%\Big) \\ &+ \textit{ProcurementCost}_{WH}(t) \end{aligned}$$

$$\begin{aligned} \textit{Cost with additional 4\% margin}_{RH}(t) = &\Big(\textit{ProcurementCost}_{RH}(t) \times 4\%\Big) \\ &+ \textit{ProcurementCost}_{RH}(t) \end{aligned}$$

$$\begin{aligned} \textit{Cost with additional 4\% margin}_{BC}(t) = &\Big(\textit{ProcurementCost}_{BC}(t) \times 4\%\Big) \\ &+ \textit{ProcurementCost}_{BC}(t) \end{aligned}$$

On top of this 4% margin ATAG adds a 20% margin, which is calculated as:

$$\begin{aligned} \textit{Cost with additional 20\% margin}_{WH}(t) = &\Big(\textit{Cost with additional 4\% margin}_{WH}(t) \times 20\%\Big) \\ &+ \textit{Cost with additional 4\% margin}_{WH}(t) \end{aligned}$$

$$\begin{aligned} \textit{Cost with additional 20\% margin}_{RH}(t) = &\Big(\textit{Cost with additional 4\% margin}_{RH}(t) \times 20\%\Big) \\ &+ \textit{Cost with additional 4\% margin}_{RH}(t) \end{aligned}$$

$$\begin{aligned} \textit{Cost with additional 20\% margin}_{BC}(t) = &\Big(\textit{Cost with additional 4\% margin}_{BC}(t) \times 20\%\Big) \\ &+ \textit{Cost with additional 4\% margin}_{BC}(t) \end{aligned}$$

Disposal cost

The yield that ATAG can get from scrap is €1,40 for stainless steel.[3] The scrap yeild is calculated as:

$$\textit{Scrap yield}_{WH} = N_{WH} \times \textit{scrap price}_{WH} \times \textit{component weight}_{WH}$$

$$\textit{Scrap yield}_{RH} = N_{RH} \times \textit{scrap price}_{RH} \times \textit{component weight}_{RH}$$

$$\textit{Scrap yield}_{BC} = N_{BC} \times \textit{scrap price}_{BC} \times \textit{component weight}_{BC}$$

Where N_k is the number of components of type k, i.e. $k = WH, RH, BC$ that are leftover by the end of year 10. The value of N_k is determined with the MRP calculation. To determine the cash flow of alternative 2 (i.e. outsource + MOQ + AM), the total cash outflow is subtracted by the total inflow. Afterwards, the NPV is determined. The results are given in Table 18.

[3]https://www.metalimex.nl/prijs-berekenen

Discount rate	**10%**

Year	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**
t	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Cash outflow										
Costs for Wok Head (WH)										
Forecast in year i	*19*	*17*	*15*	*13*	*11*	*9*	*7*	*6*	*4*	*2*
Amount left from previous year		*8*	*0*	*3*	*8*	*6*	*6*	*8*	*2*	*7*
Amount to order in year i		*9*	*15*	*10*	*3*	*3*	*1*	*-2*	*2*	*-5*
Parts per batch produced (MOQ per batch)	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*
Amount of batches to order	*3*	*1*	*2*	*2*	*1*	*1*	*1*	*0*	*1*	*0*
Material cost per batch	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*
Print cost per batch	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*
Heat treatment cost per batch	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*
Post processing cost per batch	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*
Shippinng cost per batch	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*
Cost for WH excl. 4% margin	€ 7.788,18	€ 2.596,06	€ 5.192,12	€ 5.192,12	€ 2.596,06	€ 2.596,06	€ 2.596,06	€ -	€ 2.596,06	€ -
Price reduction of 15% from outsource company	€ 6.619,95	€ 2.206,65	€ 4.413,30	€ 4.413,30	€ 2.206,65	€ 2.206,65	€ 2.206,65	€ -	€ 2.206,65	€ -
Cost with additional margin of 4%	*€ 6.884,75*	*€ 2.294,92*	*€ 4.589,83*	*€ 4.589,83*	*€ 2.294,92*	*€ 2.294,92*	*€ 2.294,92*	*€ -*	*€ 2.294,92*	*€ -*
WH Cost per year incl. 20% margin	**€ 8.261,70**	**€ 2.753,90**	**€ 5.507,80**	**€ 5.507,80**	**€ 2.753,90**	**€ 2.753,90**	**€ 2.753,90**	**€ -**	**€ 2.753,90**	**€ -**
Costs for Roast Head (RH)										
Forecast in year i	*19*	*17*	*15*	*13*	*11*	*9*	*7*	*6*	*4*	*2*
Amount left from previous year		*8*	*0*	*3*	*8*	*6*	*6*	*8*	*2*	*7*
Amount to order in year i		*9*	*15*	*10*	*3*	*3*	*1*	*-2*	*2*	*-5*
Parts per batch produced (MOQ per batch)	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*	*9*
Amount of batches to order	*3*	*1*	*2*	*2*	*1*	*1*	*1*	*0*	*1*	*0*
Material cost per batch	*€ 487,57*	*€ 487,57*	*€ 487,57*	*€ 487,57*	*€ 487,57*	*€ 487,57*	*€ 487,57*	*€ 487,57*	*€ 487,57*	*€ 487,57*
Print cost per batch	*€ 1.388,87*	*€ 1.388,87*	*€ 1.388,87*	*€ 1.388,87*	*€ 1.388,87*	*€ 1.388,87*	*€ 1.388,87*	*€ 1.388,87*	*€ 1.388,87*	*€ 1.388,87*
Heat treatment cost per batch	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*
Post processing cost per batch	*€ 963,26*	*€ 963,26*	*€ 963,26*	*€ 963,26*	*€ 963,26*	*€ 963,26*	*€ 963,26*	*€ 963,26*	*€ 963,26*	*€ 963,26*
Shippinng cost per batch	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*
Cost for RH excl. 4% margin	€ 9.166,35	€ 3.055,45	€ 6.110,90	€ 6.110,90	€ 3.055,45	€ 3.055,45	€ 3.055,45	€ -	€ 3.055,45	€ -
Price reduction of 15% from outsource company	€ 7.791,40	€ 2.597,13	€ 5.194,27	€ 5.194,27	€ 2.597,13	€ 2.597,13	€ 2.597,13	€ -	€ 2.597,13	€ -
Cost with additional margin of 4%	*€ 8.103,05*	*€ 2.701,02*	*€ 5.402,04*	*€ 5.402,04*	*€ 2.701,02*	*€ 2.701,02*	*€ 2.701,02*	*€ -*	*€ 2.701,02*	*€ -*
RH Cost per year incl. 20% margin	**€ 9.723,66**	**€ 3.241,22**	**€ 6.482,44**	**€ 6.482,44**	**€ 3.241,22**	**€ 3.241,22**	**€ 3.241,22**	**€ -**	**€ 3.241,22**	**€ -**
Costs for Burner cup (BC)										
Forecast in year i	*3*	*3*	*3*	*2*	*2*	*2*	*2*	*1*	*1*	*1*
Amount left from previous year		*1*	*2*	*3*	*1*	*3*	*1*	*3*	*2*	*1*
Amount to order in year i		*2*	*1*	*-1*	*1*	*-1*	*1*	*-2*	*-1*	*0*
Parts per batch produced (MOQ per batch)	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*
Amount of batches to order	*1*	*1*	*1*	*0*	*1*	*0*	*1*	*0*	*0*	*0*
Material cost per batch	*€ 818,81*	*€ 818,81*	*€ 818,81*	*€ 818,81*	*€ 818,81*	*€ 818,81*	*€ 818,81*	*€ 818,81*	*€ 818,81*	*€ 818,81*
Print cost per batch	*€ 3.238,88*	*€ 3.238,88*	*€ 3.238,88*	*€ 3.238,88*	*€ 3.238,88*	*€ 3.238,88*	*€ 3.238,88*	*€ 3.238,88*	*€ 3.238,88*	*€ 3.238,88*
Heat treatment cost per batch	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*
Post processing cost per batch	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*
Shippinng cost per batch	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*
Cost for BC excl. 4% margin	€ 5.171,39	€ 5.171,39	€ 5.171,39	€ -	€ 5.171,39	€ -	€ 5.171,39	€ -	€ -	€ -
Price reduction of 15% from outsource company	€ 4.395,68	€ 4.395,68	€ 4.395,68	€ -	€ 4.395,68	€ -	€ 4.395,68	€ -	€ -	€ -
Cost with additional margin of 4%	*€ 4.571,51*	*€ 4.571,51*	*€ 4.571,51*	*€ -*	*€ 4.571,51*	*€ -*	*€ 4.571,51*	*€ -*	*€ -*	*€ -*
BC Cost per year incl. 20% margin	**€ 5.485,81**	**€ 5.485,81**	**€ 5.485,81**	**€ -**	**€ 5.485,81**	**€ -**	**€ 5.485,81**	**€ -**	**€ -**	**€ -**
Total ouflow alternative 2	***€ 23.471,18***	***€ 11.480,93***	***€ 17.476,05***	***€ 11.990,24***	***€ 11.480,93***	***€ 5.995,12***	***€ 11.480,93***	***€ -***	***€ 5.995,12***	***€ -***
Cash inflow										
Amount left over by the end of year 10										5
Scrap yield										€ 2,17
Amount left over by the end of year 10										5
Scrap yield										€ 2,52
Amount left over by the end of year 10										0
Scrap yield										€ -
Total inflow alternative 2	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 2,17**
Cash flow alternative 2	***€ 23.471,18***	***€ 11.480,93***	***€ 17.476,05***	***€ 11.990,24***	***€ 11.480,93***	***€ 5.995,12***	***€ 11.480,93***	***€ -***	***€ 5.995,12***	***€ -2,17***
NPV	**€ 21.337,43**	**€ 9.488,37**	**€ 13.130,02**	**€ 8.189,50**	**€ 7.128,76**	**€ 3.384,09**	**€ 5.891,53**	**€ -**	**€ 2.542,52**	**€ -0,84**
Cumulative NPV	**€ 21.337,43**	**€ 30.825,81**	**€ 43.955,82**	**€ 52.145,32**	**€ 59.274,08**	**€ 62.658,17**	**€ 68.549,70**	**€ 68.549,70**	**€ 71.092,22**	**€ 71.091,38**

Table 18: LCC result of alternative 2: outsource + MOQ + AM.

J LCC calculation alternative 3: repair failed components

J.1 Cost related to repairing failed components

All the costs that are related to fixing the malfunction are electricity cost, labour cost, abrasive cost, shipping-, and return cost. Each of these costs is explained below.

Electricity cost

Electricity cost originates from the blasting machine that ATAG owes. The machine ATAG owes is the blasting machine 220 litres.[4] The machine works via a compressor. For the blasting machine, a compressor with a minimum net output of 250 litres per minute (suction capacity: +/- 350 ltr/min) is used. Thus, the electricity is calculated as:

$$\begin{aligned} Electricity\ cost_{WH} = &\ Compressor\ power\ (in\ kW) \times \\ &\ number\ of\ operating\ hours\ for\ blasting\ per\ year_{WH} \times \\ &\ cost\ of\ electricity\ (expressed\ in\ euros\ per\ kWh) \end{aligned}$$

$$\begin{aligned} Electricity\ cost_{RH} = &\ Compressor\ power\ (in\ kW) \times \\ &\ number\ of\ operating\ hours\ for\ blasting\ per\ year_{RH} \times \\ &\ cost\ of\ electricity\ (expressed\ in\ euros\ per\ kWh) \end{aligned}$$

$$\begin{aligned} Electricity\ cost_{BC} = &\ Compressor\ power\ (in\ kW) \times \\ &\ number\ of\ operating\ hours\ for\ blasting\ per\ year_{BC} \times \\ &\ cost\ of\ electricity\ (expressed\ in\ euros\ per\ kWh) \end{aligned}$$

The compressor power is 2250 Watt per hour (equals 2,25 kWh).[5] The electricity cost per kWh is €0,24.[6] The number of operating hours for blasting per year is dependent on the amount that is repaired for the components, i.e. 40% of the forecasted amount is used for repair for the wok head, and 25% of the forecasted amount is used for repair for the roast head and burner cup. Further, the number of operating hours for blasting is also dependent on the amount of time that is needed to blast one component, i.e. 5 minutes per component.

Labour cost

To blast the components an engineer is needed. Blasting a component takes around 3 to 5 minutes.[7] The labour cost is estimated to be around €25 per hour. Thus, the labour cost is determined as:

$$Labour\ Cost_{WH} = number\ of\ operating\ hours\ for\ blasting\ per\ year_{WH} \times €25$$

$$Labour\ Cost_{RH} = number\ of\ operating\ hours\ for\ blasting\ per\ year_{RH} \times €25$$

$$Labour\ Cost_{BC} = number\ of\ operating\ hours\ for\ blasting\ per\ year_{BC} \times €25$$

[4] Retrieved from PowerPlus tools website.

[5] Retrieved from HBM Machines: 3 PK - 50 Liter Compressor MB3650 - 365 Liter Per Minute.

[6] Retrieved from consumentenbond.nl.

[7] Factual information from an internal specialist at ATAG, Herngreen (2021).

Abrasive cost

ATAG uses normal corundum to blast the component. The material is usually supplied in a bag of 25 kilograms. The price of normal corundum is €59,90 per 25 kilogram.[8] Thus, per kilogram we pay €2,40. The amount of abrasive that is used is based on the number of times a repair takes place. On average 15 kilograms of normal corundum is needed to blast a component of the FV wok burner. Thus, the abrasive cost is calculated as:

$$Abrasive\ Cost_{WH} = \#\ of\ repairs_{WH} \times (15\ kg\ of\ normal\ corundum) \times €2{,}40$$
$$Abrasive\ Cost_{RH} = \#\ of\ repairs_{RH} \times (15\ kg\ of\ normal\ corundum) \times €2{,}40$$
$$Abrasive\ Cost_{BC} = \#\ of\ repairs_{BC} \times (15\ kg\ of\ normal\ corundum) \times €2{,}40$$

Shipping cost

Shipping cost is the cost to send the new or refurbished component of the FV wok burner to the consumer. The shipping cost is added in the 4% margin as mentioned in Section 2.4. Therefore, we do not make a separate calculation for the shipping cost.

Return cost

The return cost is the cost that the consumer pays to send the failed component to the service centre in Duiven. However, the return cost is reimbursed by ATAG if the consumer falls within the warranty period. We assume that during the ten years of service all the return costs are reimbursed by ATAG. To send a return package to the service centre in Duiven differs per country. The weight of the components for alternatives 1 and 2 is given in Table 19 and 20.

Component	*Material*	*Mass in kg*
Wok head	Brass	0,32
Roast head	Aluminium	0,12
Burner cup	Aluminium	0,46

Table 19: Component weights in alternative 1: MOQ + CM.

Component	*Material*	*Mass in kg*
Wok head	SS 316L	0,31
Roast head	SS 316L	0,36
Burner cup	SS 316L	1,37

Table 20: Component weights in alternative 2: outsource + MOQ + AM.

Notice that the components for both alternatives do not weigh more than 2 kg each. If we take a look at the shipping prices that DHL charges, we see that a package with a weight of up to 2-kilogram cost €3,95 to send it to the service centre in Duiven.[9] The return cost is determined as:

$$Return\ Cost_{WH} = \#\ of\ repairs_{WH} \times €3{,}95$$
$$Return\ Cost_{RH} = \#\ of\ repairs_{RH} \times €3{,}95$$
$$Return\ Cost_{BC} = \#\ of\ repairs_{BC} \times €3{,}95$$

Total cost for repair

The total cost for repair is the sum of all the costs that incur for repairing one component, i.e.:

$$Repair\ Cost_{WH} = Electricity\ cost_{WH} + Labour\ cost_{WH} + Abrasive\ cost_{WH} + Return\ cost_{WH}$$
$$Repair\ Cost_{RH} = Electricity\ cost_{RH} + Labour\ cost_{RH} + Abrasive\ cost_{RH} + Return\ cost_{RH}$$
$$Repair\ Cost_{BC} = Electricity\ cost_{BC} + Labour\ cost_{BC} + Abrasive\ cost_{BC} + Return\ cost_{BC}$$

[8] Retrieved from torros.nl.

[9] Retrieved from the DHL website.

Additional marginal cost

As mentioned before, ATAG adds a 4% and 20% margin on the procurement price. In this alternative, these percentages are used for repair, orders from Slovenia (i.e. alternative 1), and outsourcing (i.e. alternative 2). The 4% and 20% are calculated the same way as explained in Appendix H, and I. However, the 4% and 20% for repair are calculated slightly differently. Here, the 4% margin is calculated as:

$$\begin{aligned}
\textit{Cost with additional 4\% margin}_{WH}(t) &= \Big(\textit{Repair cost}_{WH}(t) \times 4\%\Big) \\
&\quad + \textit{Repair cost}_{WH}(t) \\
\textit{Cost with additional 4\% margin}_{RH}(t) &= \Big(\textit{Repair cost}_{RH}(t) \times 4\%\Big) \\
&\quad + \textit{Repair cost}_{RH}(t) \\
\textit{Cost with additional 4\% margin}_{BC}(t) &= \Big(\textit{Repair cost}_{BC}(t) \times 4\%\Big) \\
&\quad + \textit{Repair cost}_{BC}(t)
\end{aligned}$$

On top of this 4% margin ATAG adds a 20% margin, which is calculated as:

$$\begin{aligned}
\textit{Cost with additional 20\% margin}_{WH}(t) &= \Big(\textit{Cost with additional 4\% margin}_{WH}(t) \times 20\%\Big) \\
&\quad + \textit{Cost with additional 4\% margin}_{WH}(t) \\
\textit{Cost with additional 20\% margin}_{RH}(t) &= \Big(\textit{Cost with additional 4\% margin}_{RH}(t) \times 20\%\Big) \\
&\quad + \textit{Cost with additional 4\% margin}_{RH}(t) \\
\textit{Cost with additional 20\% margin}_{BC}(t) &= \Big(\textit{Cost with additional 4\% margin}_{BC}(t) \times 20\%\Big) \\
&\quad + \textit{Cost with additional 4\% margin}_{BC}(t)
\end{aligned}$$

J.2 Cost related to alternative 1: MOQ + CM

The cost related to placing an order are the same as the cost factors explained in Section H. Here we only change the number of components that are ordered from Slovenia, i.e. 60% of the forecasted amount is ordered with an MOQ of 50 for the wok head, and 75% of the forecasted amount is ordered with an MOQ of 50 for the roast head and burner cup.

J.3 Cost related to alternative 2: outsource + MOQ + AM

The cost related to outsourcing are similar to the cost factors explained in Appendix I. Here, we also consider a price reduction of 15% since the value of the components is above £100.000 (see Appendix I). Further, we only change the number of components that should be outsourced, i.e. 60% of the forecasted amount is outsourced for the wok head, and 75% of the forecasted amount is outsourced for the roast head and burner cup.

Results

To determine the cash flow of alternatives 3a (i.e. repair + MOQ + CM), and 3b, the total cash outflow is subtracted by the total inflow. The total cash outflow in year t is determined as:

$$\textit{Cash outflow}(t) = \textit{Wok head cost}(t) + \textit{Roast head cost}(t) + \textit{Burner cup cost}(t)$$

Where $\textit{Wok head cost}(t) = \textit{Repair}_{WH}(t) + \textit{Orders with MOQ/ outsource}_{WH}(t)$, $\textit{Roast head cost}(t) = \textit{Repair}_{RH}(t) + \textit{Orders with MOQ/ outsource}_{RH}(t)$, and

$Burner\ cup\ cost(t) = Repair(t)_{BC} + Orders\ with\ MOQ/\ outsource_{BC}(t)$. Further, we have a cash inflow only at the end of year 10. This inflow is based on the scrap yield orders with an MOQ of 50 or outsourcing and is determined as:

$$\begin{aligned} Cash\ inflow(t=10) = & \ Scrap\ yield\ from\ orders\ with\ MOQ/\ outsource_{WH} \\ & + Scrap\ yield\ from\ orders\ with\ MOQ/\ outsource_{RH} \\ & + Scrap\ yield\ from\ orders\ with\ MOQ/\ outsource_{BC} \end{aligned}$$

The cash flow in year t (C_t) is determined by subtracting the cash inflow by the cash outflow. Afterwards we determined the NPV with a discount rate of 10% (Alofs, 2021; Kleinhaarhuis, 2021; Noorel, 2021).

To determine the cash flow of alternatives 3a and 3b, the total cash outflow is subtracted by the total inflow. Afterwards, the NPV is determined. The results of the LCC calculation of this alternative is given in Table X, Y, 21, and 22.

—Confidential—

Discount rate	10%

Year	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
t	1	2	3	4	5	6	7	8	9	10
Cash outflow										
Costs for Wok Head (WH)										
Outsource 60%										
Forecast in year t	19	17	15	13	11	9	7	6	4	2
Amount used for outsourcing (60%)	12	11	9	8	7	6	5	4	3	2
Amount left from previous year		6	4	4	5	7	1	5	1	7
Amount to order in year t		5	5	4	2	-1	4	-1	2	-5
Parts per batch produced (MOQ per batch)	9	9	9	9	9	9	9	9	9	9
Amount of batches to order	2	1	1	1	1	0	1	0	1	0
Material cost per batch	€ 410,94	€ 410,94	€ 410,94	€ 410,94	€ 410,94	€ 410,94	€ 410,94	€ 410,94	€ 410,94	€ 410,94
Print cost per batch	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42
Heat treatment cost per batch	€ 174,93	€ 174,93	€ 174,93	€ 174,93	€ 174,93	€ 174,93	€ 174,93	€ 174,93	€ 174,93	€ 174,93
Post processing cost per batch	€ 897,95	€ 897,95	€ 897,95	€ 897,95	€ 897,95	€ 897,95	€ 897,95	€ 897,95	€ 897,95	€ 897,95
Shippinng cost per batch	€ 40,82	€ 40,82	€ 40,82	€ 40,82	€ 40,82	€ 40,82	€ 40,82	€ 40,82	€ 40,82	€ 40,82
Cost for WH excl. 4% margin	€ 5.192,12	€ 2.596,06	€ 2.596,06	€ 2.596,06	€ 2.596,06	€ -	€ 2.596,06	€ -	€ 2.596,06	€ -
Price reduction of 15% from outsource company	€ 4.413,30	€ 2.206,65	€ 2.206,65	€ 2.206,65	€ 2.206,65	€ -	€ 2.206,65	€ -	€ 2.206,65	€ -
Cost with additional margin of 4%	€ 4.589,83	€ 2.294,92	€ 2.294,92	€ 2.294,92	€ 2.294,92	€ -	€ 2.294,92	€ -	€ 2.294,92	€ -
WH Cost per year incl. 20% margin	**€ 5.507,80**	**€ 2.753,90**	**€ 2.753,90**	**€ 2.753,90**	**€ 2.753,90**	**€ -**	**€ 2.753,90**	**€ -**	**€ 2.753,90**	**€ -**
Repair 40% of the components										
Amount used for repair (40%)	7	6	6	5	4	3	2	2	1	0
Number of minutes to blast one component	5	5	5	5	5	5	5	5	5	5
Number of operating hours for blasting	0,58	0,50	0,50	0,42	0,33	0,25	0,17	0,17	0,08	0,00
Compressor power in kWh	2,25	2,25	2,25	2,25	2,25	2,25	2,25	2,25	2,25	2,25
Electricity cost per kWh	€ 0,24	€ 0,24	€ 0,24	€ 0,24	€ 0,24	€ 0,24	€ 0,24	€ 0,24	€ 0,24	€ 0,24
Total Electricity cost	€ 0,32	€ 0,27	€ 0,27	€ 0,23	€ 0,18	€ 0,14	€ 0,09	€ 0,09	€ 0,05	€ -
Labor cost per hour	€ 25,00	€ 25,00	€ 25,00	€ 25,00	€ 25,00	€ 25,00	€ 25,00	€ 25,00	€ 25,00	€ 25,00
Total labor cost per year	€ 14,58	€ 12,50	€ 12,50	€ 10,42	€ 8,33	€ 6,25	€ 4,17	€ 4,17	€ 2,08	€ -
Abrasive cost per kg	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40
Number kg corondum needed to blast one component	10,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00
Total abrasive cost per year	€ 168,00	€ 144,00	€ 144,00	€ 120,00	€ 96,00	€ 72,00	€ 48,00	€ 48,00	€ 24,00	€ -
Return cost per shipping from Netherlands	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95
Return cost per year from Netherlands	€ 27,65	€ 23,70	€ 23,70	€ 19,75	€ 15,80	€ 11,85	€ 7,90	€ 7,90	€ 3,95	€ -
Cost per year alternative 3a	€ 210,55	€ 180,47	€ 180,47	€ 150,39	€ 120,31	€ 90,24	€ 60,16	€ 60,16	€ 30,08	€ -
Additional marginal of 4% from ATAG Benelux	€ 218,97	€ 187,69	€ 187,69	€ 156,41	€ 125,13	€ 93,84	€ 62,56	€ 62,56	€ 31,28	€ -
WH Cost per year incl. 20% margin	**€ 262,76**	**€ 225,23**	**€ 225,23**	**€ 187,69**	**€ 150,15**	**€ 112,61**	**€ 75,08**	**€ 75,08**	**€ 37,54**	**€ -**
Costs for Roast Head (RH)										
Outsource 75%										
Forecast in year t	19	17	15	13	11	9	7	6	4	2
Amount used for outsourcing (75%)	15	13	12	10	9	7	6	5	3	2
Amount left from previous year		3	8	5	4	4	6	0	4	1
Amount to order in year t		10	4	5	5	3	0	5	-1	1
Parts per batch produced (MOQ per batch)	9	9	9	9	9	9	9	9	9	9
Amount of batches to order	2	2	1	1	1	1	0	1	0	1
Material cost per batch	€ 410,94	€ 410,94	€ 410,94	€ 410,94	€ 410,94	€ 410,94	€ 410,94	€ 410,94	€ 410,94	€ 410,94
Print cost per batch	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42	€ 1.071,42
Heat treatment cost per batch	€ 174,93	€ 174,93	€ 174,93	€ 174,93	€ 174,93	€ 174,93	€ 174,93	€ 174,93	€ 174,93	€ 174,93
Post processing cost per batch	€ 897,95	€ 897,95	€ 897,95	€ 897,95	€ 897,95	€ 897,95	€ 897,95	€ 897,95	€ 897,95	€ 897,95
Shippinng cost per batch	€ 40,82	€ 40,82	€ 40,82	€ 40,82	€ 40,82	€ 40,82	€ 40,82	€ 40,82	€ 40,82	€ 40,82
Cost for RH excl. 4% margin	€ 5.192,12	€ 5.192,12	€ 2.596,06	€ 2.596,06	€ 2.596,06	€ 2.596,06	€ -	€ 2.596,06	€ -	€ 2.596,06
Price reduction of 15% from outsource company	€ 4.413,30	€ 4.413,30	€ 2.206,65	€ 2.206,65	€ 2.206,65	€ 2.206,65	€ -	€ 2.206,65	€ -	€ 2.206,65
Cost with additional margin of 4%	€ 4.589,83	€ 4.589,83	€ 2.294,92	€ 2.294,92	€ 2.294,92	€ 2.294,92	€ -	€ 2.294,92	€ -	€ 2.294,92
RH Cost per year incl. 20% margin	**€ 5.507,80**	**€ 5.507,80**	**€ 2.753,90**	**€ 2.753,90**	**€ 2.753,90**	**€ 2.753,90**	**€ -**	**€ 2.753,90**	**€ -**	**€ 2.753,90**
Repair 25% of the components										
Amount used for repair (25%)	4	4	3	3	2	2	1	1	1	0
Number of minutes to blast one component	5	5	5	5	5	5	5	5	5	5
Number of operating hours for blasting	0,33	0,33	0,25	0,25	0,17	0,17	0,08	0,08	0,08	0,00
Compressor power in kWh	2,25	2,25	2,25	2,25	2,25	2,25	2,25	2,25	2,25	2,25
Electricity cost per kWh	€ 0,24	€ 0,24	€ 0,24	€ 0,24	€ 0,24	€ 0,24	€ 0,24	€ 0,24	€ 0,24	€ 0,24
Total Electricity cost	€ 0,18	€ 0,18	€ 0,14	€ 0,14	€ 0,09	€ 0,09	€ 0,05	€ 0,05	€ 0,05	€ -
Labor cost per hour	€ 25,00	€ 25,00	€ 25,00	€ 25,00	€ 25,00	€ 25,00	€ 25,00	€ 25,00	€ 25,00	€ 25,00
Total labor cost per year	€ 8,33	€ 8,33	€ 6,25	€ 6,25	€ 4,17	€ 4,17	€ 2,08	€ 2,08	€ 2,08	€ -
Abrasive cost per kg	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40
Number kg corondum needed to blast one component	10,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00
Total abrasive cost per year	€ 96,00	€ 96,00	€ 72,00	€ 72,00	€ 48,00	€ 48,00	€ 24,00	€ 24,00	€ 24,00	€ -
Return cost per shipping from Netherlands	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95
Return cost per year from Netherlands	€ 15,80	€ 15,80	€ 11,85	€ 11,85	€ 7,90	€ 7,90	€ 3,95	€ 3,95	€ 3,95	€ -
Cost per year alternative 3a	€ 120,31	€ 120,31	€ 90,24	€ 90,24	€ 60,16	€ 60,16	€ 30,08	€ 30,08	€ 30,08	€ -
Additional marginal of 4% from ATAG Benelux	€ 125,13	€ 125,13	€ 93,84	€ 93,84	€ 62,56	€ 62,56	€ 31,28	€ 31,28	€ 31,28	€ -
RH Cost per year incl. 20% margin	**€ 150,15**	**€ 150,15**	**€ 112,61**	**€ 112,61**	**€ 75,08**	**€ 75,08**	**€ 37,54**	**€ 37,54**	**€ 37,54**	**€ -**

Table 21: LCC result of alternative 3b: repair + outsource + MOQ + AM.

Costs for Burner cup (BC)										
Outsource 75%										
Forecast in year t	*3*	*3*	*3*	*2*	*2*	*2*	*2*	*1*	*1*	*1*
Amount used for outsourcing (75%)	*3*	*3*	*3*	*2*	*2*	*2*	*2*	*1*	*1*	*1*
Amount left from previous year		*1*	*2*	*3*	*1*	*3*	*1*	*3*	*2*	*1*
Amount to order in year t		*2*	*1*	*-1*	*1*	*-1*	*1*	*-2*	*-1*	*0*
Parts per batch produced (MOQ per batch)	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*
Amount of batches to order	*1*	*1*	*1*	*0*	*1*	*0*	*1*	*0*	*0*	*0*
Material cost per batch	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*	*€ 410,94*
Print cost per batch	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*	*€ 1.071,42*
Heat treatment cost per batch	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*	*€ 174,93*
Post processing cost per batch	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*	*€ 897,95*
Shippinng cost per batch	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*	*€ 40,82*
Cost for BC excl. 4% margin	€ 2.596,06	€ 2.596,06	€ 2.596,06	€ -	€ 2.596,06	€ -	€ 2.596,06	€ -	€ -	€ -
Price reduction of 15% from outsource company	€ 2.206,65	€ 2.206,65	€ 2.206,65	€ -	€ 2.206,65	€ -	€ 2.206,65	€ -	€ -	€ -
Cost with additional margin of 4%	*€ 2.294,92*	*€ 2.294,92*	*€ 2.294,92*	*€ -*	*€ 2.294,92*	*€ -*	*€ 2.294,92*	*€ -*	*€ -*	*€ -*
BC Cost per year incl. 20% margin	**€ 2.753,90**	**€ 2.753,90**	**€ 2.753,90**	**€ -**	**€ 2.753,90**	**€ -**	**€ 2.753,90**	**€ -**	**€ -**	**€ -**
Repair 25% of the components										
Amount used for repair (25%)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Number of minutes to blast one component	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*
Number of operating hours for blasting	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*
Compressor power in kWh	*2,25*	*2,25*	*2,25*	*2,25*	*2,25*	*2,25*	*2,25*	*2,25*	*2,25*	*2,25*
Electricity cost per kWh	*€ 0,24*	*€ 0,24*	*€ 0,24*	*€ 0,24*	*€ 0,24*	*€ 0,24*	*€ 0,24*	*€ 0,24*	*€ 0,24*	*€ 0,24*
Total Electricity cost	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Labor cost per hour	*€ 25,00*	*€ 25,00*	*€ 25,00*	*€ 25,00*	*€ 25,00*	*€ 25,00*	*€ 25,00*	*€ 25,00*	*€ 25,00*	*€ 25,00*
Total labor cost per year	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Abrasive cost per kg	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40	€ 2,40
Number kg corondum needed to blast one component	10,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00
Total abrasive cost per year	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Return cost per shipping from Netherlands	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95	€ 3,95
Return cost per year from Netherlands	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Cost per year alternative 3a	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Additional marginal of 4% from ATAG Benelux	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
BC Cost per year incl. 20% margin	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Total outflow alternative 3b	***€ 14.182,42***	***€ 11.390,98***	***€ 8.599,54***	***€ 5.808,10***	***€ 8.486,93***	***€ 2.941,59***	***€ 5.620,41***	***€ 2.866,51***	***€ 2.828,98***	***€ 2.753,90***
Cash inflow										
Amount left over by the end of year 10										5
Scrap yield										€ 2,17
Amount left over by the end of year 10										8
Scrap yield										€ 4,03
Amount left over by the end of year 10										0
Scrap yield										€ -
Total inflow alternative 3b	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ 6,20**
Cash flow alternative 3b	***€ 14.182,42***	***€ 11.390,98***	***€ 8.599,54***	***€ 5.808,10***	***€ 8.486,93***	***€ 2.941,59***	***€ 5.620,41***	***€ 2.866,51***	***€ 2.828,98***	***€ 2.747,70***
NPV	**€ 12.893,11**	**€ 9.414,03**	**€ 6.460,96**	**€ 3.967,01**	**€ 5.269,71**	**€ 1.660,45**	**€ 2.884,16**	**€ 1.337,25**	**€ 1.199,76**	**€ 1.059,36**
Cumulative NPV	**€ 12.893,11**	**€ 22.307,14**	**€ 28.768,10**	**€ 32.735,11**	**€ 38.004,83**	**€ 39.665,28**	**€ 42.549,44**	**€ 43.886,69**	**€ 45.086,45**	**€ 46.145,81**

Table 22: LCC result of alternative 3b: repair + outsource + MOQ + AM (continued).

K LCC calculation alternative 4: invest in new machine

This alternative is divided into two sub alternatives. In the first sub alternative, the LCC calculation is based on the M290 machine, and in the second sub alternative, the LCC calculation is based on the M400-4 machine. The cost factors we used are the same in both sub alternatives. The costs for each sub alternative are separated into two parts. In the first part, we determine the cost related to buying the new 3D printing machine, and in the second part, we determine the costs for printing the FV wok burner per service component. We used the predicted amount that is needed per year, determined in Section 4.1, as input for the second part.

K.1 Cost related to buying a 3D printing machine

The cost related to buying a 3D printing machine is divided into three main costs namely, the acquisition-, operation-, and repair and maintenance costs. Each of these costs is explained in detail below.

Acquisition cost

The acquisition cost consists of machine, installation, packaging, and freight & duty cost.

Machine cost
The first cost we considered is the machine cost. In this alternative, we do an LCC analysis based on two types of machines (see Appendix F for the machine selection), i.e. M290, and M400-4. The M290 machine cost around €550.000 and the M400-4 machine cost around €1.600.000.[10]

Installation cost
Installation cost refers to the costs to install the machine. For this activity, a machinist is needed. The price of the machinist is around €30 per hour. The amount of time to install the machine can take up to 7 working days, i.e. around 8 hours per day.[11] The installation cost is calculated as:

$$\textit{Installation cost} = \#\ \textit{of hours on installation} \times \textit{machinist cost}$$

Packaging cost
The cost of packing the machines depends on the size of the machine. Further, we assume that the machines are packed in a combination of bubble wrap, cardboard, and shrink wrapping. The packaging cost is calculated as:

$$\textit{Packaging cost} = \textit{package volume} \times \textit{packaging material price}$$

The M 290 machine dimension is 2500 x 1300 x 2190 mm (W x D x H). The M 400-4 machine dimension is 4181 x 1613 x 2355 mm (W x D x H) .

Freight & duty cost
Taxes in Slovenia are 22% of the value of the imported good.[12] The threshold for duties is 4.2% on average.[13] Freight cost depends on the truckload and the weight of the goods. Shipping

[10]Data retrieved from representative of EOS GmbH, ten Pas (2021).
[11]Estimate by internal specialists of ATAG.
[12]Retrieved from: `https://www.easyship.com/countries/shipping-to-slovenia`
[13]`https://www.objectif-import-export.fr/en/international-marketplaces/country/slovenia/regulations-customs`

the M290 machine with direct shipping costs around €800.[14] The same holds for the M400-4 machine. The freight cost for both machines is the same because of less than a full truckload.

Operation cost

The operation cost consists of the space-, electricity-, and downtime cost. Each of these costs is explained below.

Space cost
Placing a machine in the manufacturer building in Slovenia costs money. The recommended installation space needed for the M290 machine is min. 4800 x 3600 x 2900 mm, and the recommended installation space needed for the M400-4 machine is min. 6500 x 6000 x 3300 mm.[15] The average rents of leased industrial and logistic properties in selected cities of Slovenia ranged from 6.5 to 11.5 euros per square meter per month.[16] Thus, we take an average of €9 per square meter per month for the rent price.

The space cost is calculated as:

$$\textit{Space cost= required space size in } m^2 \times \textit{ rent price per } m^2$$

Electricity cost
The price that a manufacturer uses for electricity is €0,111 per kWh.[17] The maximum power consumption of the M290 machine is between 2,4 and 8,5 kW per hour, and the maximum power consumption of the M400-4 machine is between 22 and 45 kW per hour.[18] We take the average of these values to determine the electricity cost. Further, a standard facility runs 2000 hours per year.[19] Thus, the annual electricity cost is determined as:

$$\textit{Annual electricity cost = 2000} \times \textit{ power consumption per hour} \times \textit{ electricity cost per kWh}$$

Downtime cost
Downtime cost relates to the cost when the machine is not in use. This is when the machine is being repaired or when yearly service takes place. However, we could not find any specific downtime data for both machines. An article mentioned that every factory experiences at least 5% of productivity up to 20%.[20] Therefore, we assumed to take the average which is 12,5% of the total operating hours as downtime, which is 12,5% times 2000 equals 250 hours.

Further, the downtime cost depends on how many units are produced. To print the FV wok components takes up to a week.[21] We know that the M 290 machine can produce up to 2 units per batch. Since we do not know what the profit margin is we assume that in this case, it is €50. Thus, we can conclude that the downtime cost is 100 euros per working week. After converting the 250 hours of downtime to working weeks we get 6,25 weeks. Thus, the downtime cost per year is 6,25 weeks times €100 for the M 290 machine.

[14]Retrieved from: https://www.eurosender.com/order/details
[15]Retrieved from the official website of EOS GmbH.
[16]https://www.statista.com/statistics/1023436/average-monthly-rents-for-industrial-and-logistic-rents-slovenia/
[17]Retrieved from: https://nl.globalpetrolprices.com/Slovenia/electricity_prices/
[18]Retrieved from the official website of EOS GmbH.
[19]Retrieved from the book: Engineering economy.
[20]Retrieved from: https://oden.io/blog/downtime-in-manufacturing-the-true-cost/.
[21]Expert opinion within ATAG Benelux

The M 400-4 machine is four times more productive and can produce at least 9 pieces per week. We assume the same profit margin here, i.e. €50. So, the downtime cost is 9 times €50 equals €450. Again after converting the 250 hours of downtime to working weeks, we get 6,25 weeks. Thus, the downtime cost per year is 6,25 weeks times €450 for the M 400-4 machine.[22]

Repair and maintenance cost

When the machine is broken down or some kind of error occurs, an engineer or technician is involved to fix the malfunction. Repair and maintenance are needed depending on how much the 3D printing machine is occupied in Slovenia. The maintenance service cost is calculated based on the amount of service that is needed per year per machine. Now, let's assume that the M290 machine needs maintenance service every six months, and the M400-4 machine every 12 months (Spickova, & Myskova, 2015). The service cost is determined as:

$$\textit{Service cost per year} = \#\textit{ of service per year} \times \textit{service cost per service}$$

Further, unplanned failures can also occur. Let's say that 2 unplanned failure occurs every year for the M290 machine and 1 unplanned failure for the M400-4 machine (Spickova, & Myskova, 2015). The failure cost is calculated as:

$$\textit{Unplanned failure cost per year} = \#\textit{ of failures per year} \times \textit{repair cost per failure}$$

Total cost related to buying a 3D printing machine

The total cost is defined as follows:

$$\textit{Total machine cost(t)= Acquisition cost(t)+ Operation cost(t) + Repair \& Maintenance cost(t)}$$

Where t is the year in which the costs are made. Now, as mentioned in Section 4.5, we only take a percentage of the total machine cost since the machine is used for other purposes as well. The M290 machine can produce up to 5000 pieces per year.[23] The M400-4 machine is four times more productive, thus it can produce up to 20000 pieces per year. The cost of the first part for the M290 machine is determined as:

$$\textit{Total machine cost FV wok burner (t)} = \textit{Total machine cost(t)} \times \frac{5000}{\#\textit{of FV wok burner components to produce in year i}}$$

The cost of the first part for the M400-4 machine is determined as:

$$\textit{Total machine cost FV wok burner (t)} = \textit{Total machine cost(t)} \times \frac{20000}{\#\textit{of FV wok burner components to produce in year i}}$$

K.2 Cost related to printing the FV wok burner

Making CAD model cost

Within ATAG, the CAD model was already developed. However, the CAD still has to be transformed into an STL file. This only takes a few minutes. ATAG only has to send the CAD file to Slovenia so they can print the part. Thus, we can neglect the cost that occurs in this stage since Slovenia, technically, does not have to make a new CAD file.

[22]Retrieved from: `https://oden.io/blog/downtime-in-manufacturing-the-true-cost/`.

[23]Retrieved from `https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/simply-production-eos-m-290/`

Machine setup cost

When it comes to machine setup cost, an AM specialist has to adjust the building parameters on the machine to the right energy source, layer thickness, dimension et cetera. Setting up the machine according to the right parameters takes 5 minutes or less (Herngreen, 2021). Again, this step can be neglected since it does not add any value to the cost calculation.

Material cost

For building the three parts the material SS 316L is needed. The price for SS 316L is €75 per kg.[24] Further, the material cost is based on the volume of the components. Thus, the material cost is determined as:

$$\textit{Material cost per part} = \textit{volume per component} \times \textit{material price}$$

Print cost

The amount that can be printed per batch differs per machine. The machine type M290 can print 2 pieces of each roast head and the wok head in one batch and 1 piece of the burner cup in one batch. The machine type M400-4 is 4 times more productive and can print 9 pieces of each roast head and the wok head in one batch and 4 pieces of the burner cup in one batch (Wennington, 2021). The mass and volume of the FV wok components are given in Table 20. Since it was difficult to determine the print cost we took 40% off from the print price we retrieved from the outsource manufacturer. ATAG expects that the print price will be lower since this will happen in-house and thus we took 40% of from the original price we retrieved.

Heat treatment cost

To print the FV wok burner components a heat treatment is necessary. This treatment is a stress relief cycle at a high temperature in a furnace. Depending on the material, this is at a different temperature duration but improves material properties post-build. During the heat treatment process the component is heated without letting it reach its melting, stage, and then cooling the metal in a controlled way to select desired mechanical properties. This cost around €90 per production batch.[25]

Removal/Post processing cost

After a part is completed, it has to be removed from the machine. During this stage, several different process steps are required. An Electrical Discharge Machining (EDM) removal from a platform that removes components from the build platform is needed. Hand finishing is a manual process to remove burrs/tap holes. Computer Numerical Control (CNC) machining is a much more accurate way to build to tight tolerances. There are other methods such as chemical milling, polishing, blasting et cetera. Further, additional cleaning is also required. Parts may have supporting structures that have to be removed. All in all, we can say that during this process labour and special tooling cost incur. The total cost for removal and post-processing is €538,77 for the wok head per 9 pieces, €577,96 for the roast head per 9 pieces, and €538,77 for the burner cup per 4 pieces. Note, that we also took 40% off from the original price we retrieved from the outsource manufacturer.

Application cost

The burner cup and the roast head need an additional step. Both of these components have to be painted. However, no data was available regarding the painting process and was therefore

[24] Data retrieved from representative of EOS GmbH, ten Pas (2021)).

[25] Data retrieved from external AM specialist, Wennington (2021)

left out of scope.

Total cost related to printing

The cost related to printing is divided into several costs factors namely: material cost, print cost, heat treatment cost, and post-processing cost. Thus, the cost related to printing is calculated as:

$$\begin{aligned}Cost\ related\ to\ printing_{WH}(t) = {} & material\ cost_{WH}(t) + print\ cost_{WH}(t) + heat\ treatment\ cost_{WH}(t)\\ & + post\ processing\ cost_{WH}(t)\end{aligned}$$

$$\begin{aligned}Cost\ related\ to\ printing_{RH}(t) = {} & material\ cost_{RH}(t) + print\ cost_{RH}(t) + heat\ treatment\ cost_{RH}(t)\\ & + post\ processing\ cost_{RH}(t)\end{aligned}$$

$$\begin{aligned}Cost\ related\ to\ printing_{BC}(t) = {} & material\ cost_{BC}(t) + print\ cost_{BC}(t) + heat\ treatment\ cost_{BC}(t)\\ & + post\ processing\ cost_{BC}(t)\end{aligned}$$

Additional marginal cost

Additional cost relates to transport cost from Slovenia to Duiven, customs, packaging cost of the service components (including labelling), storage cost in Duiven and sending the component to the consumer. The additional cost are based on a 4 and 20% margin. The cost with additional 4% margin is determined as:

$$\begin{aligned}Cost\ with\ additional\ 4\%\ margin_{WH}(t) = {} & \big(Cost\ related\ to\ printing_{WH}(t) \times 4\%\big)\\ & + Cost\ related\ to\ printing_{WH}(t)\\ Cost\ with\ additional\ 4\%\ margin_{RH}(t) = {} & \big(Cost\ related\ to\ printing_{RH}(t) \times 4\%\big)\\ & + Cost\ related\ to\ printing_{RH}(t)\\ Cost\ with\ additional\ 4\%\ margin_{BC}(t) = {} & \big(Cost\ related\ to\ printing_{BC}(t) \times 4\%\big)\\ & + Cost\ related\ to\ printing_{BC}(t)\end{aligned}$$

On top of this 4% margin ATAG adds a 20% margin, which is calculated as:

$$\begin{aligned}Cost\ with\ additional\ 20\%\ margin_{WH}(t) = {} & \big(Cost\ with\ additional\ 4\%\ margin_{WH}(t) \times 20\%\big)\\ & + Cost\ with\ additional\ 4\%\ margin_{WH}(t)\\ Cost\ with\ additional\ 20\%\ margin_{RH}(t) = {} & \big(Cost\ with\ additional\ 4\%\ margin_{RH}(t) \times 20\%\big)\\ & + Cost\ with\ additional\ 4\%\ margin_{RH}(t)\\ Cost\ with\ additional\ 20\%\ margin_{BC}(t) = {} & \big(Cost\ with\ additional\ 4\%\ margin_{BC}(t) \times 20\%\big)\\ & + Cost\ with\ additional\ 4\%\ margin_{BC}(t)\end{aligned}$$

Disposal cost

In this alternative, the assumption was that ATAG can order 3D printed parts from Slovenia without any MOQ. Thus, orders are filled from the production line and therefore we do not incur a disposal cost for ATAG.

Results

In this alternative, we do not have a cash inflow since we will not have any disposal. Thus, the cash flow of alternatives 4a (i.e. invest in a small AM machine) and 4b in year t is determined as:

$$\begin{aligned} \textit{Cash flow}(t) = {} & \textit{Cost related to investing in a new machine}(t) \\ & + \textit{Wok head cost}(t) + \textit{Roast head cost}(t) + \textit{Burner cup cost}(t) \end{aligned}$$

Where *Cost related to investing in a new machine*(t) is equal to the *Total machine cost FV wok burner (t)*, *Wok head cost*(t) is equal to the *Cost with additional 20% margin*$_{WH}(t)$, *Roast head cost*(t) is equal to the *Cost with additional 20% margin*$_{RH}(t)$, and *Burner cup cost*(t) is equal to the *Cost with additional 20% margin*$_{BC}(t)$ (see Appendix K). Afterwards we determined the NPV with a discount rate of 10% (Alofs, 2021; Kleinhaarhuis, 2021; Noorel, 2021).

The results of the LCC calculation of this alternative is given Table 23, 24, 25, and 26.

Discount rate	**10,0%**

Year	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**
t	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
					Part 1: Costs related to investment in machine M290					
					Acquisition costs					
Machine cost	€ 550.000,00									
Installation (hours)	*40*									
Machinist cost per h.	*€ 30,00*									
Installation cost	€ 1.200,00									
Dimension package (in m^3)	*7,1175*									
Packaging price per m^3	*€ 50,00*									
Packaging price	355,875									
Freight	€ 800,00									
Duties (4,2%)	€ 23.100,00									
Taxes (22%)	€ 121.000,00									
					Operation costs					
Space dimension (m^2)	*17,28*									
Rent price per month per m^2	*€ 9,00*									
Annual rent cost	€ 1.866,24	€ 1.866,24	€ 1.866,24	€ 1.866,24	€ 1.866,24	€ 1.866,24	€ 1.866,24	€ 1.866,24	€ 1.866,24	€ 1.866,24
Electrcity cost per kWh	€ 0,11									
Facility operation hours/year	2000									
Power consumption per hour	5,45									
Annual electricity cost	€ 1.209,90	€ 1.209,90	€ 1.209,90	€ 1.209,90	€ 1.209,90	€ 1.209,90	€ 1.209,90	€ 1.209,90	€ 1.209,90	€ 1.209,90
Amount of weeks not in use	6,25									
Downtime price per week	100									
Downtime cost per year	€ 625,00	€ 625,00	€ 625,00	€ 625,00	€ 625,00	€ 625,00	€ 625,00	€ 625,00	€ 625,00	€ 625,00
					Repair and maintenance costs					
Amount of service per year	1									
Service cost per service	€ 2.500,00									
Service cost per year	€ 2.500,00	€ 2.500,00	€ 2.500,00	€ 2.500,00	€ 2.500,00	€ 2.500,00	€ 2.500,00	€ 2.500,00	€ 2.500,00	€ 2.500,00
Unplanned failures per year	3									
Failure cost per failure	€ 5.000,00									
Failure cost per year	€ 15.000,00	€ 15.000,00	€ 15.000,00	€ 15.000,00	€ 15.000,00	€ 15.000,00	€ 15.000,00	€ 15.000,00	€ 15.000,00	€ 15.000,00
Total cost machine	€ 717.657,12	€ 21.201,14	€ 21.201,14	€ 21.201,14	€ 21.201,14	€ 21.201,14	€ 21.201,14	€ 21.201,14	€ 21.201,14	€ 21.201,14
Max production amount	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
Amount needed for FV wok burner	41	37	33	28	24	20	16	13	9	5
Total cost used for the FV wok burner	**€ 5.884,79**	**€ 156,89**	**€ 139,93**	**€ 118,73**	**€ 101,77**	**€ 84,80**	**€ 67,84**	**€ 55,12**	**€ 38,16**	**€ 21,20**

Table 23: LCC result of alternative 4a: invest in a small AM machine.

Part 2: Costs related to printing the components with M290 machine										
3D printing costs of Wok Head (WH)										
Forecast in year i	*19*	*17*	*15*	*13*	*11*	*9*	*7*	*6*	*4*	*2*
Volume WH (in kg)	*0,31*									
Material price per kg	*€ 75,00*									
Material cost per part	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*
Material cost per year	€ 441,75	€ 395,25	€ 348,75	€ 302,25	€ 255,75	€ 209,25	€ 162,75	€ 139,50	€ 93,00	€ 46,50
Print cost per batch	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*
Batches per year (2 pieces in one batch)	*9,5*	*8,5*	*7,5*	*6,5*	*5,5*	*4,5*	*3,5*	*3*	*2*	*1*
Print cost per year	€ 6.107,09	€ 5.464,24	€ 4.821,39	€ 4.178,54	€ 3.535,69	€ 2.892,83	€ 2.249,98	€ 1.928,56	€ 1.285,70	€ 642,85
Heat treatment cost per batch	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*
Batches per year (2 pieces in one batch)	*9,5*	*8,5*	*7,5*	*6,5*	*5,5*	*4,5*	*3,5*	*3*	*2*	*1*
Heat treatment cost per year	€ 855,00	€ 765,00	€ 675,00	€ 585,00	€ 495,00	€ 405,00	€ 315,00	€ 270,00	€ 180,00	€ 90,00
Post processing cost per 2 pieces	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*
Post processing cost per year	€ 5.118,32	€ 4.579,55	€ 4.040,78	€ 3.502,01	€ 2.963,24	€ 2.424,47	€ 1.885,70	€ 1.616,31	€ 1.077,54	€ 538,77
Amount of labor hours needed per part	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*
Labor cost per hour	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*
Labor cost per year	€ 285,00	€ 255,00	€ 225,00	€ 195,00	€ 165,00	€ 135,00	€ 105,00	€ 90,00	€ 60,00	€ 30,00
3D printing cost WH (excl. additional cost)	*€ 12.807,16*	*€ 11.459,04*	*€ 10.110,92*	*€ 8.762,79*	*€ 7.414,67*	*€ 6.066,55*	*€ 4.718,43*	*€ 4.044,37*	*€ 2.696,24*	*€ 1.348,12*
Cost with additional margin of 4%	€ 13.319,45	€ 11.917,40	€ 10.515,35	€ 9.113,30	€ 7.711,26	€ 6.309,21	€ 4.907,16	€ 4.206,14	€ 2.804,09	€ 1.402,05
WH Cost per year incl. 20% margin	**€ 15.983,33**	**€ 14.300,88**	**€ 12.618,42**	**€ 10.935,97**	**€ 9.253,51**	**€ 7.571,05**	**€ 5.888,60**	**€ 5.047,37**	**€ 3.364,91**	**€ 1.682,46**
3D printing costs of Roast Head (RH)										
Forecast in year i	*19*	*17*	*15*	*13*	*11*	*9*	*7*	*6*	*4*	*2*
Volume RH (in kg)	*0,36*									
Material price per kg	*€ 75,00*									
Material cost per part	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*
Material cost per year	€ 513,00	€ 459,00	€ 405,00	€ 351,00	€ 297,00	€ 243,00	€ 189,00	€ 162,00	€ 108,00	€ 54,00
Print cost per batch	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*
Batches per year (2 pieces in one batch)	*9,5*	*8,5*	*7,5*	*6,5*	*5,5*	*4,5*	*3,5*	*3*	*2*	*1*
Print cost per year	€ 7.916,56	€ 7.083,24	€ 6.249,92	€ 5.416,59	€ 4.583,27	€ 3.749,95	€ 2.916,63	€ 2.499,97	€ 1.666,64	€ 833,32
Heat treatment cost per batch	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*
Batches per year (2 pieces in one batch)	*9,5*	*8,5*	*7,5*	*6,5*	*5,5*	*4,5*	*3,5*	*3*	*2*	*1*
Heat treatment cost per year	€ 855,00	€ 765,00	€ 675,00	€ 585,00	€ 495,00	€ 405,00	€ 315,00	€ 270,00	€ 180,00	€ 90,00
Post processing cost per 2 pieces	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*
Post processing cost per year	€ 5.490,58	€ 4.912,63	€ 4.334,67	€ 3.756,71	€ 3.178,76	€ 2.600,80	€ 2.022,85	€ 1.733,87	€ 1.155,91	€ 577,96
Amount of labor hours needed per part	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*
Labor cost per hour	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*
Labor cost per year	€ 285,00	€ 255,00	€ 225,00	€ 195,00	€ 165,00	€ 135,00	€ 105,00	€ 90,00	€ 60,00	€ 30,00
3D printing cost RH (excl. additional cost)	*€ 15.060,14*	*€ 13.474,86*	*€ 11.889,59*	*€ 10.304,31*	*€ 8.719,03*	*€ 7.133,75*	*€ 5.548,47*	*€ 4.755,83*	*€ 3.170,56*	*€ 1.585,28*
Cost with additional margin of 4%	€ 15.662,55	€ 14.013,86	€ 12.365,17	€ 10.716,48	€ 9.067,79	€ 7.419,10	€ 5.770,41	€ 4.946,07	€ 3.297,38	€ 1.648,69
RH Cost per year incl. 20% margin	**€ 18.795,06**	**€ 16.816,63**	**€ 14.838,20**	**€ 12.859,78**	**€ 10.881,35**	**€ 8.902,92**	**€ 6.924,49**	**€ 5.935,28**	**€ 3.956,85**	**€ 1.978,43**
3D printing costs of Burner Cup (BC)										
Forecast in year i	*3*	*3*	*3*	*2*	*2*	*2*	*2*	*1*	*1*	*1*
Volume BC (in kg)	*1,37*									
Material price per kg	*€ 75,00*									
Material cost per part	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*
Material cost per year	€ 308,25	€ 308,25	€ 308,25	€ 205,50	€ 205,50	€ 205,50	€ 205,50	€ 102,75	€ 102,75	€ 102,75
Print cost per batch	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*
Batches per year (1 piece in one batch)	*3*	*3*	*3*	*2*	*2*	*2*	*2*	*1*	*1*	*1*
Print cost per year	€ 5.829,98	€ 5.829,98	€ 5.829,98	€ 3.886,66	€ 3.886,66	€ 3.886,66	€ 3.886,66	€ 1.943,33	€ 1.943,33	€ 1.943,33
Heat treatment cost per batch	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*
Batches per year (1 piece in one batch)	*3*	*3*	*3*	*2*	*2*	*2*	*2*	*1*	*1*	*1*
Heat treatment cost per year	€ 270,00	€ 270,00	€ 270,00	€ 180,00	€ 180,00	€ 180,00	€ 180,00	€ 90,00	€ 90,00	€ 90,00
Post processing cost per piece	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*
Post processing cost per year	€ 1.616,31	€ 1.616,31	€ 1.616,31	€ 1.077,54	€ 1.077,54	€ 1.077,54	€ 1.077,54	€ 538,77	€ 538,77	€ 538,77
Amount of labor hours needed per part	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*
Labor cost per hour	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*
Labor cost per year	€ 45,00	€ 45,00	€ 45,00	€ 30,00	€ 30,00	€ 30,00	€ 30,00	€ 15,00	€ 15,00	€ 15,00
3D printing cost BC (excl. additional cost)	*€ 8.069,54*	*€ 8.069,54*	*€ 8.069,54*	*€ 5.379,70*	*€ 5.379,70*	*€ 5.379,70*	*€ 5.379,70*	*€ 2.689,85*	*€ 2.689,85*	*€ 2.689,85*
Cost with additional margin of 4%	€ 8.392,33	€ 8.392,33	€ 8.392,33	€ 5.594,88	€ 5.594,88	€ 5.594,88	€ 5.594,88	€ 2.797,44	€ 2.797,44	€ 2.797,44
BC Cost per year incl. 20% margin	**€ 10.070,79**	**€ 10.070,79**	**€ 10.070,79**	**€ 6.713,86**	**€ 6.713,86**	**€ 6.713,86**	**€ 6.713,86**	**€ 3.356,93**	**€ 3.356,93**	**€ 3.356,93**
Total cost alternative 4a	***€ 50.733,97***	***€ 41.345,19***	***€ 37.667,34***	***€ 30.628,33***	***€ 26.950,48***	***€ 23.272,64***	***€ 19.594,80***	***€ 14.394,70***	***€ 10.716,86***	***€ 7.039,01***
NPV	**€ 46.121,79**	**€ 34.169,58**	**€ 28.300,03**	**€ 20.919,56**	**€ 16.734,13**	**€ 13.136,80**	**€ 10.055,23**	**€ 6.715,24**	**€ 4.544,99**	**€ 2.713,84**
Cumulative NPV	**€ 46.121,79**	**€ 80.291,37**	**€ 108.591,40**	**€ 129.510,96**	**€ 146.245,09**	**€ 159.381,89**	**€ 169.437,11**	**€ 176.152,35**	**€ 180.697,34**	**€ 183.411,19**

Table 24: LCC result of alternative 4a: invest in a small AM machine (continued).

Discount rate	**10,0%**

Year	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**
t	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Part 1: Costs related to investment in machine M400-4										
Acquisition costs										
Machine cost	€ 1.600.000,00									
Installation (hours)	*56*									
Machinist cost per h.	*€ 30,00*									
Installation cost	€ 1.680,00									
Dimension package (in m^3)	*15,88200932*									
Packaging price per m^3	*€ 50,00*									
Packaging price	794,1004658									
Freight	€ 800,00									
Duties (4,2%)	€ 67.200,00									
Taxes (22%)	€ 352.000,00									
Operation costs										
Space dimension (m^2)	*23,4*									
Rent price per month per m^2	*€ 9,00*									
Rent cost per year	€ 2.527,20	€ 2.527,20	€ 2.527,20	€ 2.527,20	€ 2.527,20	€ 2.527,20	€ 2.527,20	€ 2.527,20	€ 2.527,20	€ 2.527,20
Electrcity cost per kWh	€ 0,11									
Facility operation hours/year	2000									
Power consumption per hour	33,5									
Electricity cost	€ 7.437,00	€ 7.437,00	€ 7.437,00	€ 7.437,00	€ 7.437,00	€ 7.437,00	€ 7.437,00	€ 7.437,00	€ 7.437,00	€ 7.437,00
Amount of weeks not in use	6,25									
Downtime price per week	450									
Downtime cost per year	€ 2.812,50	€ 2.812,50	€ 2.812,50	€ 2.812,50	€ 2.812,50	€ 2.812,50	€ 2.812,50	€ 2.812,50	€ 2.812,50	€ 2.812,50
Repair and maintenance costs										
Amount of service per year	2									
Service cost per service	€ 2.000,00									
Service cost per year	€ 4.000,00	€ 4.000,00	€ 4.000,00	€ 4.000,00	€ 4.000,00	€ 4.000,00	€ 4.000,00	€ 4.000,00	€ 4.000,00	€ 4.000,00
Unplanned failures per year	1									
Failure cost per failure	€ 7.000,00									
Failure cost per year	€ 7.000,00	€ 7.000,00	€ 7.000,00	€ 7.000,00	€ 7.000,00	€ 7.000,00	€ 7.000,00	€ 7.000,00	€ 7.000,00	€ 7.000,00
Total cost machine	€ 2.046.250,90	€ 23.776,70	€ 23.776,70	€ 23.776,70	€ 23.776,70	€ 23.776,70	€ 23.776,70	€ 23.776,70	€ 23.776,70	€ 23.776,70
Max production amount	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000
Amount needed for FV wok burner	41	37	33	28	24	20	16	13	9	5
Total cost used for the FV wok burner	**€ 4.194,81**	**€ 43,99**	**€ 39,23**	**€ 33,29**	**€ 28,53**	**€ 23,78**	**€ 19,02**	**€ 15,45**	**€ 10,70**	**€ 5,94**

Table 25: LCC result of alternative 4b: invest in a large AM machine.

Part 2: Costs related to printing the components with M400-4 machine										
3D printing costs of Wok Head (WH)										
Forecast in year i	*19*	*17*	*15*	*13*	*11*	*9*	*7*	*6*	*4*	*2*
Volume WH (in kg)	*0,31*									
Material price per kg	*€ 75,00*									
Material cost per part	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*	*€ 23,25*
Material cost per year	€ 441,75	€ 395,25	€ 348,75	€ 302,25	€ 255,75	€ 209,25	€ 162,75	€ 139,50	€ 93,00	€ 46,50
Print cost per batch	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*	*€ 642,85*
Batches per year (9 pieces in one batch)	*2,11*	*1,89*	*1,67*	*1,44*	*1,22*	*1,00*	*0,78*	*0,67*	*0,44*	*0,22*
Print cost per year	€ 1.357,13	€ 1.214,28	€ 1.071,42	€ 928,56	€ 785,71	€ 642,85	€ 500,00	€ 428,57	€ 285,71	€ 142,86
Heat treatment cost per batch	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*
Batches per year (9 pieces in one batch)	*2,11*	*1,89*	*1,67*	*1,44*	*1,22*	*1,00*	*0,78*	*0,67*	*0,44*	*0,22*
Heat treatment cost per year	€ 190,00	€ 170,00	€ 150,00	€ 130,00	€ 110,00	€ 90,00	€ 70,00	€ 60,00	€ 40,00	€ 20,00
Post processing cost per 9 pieces	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*
Post processing cost per year	€ 1.137,40	€ 1.017,68	€ 897,95	€ 778,22	€ 658,50	€ 538,77	€ 419,04	€ 359,18	€ 239,45	€ 119,73
Amount of labor hours needed per part	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*
Labor cost per hour	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*
Labor cost per year	€ 285,00	€ 255,00	€ 225,00	€ 195,00	€ 165,00	€ 135,00	€ 105,00	€ 90,00	€ 60,00	€ 30,00
3D printing cost WH (excl. additional cost)	*€ 3.411,29*	*€ 3.052,20*	*€ 2.693,12*	*€ 2.334,04*	*€ 1.974,95*	*€ 1.615,87*	*€ 1.256,79*	*€ 1.077,25*	*€ 718,17*	*€ 359,08*
Cost with additional margin of 4%	€ 3.547,74	€ 3.174,29	€ 2.800,84	€ 2.427,40	€ 2.053,95	€ 1.680,51	€ 1.307,06	€ 1.120,34	€ 746,89	€ 373,45
WH Cost per year incl. 20% margin	**€ 4.257,28**	**€ 3.809,15**	**€ 3.361,01**	**€ 2.912,88**	**€ 2.464,74**	**€ 2.016,61**	**€ 1.568,47**	**€ 1.344,41**	**€ 896,27**	**€ 448,14**
3D printing costs of Roast Head (RH)										
Forecast in year i	*19*	*17*	*15*	*13*	*11*	*9*	*7*	*6*	*4*	*2*
Volume RH (in kg)	*0,36*									
Material price per kg	*€ 75,00*									
Material cost per part	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*	*€ 27,00*
Material cost per year	€ 513,00	€ 459,00	€ 405,00	€ 351,00	€ 297,00	€ 243,00	€ 189,00	€ 162,00	€ 108,00	€ 54,00
Print cost per batch	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*	*€ 833,32*
Batches per year (9 pieces in one batch)	*2,11*	*1,89*	*1,67*	*1,44*	*1,22*	*1,00*	*0,78*	*0,67*	*0,44*	*0,22*
Print cost per year	€ 1.759,24	€ 1.574,05	€ 1.388,87	€ 1.203,69	€ 1.018,50	€ 833,32	€ 648,14	€ 555,55	€ 370,37	€ 185,18
Heat treatment cost per batch	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*
Batches per year (9 pieces in one batch)	*2,11*	*1,89*	*1,67*	*1,44*	*1,22*	*1,00*	*0,78*	*0,67*	*0,44*	*0,22*
Heat treatment cost per year	€ 190,00	€ 170,00	€ 150,00	€ 130,00	€ 110,00	€ 90,00	€ 70,00	€ 60,00	€ 40,00	€ 20,00
Post processing cost per 9 pieces	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*	*€ 577,96*
Post processing cost per year	€ 1.220,13	€ 1.091,69	€ 963,26	€ 834,83	€ 706,39	€ 577,96	€ 449,52	€ 385,30	€ 256,87	€ 128,43
Amount of labor hours needed per part	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*
Labor cost per hour	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*
Labor cost per year	€ 285,00	€ 255,00	€ 225,00	€ 195,00	€ 165,00	€ 135,00	€ 105,00	€ 90,00	€ 60,00	€ 30,00
3D printing cost RH (excl. additional cost)	*€ 3.967,36*	*€ 3.549,75*	*€ 3.132,13*	*€ 2.714,51*	*€ 2.296,90*	*€ 1.879,28*	*€ 1.461,66*	*€ 1.252,85*	*€ 835,23*	*€ 417,62*
Cost with additional margin of 4%	€ 4.126,06	€ 3.691,74	€ 3.257,42	€ 2.823,09	€ 2.388,77	€ 1.954,45	€ 1.520,13	€ 1.302,97	€ 868,64	€ 434,32
RH Cost per year incl. 20% margin	**€ 4.951,27**	**€ 4.430,08**	**€ 3.908,90**	**€ 3.387,71**	**€ 2.866,53**	**€ 2.345,34**	**€ 1.824,15**	**€ 1.563,56**	**€ 1.042,37**	**€ 521,19**
3D printing costs of Burner Cup (BC)										
Forecast in year i	*3*	*3*	*3*	*2*	*2*	*2*	*2*	*1*	*1*	*1*
Volume BC (in kg)	*1,37*									
Material price per kg	*€ 75,00*									
Material cost per part	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*	*€ 102,75*
Material cost per year	€ 308,25	€ 308,25	€ 308,25	€ 205,50	€ 205,50	€ 205,50	€ 205,50	€ 102,75	€ 102,75	€ 102,75
Print cost per batch	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*	*€ 1.943,33*
Batches per year (4 pieces in one batch)	*0,75*	*0,75*	*0,75*	*0,5*	*0,5*	*0,5*	*0,5*	*0,25*	*0,25*	*0,25*
Print cost per year	€ 1.457,50	€ 1.457,50	€ 1.457,50	€ 971,66	€ 971,66	€ 971,66	€ 971,66	€ 485,83	€ 485,83	€ 485,83
Heat treatment cost per batch	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*	*€ 90,00*
Batches per year (4 pieces in one batch)	*0,75*	*0,75*	*0,75*	*0,5*	*0,5*	*0,5*	*0,5*	*0,25*	*0,25*	*0,25*
Heat treatment cost per year	€ 67,50	€ 67,50	€ 67,50	€ 45,00	€ 45,00	€ 45,00	€ 45,00	€ 22,50	€ 22,50	€ 22,50
Post processing cost per 4 pieces	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*	*€ 538,77*
Post processing cost per year	€ 404,08	€ 404,08	€ 404,08	€ 269,39	€ 269,39	€ 269,39	€ 269,39	€ 134,69	€ 134,69	€ 134,69
Amount of labor hours needed per part	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*	*0,5*
Labor cost per hour	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*	*€ 30,00*
Labor cost per year	€ 45,00	€ 45,00	€ 45,00	€ 30,00	€ 30,00	€ 30,00	€ 30,00	€ 15,00	€ 15,00	€ 15,00
3D printing cost BC (excl. additional cost)	*€ 2.282,32*	*€ 2.282,32*	*€ 2.282,32*	*€ 1.521,55*	*€ 1.521,55*	*€ 1.521,55*	*€ 1.521,55*	*€ 760,77*	*€ 760,77*	*€ 760,77*
Cost with additional margin of 4%	€ 2.373,62	€ 2.373,62	€ 2.373,62	€ 1.582,41	€ 1.582,41	€ 1.582,41	€ 1.582,41	€ 791,21	€ 791,21	€ 791,21
BC Cost per year incl. 20% margin	**€ 2.848,34**	**€ 2.848,34**	**€ 2.848,34**	**€ 1.898,89**	**€ 1.898,89**	**€ 1.898,89**	**€ 1.898,89**	**€ 949,45**	**€ 949,45**	**€ 949,45**
Total cost alternative 4b	***€ 16.251,71***	***€ 11.131,56***	***€ 10.157,48***	***€ 8.232,77***	***€ 7.258,69***	***€ 6.284,62***	***€ 5.310,54***	***€ 3.872,87***	***€ 2.898,79***	***€ 1.924,71***
NPV	**€ 14.774,28**	**€ 9.199,64**	**€ 7.631,47**	**€ 5.623,09**	**€ 4.507,08**	**€ 3.547,50**	**€ 2.725,15**	**€ 1.806,72**	**€ 1.229,37**	**€ 742,06**
Cumulative NPV	**€ 14.774,28**	**€ 23.973,92**	**€ 31.605,39**	**€ 37.228,48**	**€ 41.735,56**	**€ 45.283,06**	**€ 48.008,21**	**€ 49.814,93**	**€ 51.044,30**	**€ 51.786,36**

Table 26: LCC result of alternative 4b: invest in a large AM machine (continued).

L Amount to produce and travel distance input for LCA models

In Table 27 an overview of the number of pieces to produce per alternative during ten years of service is given (output of the LCC models). Notice that the amount to produce per alternative is not all the same, because we used MOQ's of 50 (alternatives 1 and 3a) and batches of 9, 4, 2, and 1 (alternatives 2, 3b). These MOQ/batches are applied using an MRP calculation and the forecasted amount explained in Appendix G. On the other hand, the amount for alternatives 4a and 4b are the same. In these two alternatives, we assumed that ATAG can order the components per piece. Thus, this amount is equal to the forecasted amount (see Appendix G).

Total pieces	*Alt. 1*	*Alt. 2*	*Alt. 3a*	*Alt. 3b*	*Alt. 4a+b*
wok head	150	108	100	*72*	*103*
WH repair			36	*36*	
roast head	150	108	100	*90*	*103*
RH repair			21	*21*	
Burner cup	50	20	50	20	20
BC repair			0	*0*	

Table 27: Input for the LCC models in GaBi Software.

The roast head and burner cup are shipped by boat from Malaysia to Rotterdam. Afterwards, it is stored in Moerdijk in the Netherlands. Whenever Slovenia needs a part for the assembly line it is shipped from Moerdijk to Slovenia. When ATAG places an order it is finally shipped from Slovenia to the warehouse in Duiven. The wok head is produced in Turkey. From Turkey, it goes straight to Slovenia by truck and when ATAG needs a wok head it is shipped to Duiven by a truck as well. For the alternatives to repair a component it was difficult to set a specific distance. However, ATAG travels on average 25 km to a consumer for repair (Kruisselbrink, 2021). Thus, we assume that for repair it takes 50 km to return and ship the broken component to and from Duiven. For outsourcing, we assumed to work with the distance from the outsource manufacturer in the UK where the components are sent by truck. An overview of the distances is given in Table 28.

	Distance by truck (in km)	*Distance by boat (in km)*
Turkey to Slovenia	1690	
Malaysia to Rotterdam		15000
Rotterdam to Moerdijk	130	
Moerdijk to Slovenia	1280	
Slovenia to Duiven	1200	
UK to Duiven	620	
Consumer to Duiven	25	
Duiven to Consumer	25	

Table 28: Travel distances per load (or component) by truck and boat.

M LCA flow charts of alternative 1: MOQ + CM

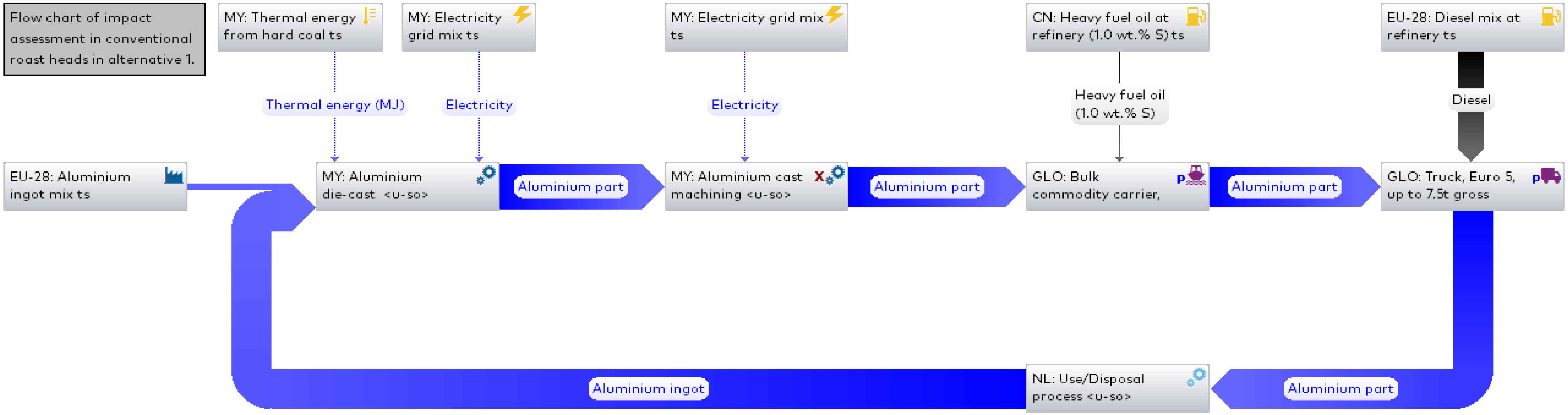

Figure 11: Flow chart of impact assessment in conventional roast heads in alternative 1: MOQ + CM.

Figure 12: Flow chart of impact assessment in conventional burner cups in alternative 1: MOQ + CM.

Component	*Process*	*Input*				*Output*			
		Parameter flow	*Quantities*	*Amount*	*Units*	*Parameter flow*	*Quantities*	*Amount*	*Units*
Roast head	MY: Aluminium die-cast	Aluminium ingot [Metals]	Mass	20,70	kg	Aluminium part [Metal parts]	Mass	19,80	kg
		Electricity [Electric power]	Energy (net calorific value)	69,15	MJ				
		Thermal energy (MJ) [Thermal energy]	Energy (net calorific value)	37,65	MJ				
	MY: Aluminium cast machining	Aluminium part [Metal parts]	Mass	19,80	kg	Aluminium part [Metal parts]	Mass	18,00	kg
		Electricity [Electric power]	Energy (net calorific value)	5,76	MJ				
	GLO: Bulk commodity carrier	Aluminium part [Metal parts]	Mass	18,00	kg	Aluminium part [Metal parts]	Mass	18,00	kg
		Heavy fuel oil (1.0 wt.% S) [Refinery products]	Mass	0,24	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Aluminium part [Metal parts]	Mass	18,00	kg	Aluminium part [Metal parts]	Mass	18,00	kg
		Diesel [Refinery products]	Mass	10,87	kg				
	NL: Use/Disposal process	Aluminium part [Metal parts]	Mass	18,00	kg	Aluminium ingot [Metals]	Mass	18,00	kg
Burner cup	MY: Aluminium die-cast	Aluminium ingot [Metals]	Mass	26,40	kg	Aluminium part [Metal parts]	Mass	25,30	kg
		Electricity [Electric power]	Energy (net calorific value)	88,50	MJ				
		Thermal energy (MJ) [Thermal energy]	Energy (net calorific value)	48,05	MJ				
	MY: Aluminium cast machining	Aluminium part [Metal parts]	Mass	25,30	kg	Aluminium part [Metal parts]	Mass	23,00	kg
		Electricity [Electric power]	Energy (net calorific value)	7,35	MJ				
	GLO: Bulk commodity carrier	Aluminium part [Metal parts]	Mass	23,00	kg	Aluminium part [Metal parts]	Mass	23,00	kg
		Heavy fuel oil (1.0 wt.% S) [Refinery products]	Mass	0,31	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Aluminium part [Metal parts]	Mass	23,00	kg	Aluminium part [Metal parts]	Mass	23,00	kg
		Diesel [Refinery products]	Mass	4,63	kg				
	NL: Use/Disposal process	Aluminium part [Metal parts]	Mass	23,00	kg	Aluminium ingot [Metals]	Mass	23,00	kg

Table 29: Input and output flows of fixed parameters in alternative 1: MOQ + CM (roast head and burner cup).

N LCA flow charts of alternative 2: outsource + MOQ + AM

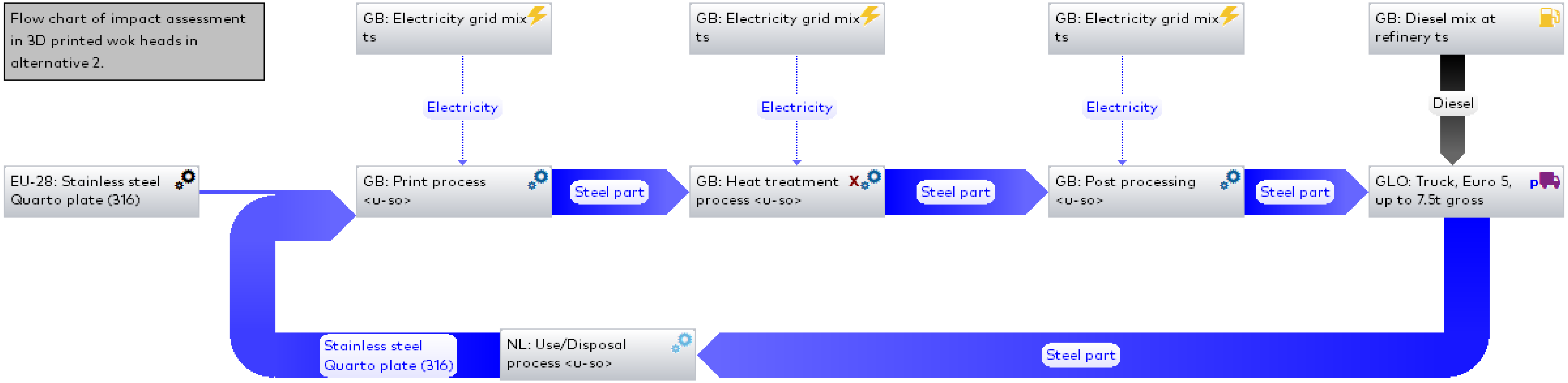

Figure 13: Flow chart of impact assessment in 3D printed wok heads in alternative 2: outsource + MOQ + AM.

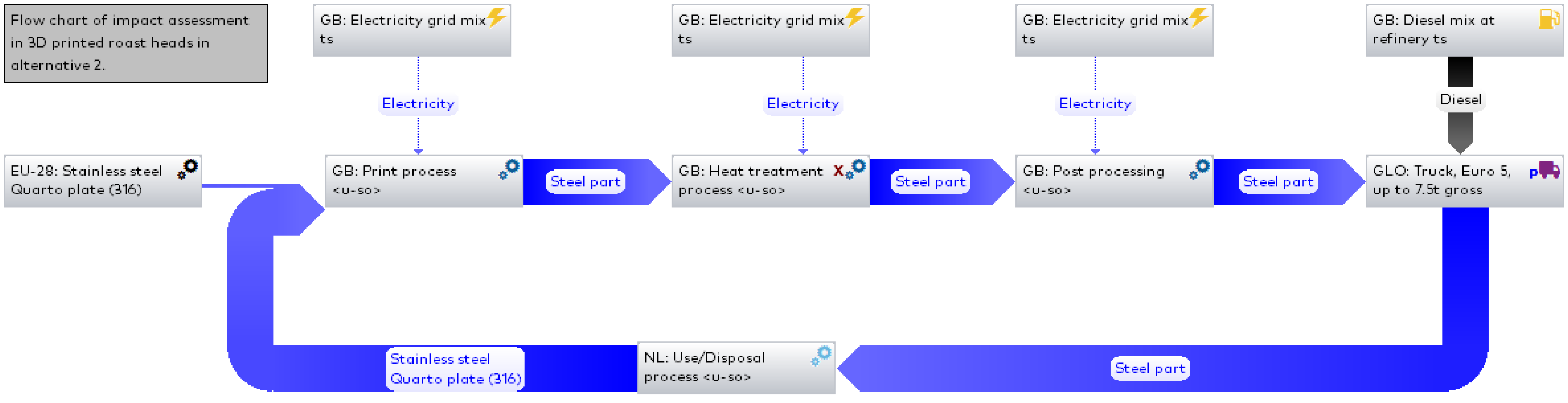

Figure 14: Flow chart of impact assessment in 3D printed roast heads in alternative 2: outsource + MOQ + AM.

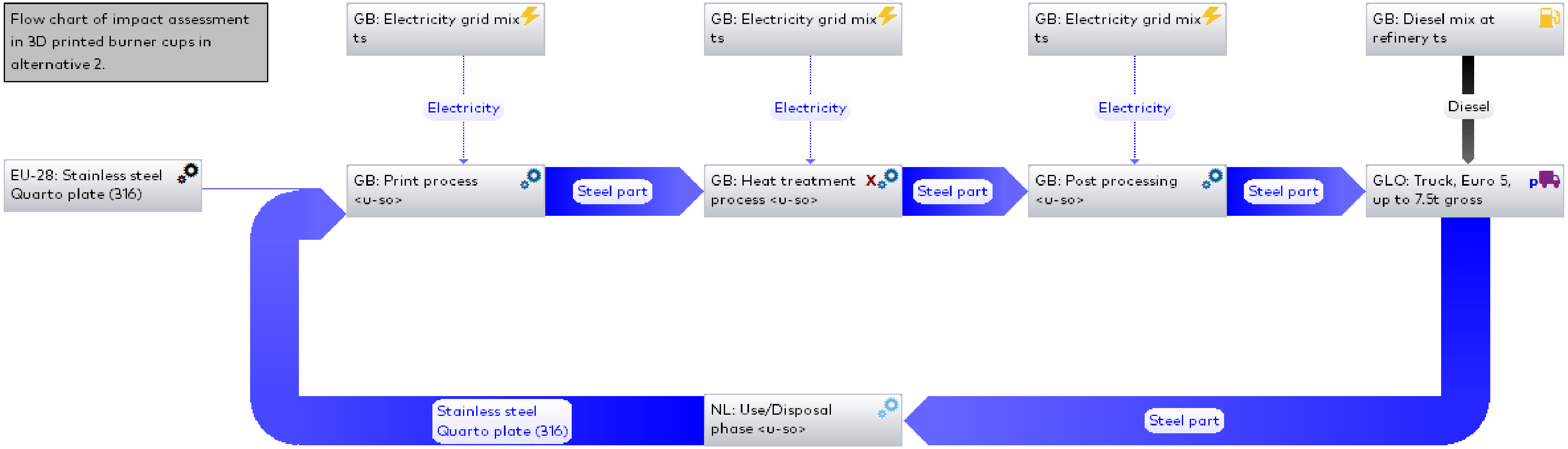

Figure 15: Flow chart of impact assessment in 3D printed burner cups in alternative 2: outsource + MOQ + AM.

Component	*Process*	*Input*				*Output*			
		Parameter flow	*Quantities*	*Amount*	*Units*	*Parameter flow*	*Quantities*	*Amount*	*Units*
Wok head	GB: Print process	Electricity [Electric power]	Energy (net calorific value)	132,84	MJ	Steel part [Metal parts]	Mass	33,48	kg
		Stainless steel Quarto plate (316) [Metals]	Mass	37,80	kg				
	GB: Heat treatment process	Electricity [Electric power]	Energy (net calorific value)	132,84	MJ	Steel part [Metal parts]	Mass	33,48	kg
		Steel part [Metal parts]	Mass	33,48	kg				
	GB: Post processing	Electricity [Electric power]	Energy (net calorific value)	11,02	MJ	Steel part [Metal parts]	Mass	33,48	kg
		Steel part [Metal parts]	Mass	33,48	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Diesel [Refinery products]	Mass	19,21	kg	Steel part [Metal parts]	Mass	33,48	kg
		Steel part [Metal parts]	Mass	33,48	kg				
	NL: Use/Disposal process	Steel part [Metal parts]	Mass	33,48	kg	Stainless steel Quarto plate (316) [Metals]	Mass	33,48	kg
Roast head	GB: Print process	Electricity [Electric power]	Energy (net calorific value)	132,84	MJ	Steel part [Metal parts]	Mass	38,88	kg
		Stainless steel Quarto plate (316) [Metals]	Mass	43,20	kg				
	GB: Heat treatment process	Electricity [Electric power]	Energy (net calorific value)	132,84	MJ	Steel part [Metal parts]	Mass	38,88	kg
		Steel part [Metal parts]	Mass	38,88	kg				
	GB: Post processing	Electricity [Electric power]	Energy (net calorific value)	11,02	MJ	Steel part [Metal parts]	Mass	38,88	kg
		Steel part [Metal parts]	Mass	38,88	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Diesel [Refinery products]	Mass	22,31	kg	Steel part [Metal parts]	Mass	38,88	kg
		Steel part [Metal parts]	Mass	38,88	kg				
	NL: Use/Disposal process	Steel part [Metal parts]	Mass	38,88	kg	Stainless steel Quarto plate (316) [Metals]	Mass	38,88	kg
Burner cup	GB: Print process	Electricity [Electric power]	Energy (net calorific value)	24,60	MJ	Steel part [Metal parts]	Mass	27,4	kg
		Stainless steel Quarto plate (316) [Metals]	Mass	29,00	kg				
	GB: Heat treatment process	Electricity [Electri power]	Energy (net calorific value)	24,60	MJ	Steel part [Metal parts]	Mass	27,4	kg
		Steel part [Metal parts]	Mass	27,40	kg				
	GB: Post processing	Electricity [Electric power]	Energy (net calorific value)	2,04	MJ	Steel part [Metal parts]	Mass	27,4	kg
		Steel part [Metal parts]	Mass	27,40	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Diesel [Refinery products]	Mass	6,55	kg	Steel part [Metal parts]	Mass	27,4	kg
		Steel part [Metal parts]	Mass	27,40	kg				
	NL: Use/Disposal process	Steel part [Metal parts]	Mass	27,40	kg	Stainless steel Quarto plate (316) [Metals]	Mass	27,4	kg

Table 30: Input and output flows of fixed parameters in alternative 2: outsource + MOQ + AM.

O LCA flow charts of alternative 3a: repair + MOQ + CM

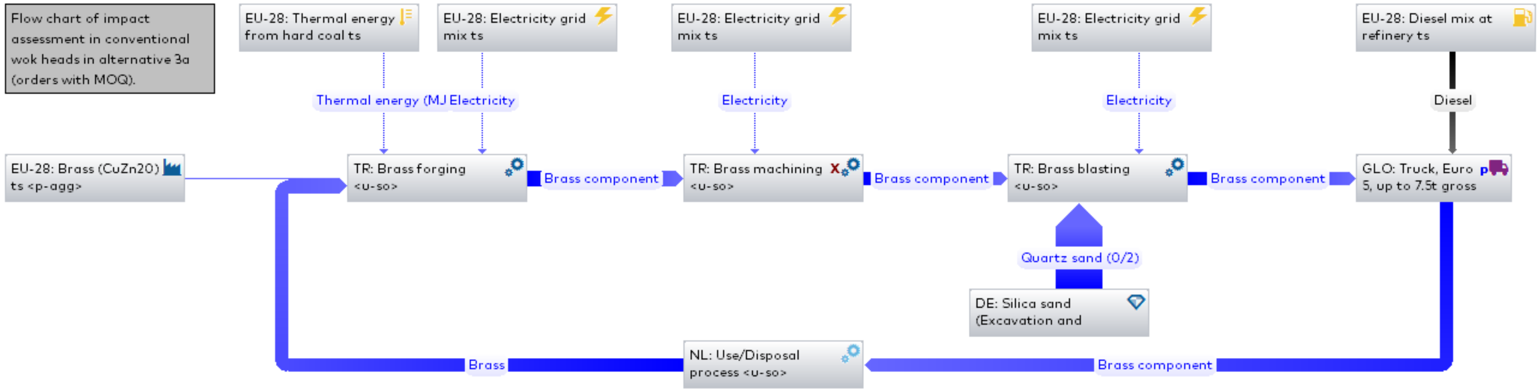

Figure 16: Flow chart of impact assessment in conventional wok heads in alternative 3a (orders with MOQ).

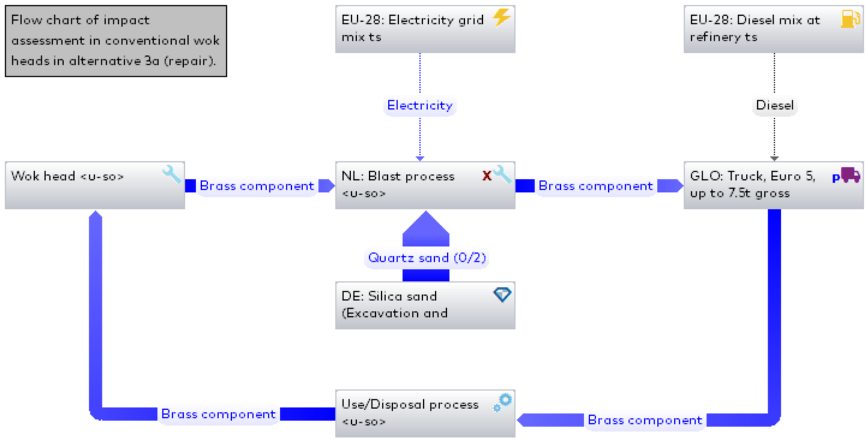

Figure 17: Flow chart of impact assessment in conventional wok heads in alternative 3a (repair).

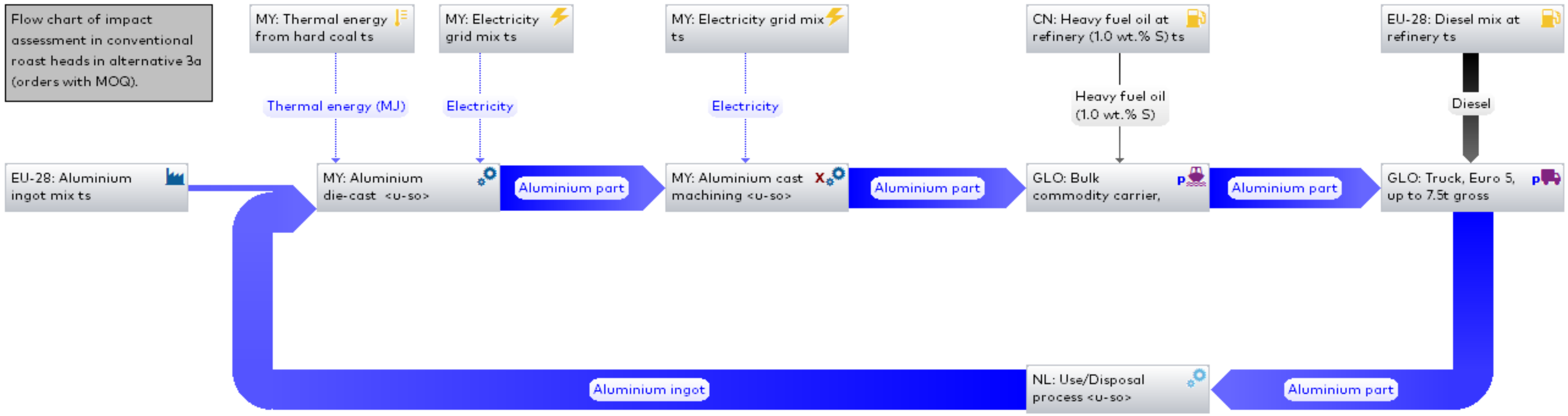

Figure 18: Flow chart of impact assessment in conventional roast heads in alternative 3a (orders with MOQ).

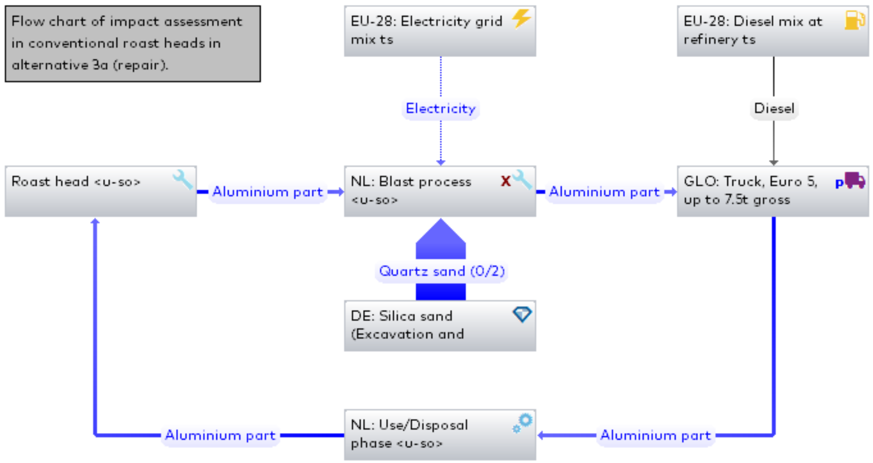

Figure 19: Flow chart of impact assessment in conventional roast heads in alternative 3a (repair).

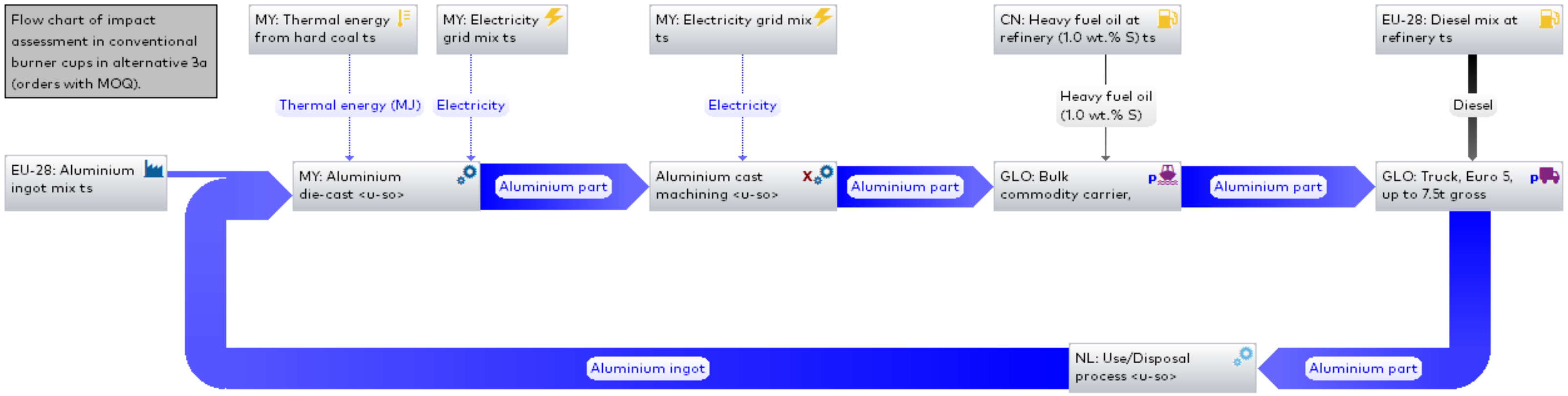

Figure 20: Flow chart of impact assessment in conventional burner cups in alternative 3a (orders with MOQ).

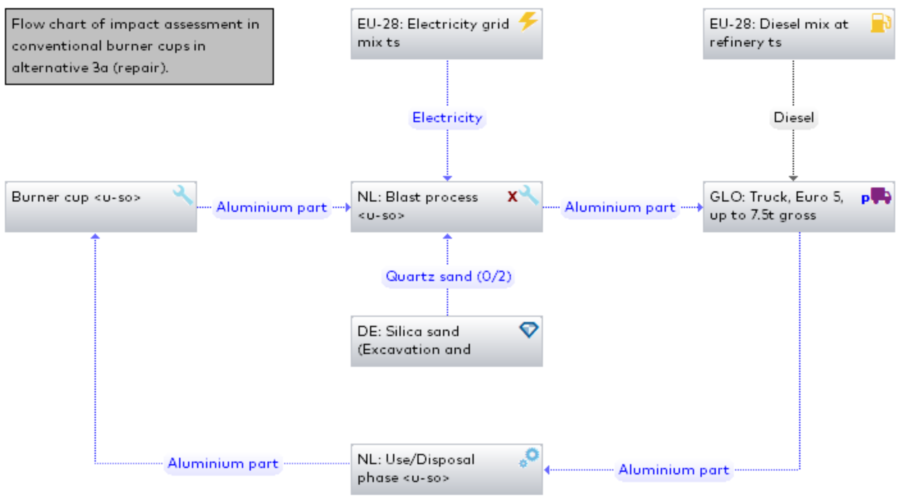

Figure 21: Flow chart of impact assessment in conventional burner cups in alternative 3a (repair).

Component	*Process*	*Input*				*Output*			
		Parameter flow	*Quantities*	*Amount*	*Units*	*Parameter flow*	*Quantities*	*Amount*	*Units*
Wok head (orders with MOQ)	TR: Brass forging	Brass [Metals]	Mass	36,80	kg	Brass component [Metal parts]	Mass	35,2	kg
		Electricity [Electric power]	Energy (net calorific value)	123,00	MJ				
		Thermal energy (MJ) [Thermal energy]	Energy (net calorific value)	66,80	MJ				
	TR: Brass machining	Brass component [Metal parts]	Mass	35,20	kg	Brass component [Metal parts]	Mass	32	kg
		Electricity [Electric power]	Energy (net calorific value)	10,20	MJ				
	TR: Brass blasting	Brass component [Metal parts]	Mass	32,00	kg	Brass component [Metal parts]	Mass	32	kg
		Electricity [Electric power]	Energy (net calorific value)	12,00	MJ				
		Quartz sand (0/2) [Minerals]	Mass	100,00	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Brass component [Metal parts]	Mass	32,00	kg	Brass component [Metal parts]	Mass	32	kg
		Diesel [Refinery products]	Mass	14,26	kg				
	NL: Use/Disposal process	Brass component [Metal parts]	Mass	32,00	kg	Brass [Metals]	Mass	32	kg
Roast head (orders with MOQ)	MY: Aluminium die-cast	Aluminium ingot [Metals]	Mass	13,80	kg	Aluminium part [Metal parts]	Mass	13,2	kg
		Electricity [Electric power]	Energy (net calorific value)	46,10	MJ				
		Thermal energy (MJ) [Thermal energy]	Energy (net calorific value)	25,10	MJ				
	MY: Aluminium cast machining	Aluminium part [Metal parts]	Mass	13,20	kg	Aluminium part [Metal parts]	Mass	12	kg
		Electricity [Electric power]	Energy (net calorific value)	3,84	MJ				
	GLO: Bulk commodity carrier	Aluminium part [Metal parts]	Mass	12,00	kg	Aluminium part [Metal parts]	Mass	12	kg
		Heavy fuel oil (1.0 wt.% S) [Refinery products]	Mass	0,16	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Aluminium part [Metal parts]	Mass	12,00	kg	Aluminium part [Metal parts]	Mass	12	kg
		Diesel [Refinery products]	Mass	4,83	kg				
	NL: Use/Disposal process	Aluminium part [Metal parts]	Mass	12,00	kg	Aluminium ingot [Metals]	Mass	12	kg
Burner cup (orders with MOQ)	MY: Aluminium die-cast	Aluminium ingot [Metals]	Mass	26,40	kg	Aluminium part [Metal parts]	Mass	25,3	kg
		Electricity [Electric power]	Energy (net calorific value)	88,50	MJ				
		Thermal energy (MJ) [Thermal energy]	Energy (net calorific value)	48,05	MJ				
	MY: Aluminium cast machining	Aluminium part [Metal parts]	Mass	25,30	kg	Aluminium part [Metal parts]	Mass	23	kg
		Electricity [Electric power]	Energy (net calorific value)	7,35	MJ				
	GLO: Bulk commodity carrier	Aluminium part [Metal parts]	Mass	23,00	kg	Aluminium part [Metal parts]	Mass	23	kg
		Heavy fuel oil (1.0 wt.% S) [Refinery products]	Mass	0,31	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Aluminium part [Metal parts]	Mass	23,00	kg	Aluminium part [Metal parts]	Mass	23	kg
		Diesel [Refinery products]	Mass	4,63	kg				
	NL: Use/Disposal process	Aluminium part [Metal parts]	Mass	23,00	kg	Aluminium ingot [Metals]	Mass	23	kg

Table 31: Input and output flows of fixed parameters in alternative 3a: repair + MOQ + CM.

Component	*Process*	*Input*				*Output*			
		Parameter flow	*Quantities*	*Amount*	*Units*	*Parameter flow*	*Quantities*	*Amount*	*Units*
Wok head (repair)	NL: Blast process	Brass component [Metal parts]	Mass	11,16	kg	Brass component [Metal parts]	Mass	11,16	kg
		Electricity [Electric power]	Energy (net calorific value)	4,32	MJ				
		Quartz sand (0/2) [Minerals]	Mass	36,00	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Brass component [Metal parts]	Mass	11,16	kg	Brass component [Metal parts]	Mass	11,16	kg
		Diesel [Refinery products]	Mass	0,00	kg				
	NL: Use/Disposal process	Brass component [Metal parts]	Mass	11,16	kg	Brass component [Metal parts]	Mass	11,16	kg
Roast head (repair)	NL: Blast process	Aluminium part [Metal parts]	Mass	2,52	kg	Aluminium part [Metal parts]	Mass	2,52	kg
		Electricity [Electric power]	Energy (net calorific value)	2,52	MJ				
		Quartz sand (0/2) [Minerals]	Mass	21,00	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Aluminium part [Metal parts]	Mass	2,52	kg	Aluminium part [Metal parts]	Mass	2,52	kg
		Diesel [Refinery products]	Mass	0,20	kg				
	NL: Use/Disposal process	Aluminium part [Metal parts]	Mass	2,52	kg	Aluminium part [Metal parts]	Mass	2,52	kg
Burner cup (repair)	NL: Blast process	Aluminium part [Metal parts]	Mass	0,00	kg	Aluminium part [Metal parts]	Mass	2,52	kg
		Electricity [Electric power]	Energy (net calorific value)	0,00	MJ				
		Quartz sand (0/2) [Minerals]	Mass	0,00	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Aluminium part [Metal parts]	Mass	0,00	kg	Aluminium part [Metal parts]	Mass	2,52	kg
		Diesel [Refinery products]	Mass	0,00	kg				
	NL: Use/Disposal process	Aluminium part [Metal parts]	Mass	0,00	kg	Aluminium part [Metal parts]	Mass	2,52	kg

Table 32: Input and output flows of fixed parameters in alternative 3a: repair + MOQ + CM (continued).

P LCA flow charts of alternative 3b: repair + outsource + MOQ + AM

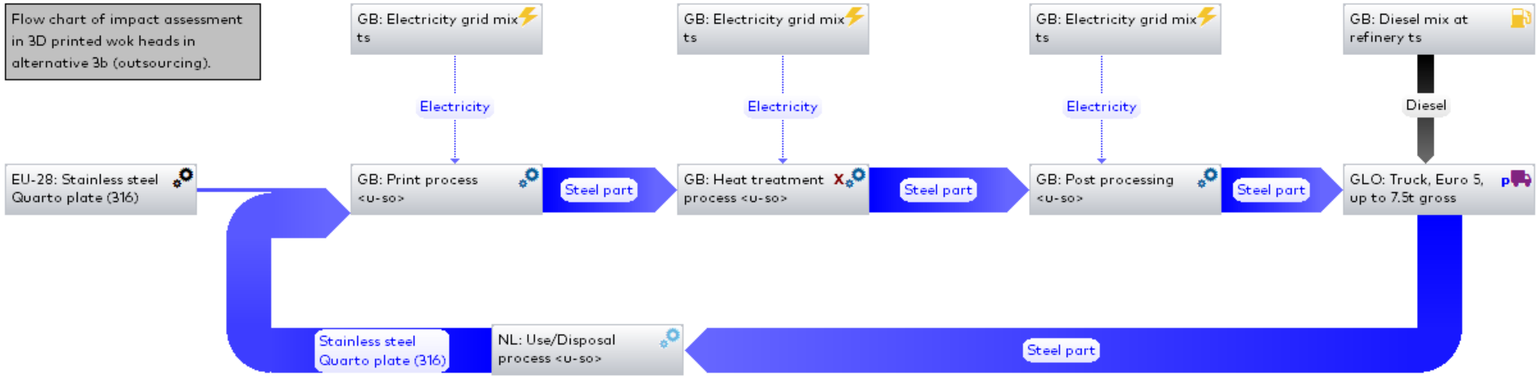

Figure 22: Flow chart of impact assessment in 3D printed wok heads in alternative 3b (outsource + MOQ).

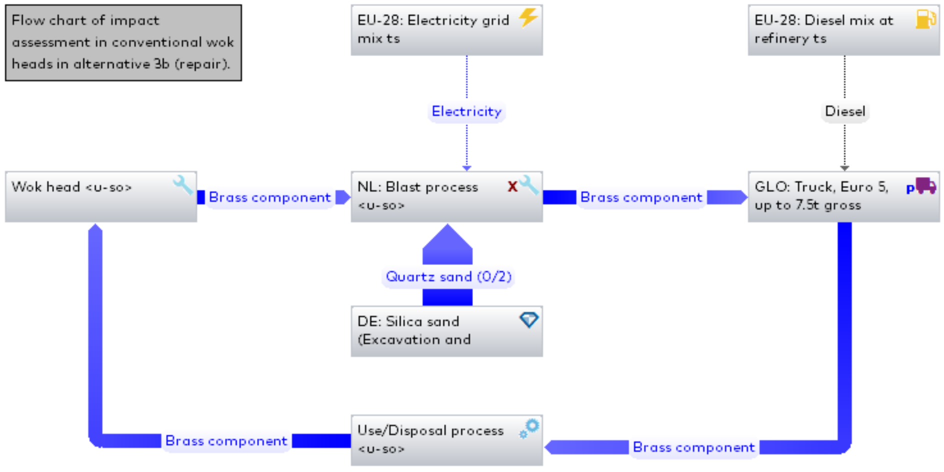

Figure 23: Flow chart of impact assessment in 3D printed wok heads in alternative 3b (repair).

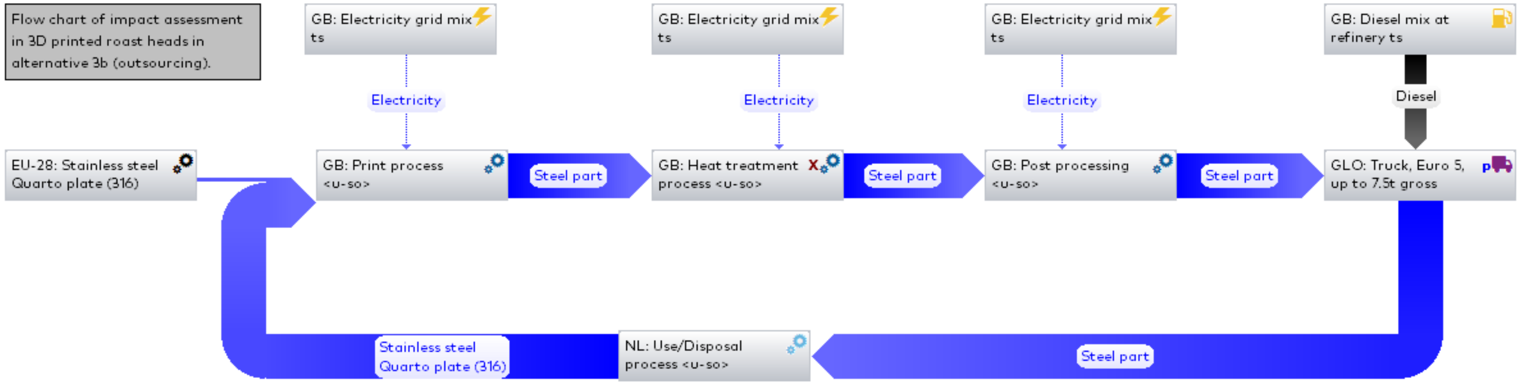

Figure 24: Flow chart of impact assessment in 3D printed roast heads in alternative 3b (outsource + MOQ).

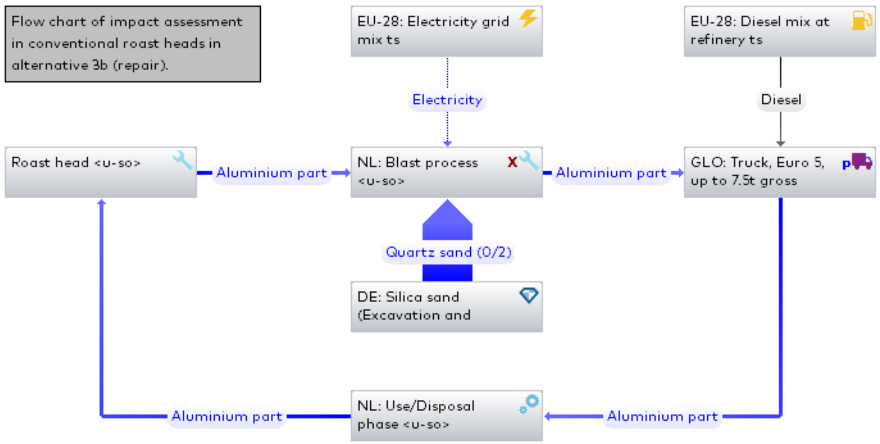

Figure 25: Flow chart of impact assessment in 3D printed roast heads in alternative 3b (repair).

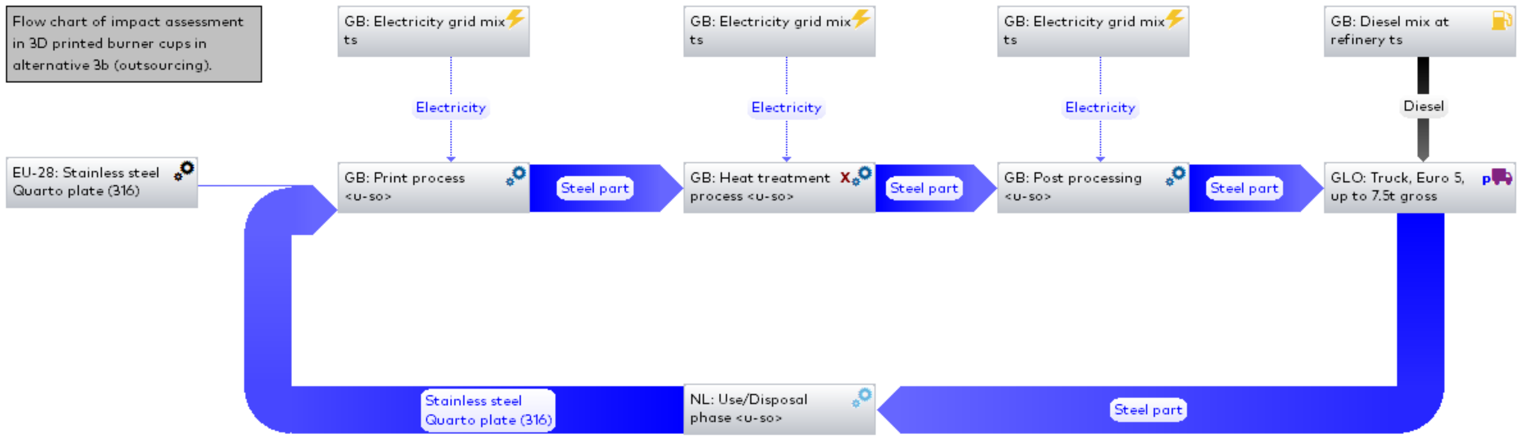

Figure 26: Flow chart of impact assessment in 3D printed burner cups in alternative 3b (outsource + MOQ).

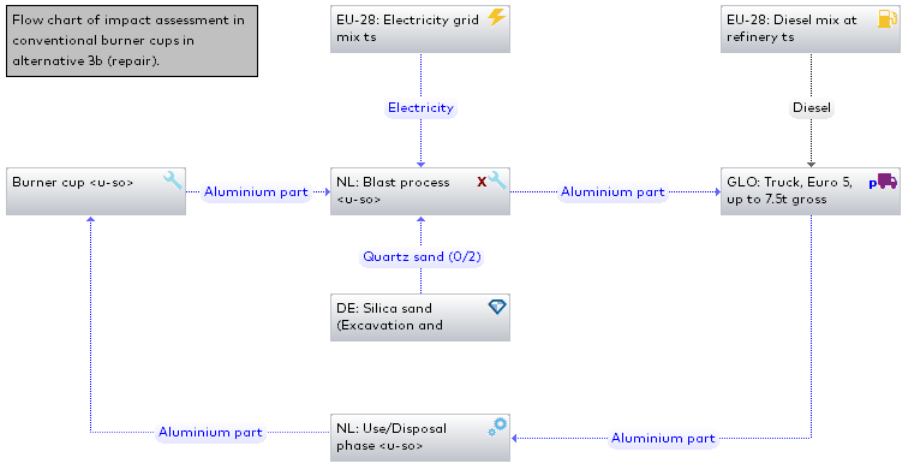

Figure 27: Flow chart of impact assessment in 3D printed burner cups in alternative 3b (repair).

Component	*Process*	*Input*				*Output*			
		Parameter flow	*Quantities*	*Amount*	*Units*	*Parameter flow*	*Quantities*	*Amount*	*Units*
Wok head *(outsource + MOQ)*	GB: Print process	Electricity [Electric power]	Energy (net calorific value)	88,56	MJ	Steel part [Metal parts]	Mass	22,32	kg
		Stainless steel Quarto plate (316) [Metals]	Mass	25,20	kg				
	GB: Heat treatment process	Electricity [Electric power]	Energy (net calorific value)	88,56	MJ	Steel part [Metal parts]	Mass	22,32	kg
		Steel part [Metal parts]	Mass	22,32	kg				
	GB: Post processing	Electricity [Electric power]	Energy (net calorific value)	7,34	MJ	Steel part [Metal parts]	Mass	22,32	kg
		Steel part [Metal parts]	Mass	22,32	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Diesel [Refinery products]	Mass	8,54	kg	Steel part [Metal parts]	Mass	22,32	kg
		Steel part [Metal parts]	Mass	22,32	kg				
	NL: Use/Disposal process	Steel part [Metal parts]	Mass	22,32	kg	Stainless steel Quarto plate (316) [Metals]	Mass	22,32	kg
Roast head (outsource + MOQ)	GB: Print process	Electricity [Electric power]	Energy (net calorific value)	110,70	MJ	Steel part [Metal parts]	Mass	32,4	kg
		Stainless steel Quarto plate (316) [Metals]	Mass	36,00	kg				
	GB: Heat treatment process	Electricity [Electric power]	Energy (net calorific value)	110,70	MJ	Steel part [Metal parts]	Mass	32,4	kg
		Steel part [Metal parts]	Mass	32,40	kg				
	GB: Post processing	Electricity [Electric power]	Energy (net calorific value)	9,18	MJ	Steel part [Metal parts]	Mass	32,4	kg
		Steel part [Metal parts]	Mass	32,40	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Diesel [Refinery products]	Mass	15,49	kg	Steel part [Metal parts]	Mass	32,4	kg
		Steel part [Metal parts]	Mass	32,40	kg				
	NL: Use/Disposal process	Steel part [Metal parts]	Mass	32,40	kg	Stainless steel Quarto plate (316) [Metals]	Mass	32,4	kg
Burner cup (outsource + MOQ)	GB: Print process	Electricity [Electric power]	Energy (net calorific value)	24,60	MJ	Steel part [Metal parts]	Mass	27,4	kg
		Stainless steel Quarto plate (316) [Metals]	Mass	29,00	kg				
	GB: Heat treatment process	Electricity [Electric power]	Energy (net calorific value)	24,60	MJ	Steel part [Metal parts]	Mass	27,4	kg
		Steel part [Metal parts]	Mass	27,40	kg				
	GB: Post processing	Electricity [Electric power]	Energy (net calorific value)	2,04	MJ	Steel part [Metal parts]	Mass	27,4	kg
		Steel part [Metal parts]	Mass	27,40	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Diesel [Refinery products]	Mass	6,55	kg	Steel part [Metal parts]	Mass	27,4	kg
		Steel part [Metal parts]	Mass	27,40	kg				
	NL: Use/Disposal process	Steel part [Metal parts]	Mass	27,40	kg	Stainless steel Quarto plate (316) [Metals]	Mass	27,4	kg

Table 33: Input and output flows of fixed parameters in alternative 3b: repair + outsource + MOQ + AM.

Component	*Process*	*Input*				*Output*			
		Parameter flow	*Quantities*	*Amount*	*Units*	*Parameter flow*	*Quantities*	*Amount*	*Units*
Wok head (repair)	NL: Blast process	Brass component [Metal parts]	Mass	11,16	kg	Brass component [Metal parts]	Mass	11,16	kg
		Electricity [Electric power]	Energy (net calorific value)	4,32	MJ				
		Quartz sand (0/2) [Minerals]	Mass	36,00	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Brass component [Metal parts]	Mass	11,16	kg	Brass component [Metal parts]	Mass	11,16	kg
		Diesel [Refinery products]	Mass	0,00	kg				
	NL: Use/Disposal process	Brass component [Metal parts]	Mass	11,16	kg	Brass component [Metal parts]	Mass	11,16	kg
Roast head (repair)	NL: Blast process	Aluminium part [Metal parts]	Mass	2,52	kg	Aluminium part [Metal parts]	Mass	2,52	kg
		Electricity [Electric power]	Energy (net calorific value)	2,52	MJ				
		Quartz sand (0/2) [Minerals]	Mass	21,00	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Aluminium part [Metal parts]	Mass	2,52	kg	Aluminium part [Metal parts]	Mass	2,52	kg
		Diesel [Refinery products]	Mass	0,20	kg				
	NL: Use/Disposal process	Aluminium part [Metal parts]	Mass	2,52	kg	Aluminium part [Metal parts]	Mass	2,52	kg
Burner cup (repair)	NL: Blast process	Aluminium part [Metal parts]	Mass	0,00	kg	Aluminium part [Metal parts]	Mass	2,52	kg
		Electricity [Electric power]	Energy (net calorific value)	0,00	MJ				
		Quartz sand (0/2) [Minerals]	Mass	0,00	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Aluminium part [Metal parts]	Mass	0,00	kg	Aluminium part [Metal parts]	Mass	2,52	kg
		Diesel [Refinery products]	Mass	0,00	kg				
	NL: Use/Disposal process	Aluminium part [Metal parts]	Mass	0,00	kg	Aluminium part [Metal parts]	Mass	2,52	kg

Table 34: Input and output flows of fixed parameters in alternative 3b: repair + outsource + MOQ + AM (continued).

Q LCA flow charts of alternatives 4a & 4b: invest in a small AM machine & invest in a large AM machine

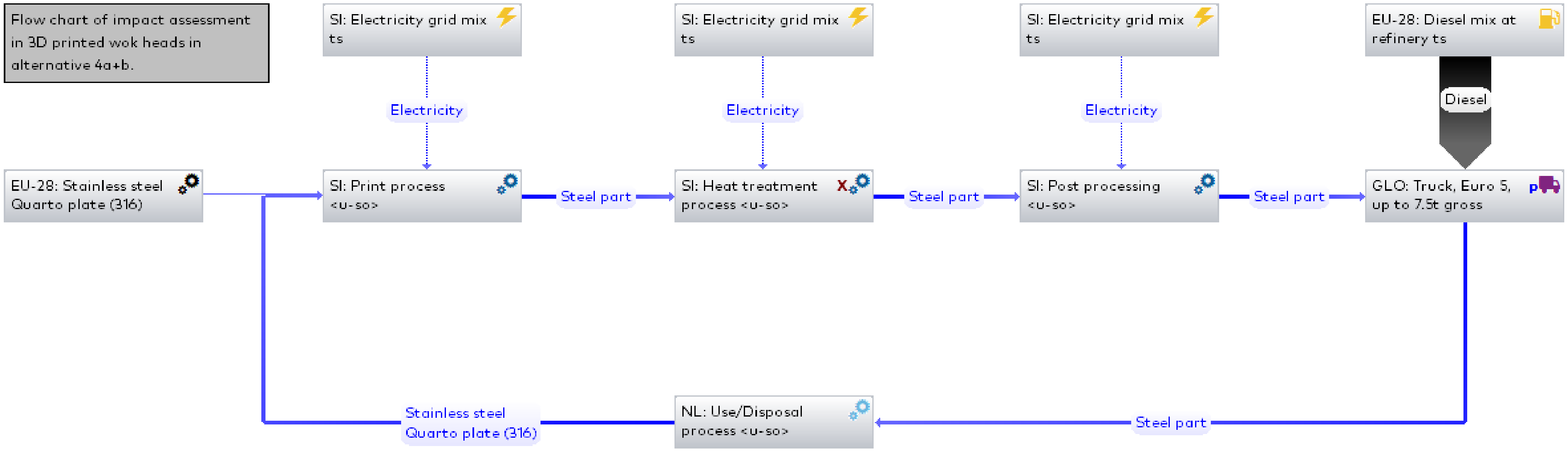

Figure 28: Flow chart of impact assessment in 3D printed wok heads in alternatives 4a & 4b.

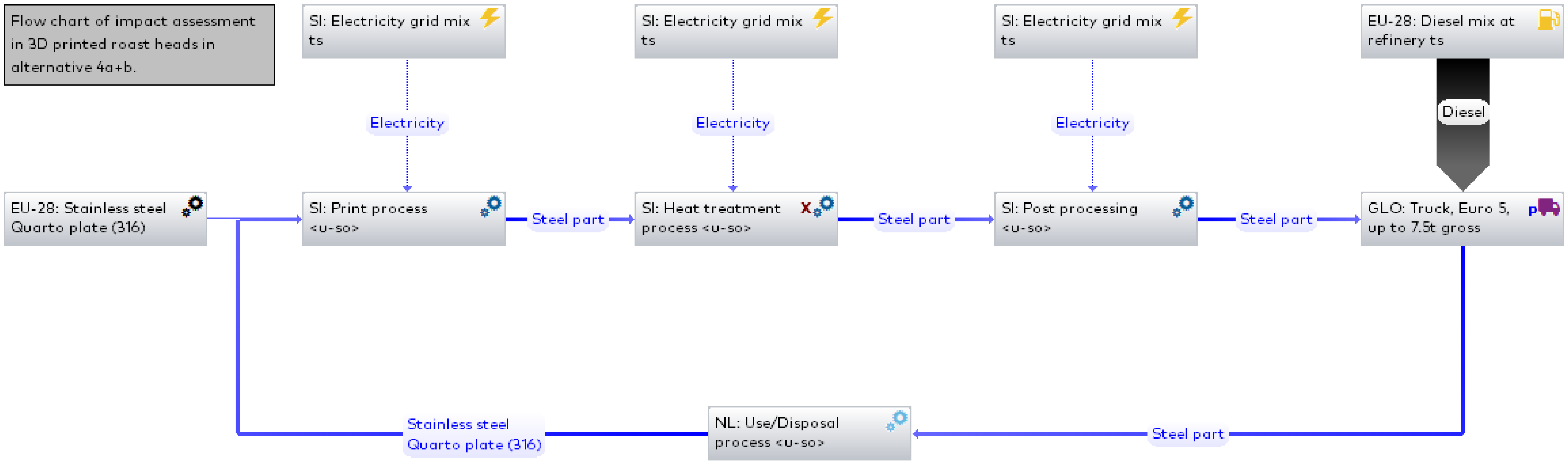

Figure 29: Flow chart of impact assessment in 3D printed roast heads in alternatives 4a & 4b.

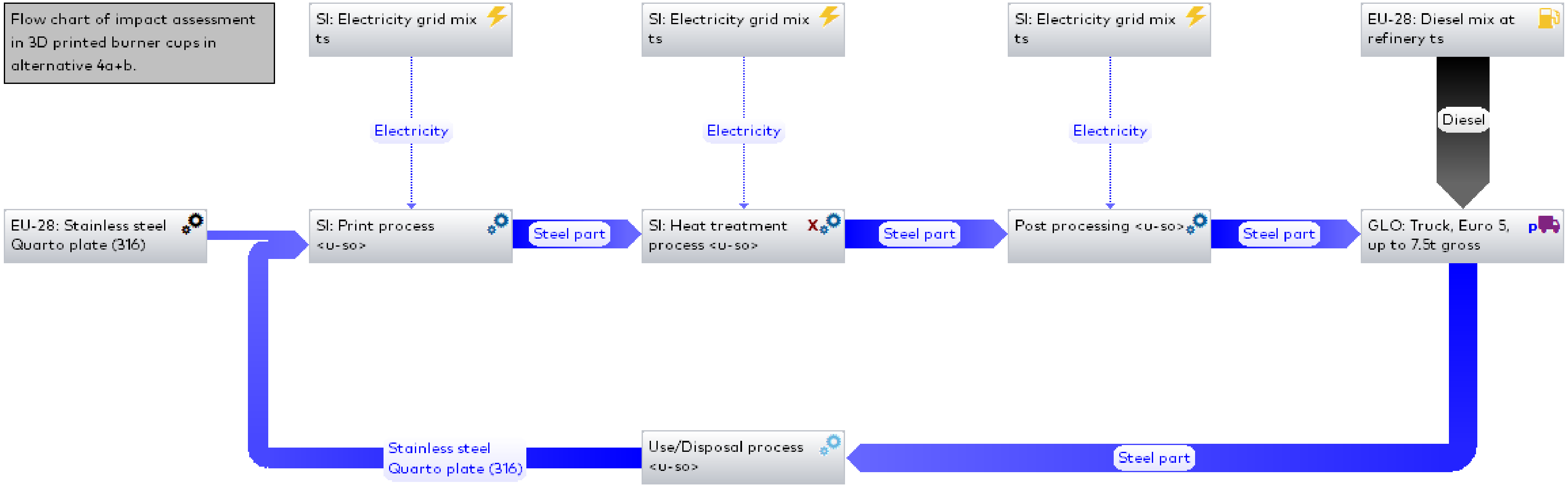

Figure 30: Flow chart of impact assessment in 3D printed burner cups in alternatives 4a & 4b.

Component	*Process*	*Input*				*Output*			
		Parameter flow	*Quantities*	*Amount*	*Units*	*Parameter flow*	*Quantities*	*Amount*	*Units*
Wok head	SI: Print process	Electricity [Electric power]	Energy (net calorific value)	126,69	MJ	Steel part [Metal parts]	Mass	31,93	kg
		Stainless steel Quarto plate (316) [Metals]	Mass	36,05	kg				
	SI: Heat treatment process	Electricity [Electric power]	Energy (net calorific value)	126,69	MJ	Steel part [Metal parts]	Mass	31,93	kg
		Steel part [Metal parts]	Mass	31,93	kg				
	SI: Post processing	Electricity [Electric power]	Energy (net calorific value)	10,51	MJ	Steel part [Metal parts]	Mass	31,93	kg
		Steel part [Metal parts]	Mass	31,93	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Diesel [Refinery products]	Mass	304,32	kg	Steel part [Metal parts]	Mass	31,93	kg
		Steel part [Metal parts]	Mass	31,93	kg				
	NL: Use/Disposal process	Steel part [Metal parts]	Mass	31,93	kg	Stainless steel Quarto plate (316) [Metals]	Mass	31,93	kg
Roast head	SI: Print process	Electricity [Electric power]	Energy (net calorific value)	126,69	MJ	Steel part [Metal parts]	Mass	37,08	kg
		Stainless steel Quarto plate (316) [Metals]	Mass	41,20	kg				
	SI: Heat treatment process	Electricity [Electric power]	Energy (net calorific value)	126,69	MJ	Steel part [Metal parts]	Mass	37,08	kg
		Steel part [Metal parts]	Mass	37,08	kg				
	SI: Post processing	Electricity [Electric power]	Energy (net calorific value)	10,51	MJ	Steel part [Metal parts]	Mass	37,08	kg
		Steel part [Metal parts]	Mass	37,08	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Diesel [Refinery products]	Mass	353,41	kg	Steel part [Metal parts]	Mass	37,08	kg
		Steel part [Metal parts]	Mass	37,08	kg				
	NL: Use/Disposal process	Steel part [Metal parts]	Mass	37,08	kg	Stainless steel Quarto plate (316) [Metals]	Mass	37,08	kg
Burner cup	SI: Print process	Electricity [Electric power]	Energy (net calorific value)	24,60	MJ	Steel part [Metal parts]	Mass	27,4	kg
		Stainless steel Quarto plate (316) [Metals]	Mass	29,00	kg				
	SI: Heat treatment process	Electricity [Electric power]	Energy (net calorific value)	24,60	MJ	Steel part [Metal parts]	Mass	27,4	kg
		Steel part [Metal parts]	Mass	27,40	kg				
	SI: Post processing	Electricity [Electric power]	Energy (net calorific value)	2,04	MJ	Steel part [Metal parts]	Mass	27,4	kg
		Steel part [Metal parts]	Mass	27,40	kg				
	GLO: Truck, Euro 5, up to 7.5t gross	Diesel [Refinery products]	Mass	6,55	kg	Steel part [Metal parts]	Mass	27,4	kg
		Steel part [Metal parts]	Mass	27,40	kg				
	NL: Use/Disposal process	Steel part [Metal parts]	Mass	27,40	kg	Stainless steel Quarto plate (316) [Metals]	Mass	27,4	kg

Table 35: Input and output flows of fixed parameters in alternatives 4a & 4b (invest in new AM machines).