sustainability

MDPI

Article

Life Cycle Assessment of a Circularity Case Study Using Additive Manufacturing

Joana R. Gouveia *,†, Sara M. Pinto †, Sara Campos †, João R. Matos †, Catarina Costa, Thiago Assis Dutra, Sílvia Esteves and Luís Oliveira

INEGI—Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial, 4200-465 Porto, Portugal; smpinto@inegi.up.pt (S.M.P.); scampos@inegi.up.pt (S.C.); jrmatos@inegi.up.pt (J.R.M.); clcosta@inegi.up.pt (C.C.); tdutra@inegi.up.pt (T.A.D.); sesteves@inegi.up.pt (S.E.); loliveira@inegi.up.pt (L.O.)

* Correspondence: jrgouveia@inegi.up.pt; Tel.: +351-229-578-710

† These authors contributed equally to this work.

Abstract: Currently, considering the rising concern in climate change, there is a clear necessity for technologies that can prolong the useful life of products through the ability to repair, re-manufacture and refurbish. As such, additive manufacturing has been a subject of research due to its design and resource consumption capabilities. However, there is a lack of more detailed information regarding environmental performances, especially in Directed Energy Deposition technology. The present paper presents a life-cycle assessment of the production and use of Directed Energy Deposition, making use of foreground data to build a life-cycle inventory and quantify the potential impacts. The equipment is analyzed for its refurbishment capabilities on an obsolete mold, and compared with the environmental impact of producing a new mold through conventional technology. The compiled inventory with detailed and primary information will enrich the current literature on this technology. The impact results show that the robot, deposition table and security cell are the most relevant subsystems for the system production impacts. In the refurbishment analysis, the refurbished mold part has lower impacts than the conventionally produced, thus showing that there is great potential in using additive manufacturing for circular economy loops.

Keywords: life cycle assessment; additive manufacturing; circular economy; refurbishment; environmental impacts; directed energy deposition

Citation: Gouveia, J.R.; Pinto, S.M.; Campos, S.; Matos, J.R.; Costa, C.; Dutra, T.A.; Esteves, S.; Oliveira, L. Life Cycle Assessment of a Circularity Case Study Using Additive Manufacturing. *Sustainability* **2022**, *14*, 9557. https://doi.org/10.3390/su14159557

Academic Editor: Giovanni De Feo

Received: 9 July 2022
Accepted: 30 July 2022
Published: 3 August 2022

1. Introduction

The industry is faced with a huge challenge: to reduce the consumption of raw materials and energy consumption, while at the same time increasing plant productivity to meet growing consumer demand.

Additive Manufacturing (AM) has been the subject of extensive research in recent years, and it is seen as a feasible alternative to traditional manufacturing procedures. This technology allows the production of constant improvements to the products created without having to change tools of great economic value; hence, it has undeniable usefulness in prototyping, which is why, early in the life of this technology, many referred to it as "rapid prototyping".

Recognized as one of the pillars of Industry 4.0, AM is changing the logic of industrial processes by redefining the way things are performed, which results in economic, efficient and sustainable improvements. The capacity to easily make very complicated components, the near-complete automation, the range of materials that may be utilized, and the quantity of material saved, all translate into cost savings by removing the need for molds, punches, and skilled personnel.

Metal additive manufacturing, particularly Directed Energy Deposition (DED) technology, has been successfully used in the repair of high and low-mass metallic components [1–13]. During its lifetime, an extrusion mold may suffer from damage due friction and wear, or even become obsolete due to new requirements and specifications. The field of remanufacturing emerges to avoid the necessity of developing and producing, for example, a new mold [14], and to reduce the expenses related to these elements by machining the damaged region and filling it with deposited material. According to the literature [7], molds that are repaired using DED technologies can last as long as the respective original mold. In contrast, the use of traditional repairing processes, such as gas tungsten arc welding (GTAW), typically results in repaired parts that last between 12.5% and 29.2% of the original life without requiring additional repair [7]. This brings potential benefits in terms of environmental impact mitigation in production processes.

Indeed, the environmental performance of AM technology has been a current topic in research, usually analyzed through life cycle assessment (LCA) studies. LCA is a a standardize methodology [15,16] commonly applied to analyze and quantify the environmental impacts of products and systems in a wide range of sectors [17–23]. This methodology allows to gather the flows of energy and materials that occur in each life cycle stage, and quantify them into environmental impacts, to identify the main hotspots that contribute most to the total environmental impacts generated. LCA can be used as a tool for support to decision makers in establishing significant impact reduction action plans. However, only a few investigate the DED technology [7,13,14,24–26]. In this small bundle, all of them fail to provide a life cycle inventory (LCI) that details the composition of the machinery and auxiliary systems, to assess the system's production in terms of environmental performance.

Three studies [24–26] conducted a comparative LCA with conventional production of steel parts and came to contrary conclusions in determining the production process with the least environmental impacts, highlighting the broad variability of the DED technology in terms of production capabilities. Nonetheless, it may not be fully understood how different part designs and materials affect the environmental performance of the DED system, since only one study provided more information in terms of energy consumption and material deposition efficiency. One of the most recent studies [26], did not take into consideration the impacts resulting from the equipment's production in both scenarios. When comparing Computer Numeric Control (CNC) technology with AM, the results quantified through the ReCiPe method, showed that neither technology is better than the other. However, when analyzing by endpoints they find that CNC technology has a higher damage to the resources than DED. Additionally, as DED is a fairly new technology when compared to the traditional ones,the operation parameters have the potential to be even more optimized. In an energy-based approach to determine the potential environmental impacts of metal powders used by the DED, one paper [27] carried out a cradle-to-gate analysis based on the cumulative energy demand (CED). The DED system's production was once again left out of the scope. The authors provided a model that determines the CED for parts made of Ti-6A1-4V by DED which was applied to a topologically optimized bracket. They find that for the paper's case study, raw material production was the most CED-intensive process step.

In one study [13], the authors analyzed the sustainability of producing a metallic mold by AM compared to conventional techniques utilized, namely die casting of zinc parts for the automotive industry. The authors found that AM has lower impacts justified by better cooling properties of AM molds. Other advantages of using AM found in this case study were less energy demand, faster processing and lower cost. Improvement opportunities were found to be related to process parameter optimization. Similarly, another study [28] performed a comparative LCA for the production of a mold core to be integrated in Carbon Fiber-Reinforced Plastics (CFRP) production. The study compared AM and conventional manufacturing, exploring four manufacturing processes: casting with low-melting alloy, milling from plaster-like material Aquapor, AM with High Impact Polystyrene (HIPS), and AM with powder materials like salt. The last one showed better environmental performance when compared to the others evaluated. In contrast, the conventional product with the low-melting alloy had the worst environmental results. The authors exalted the need for a better understanding of AM technologies to increase efficiency and reduce environmental impacts.

Cerdas et al. [29] analyzed another advantage of AM technologies: decentralized manufacturing. Through LCA, the authors compared the environmental performance between distributed and traditional centralized manufacturing system. The case study was a glass frame, assuming the same final quality of the product for both technologies. Although the authors did not establish which technology has better environmental performance, they identified three main factors influencing the impact results: energy efficiency, the composition of the electricity mix where the product is printed, and the material used. The scarcity of papers related to AM environmental analyses was exalted by Saade, Yahia and Amor [30], also mentioning the lack of transparency in some studies, which is also evidenced in this literature review. The author concluded by specifying some AM characteristics that appear to be immeasurable by usual environmental LCAs such as complex designs, individualization, decreased hazardous exposure to workers, and fewer man-hours needed.

It is clear that there is a pattern of overlooking the potential impacts of the DED system production and its influence on the overall life cycle performance. When analyzing LCA studies of other AM technologies to see if this approach is also present, only one [31] considered the AM system's production.

Faludi et al. [31] presented an LCA where the authors measured the environmental impacts of Selective Laser Melting (SLM) technology, to determine the main hotspots, whether on the machine and supporting hardware, the material used (aluminum powder), or the energy consumed. Although in virtually all instances, the usage of power during printing had the greatest impact per part, the printer embodied effects, dominated these measures in several low-utilization situations. This emphasizes the importance of including machinery production in the scope of the LCA study, meaning that the current research may be overlooking relevant environmental impacts in their studies for different degrees of printer usage. In Výtisk et al. [32], the manufacturing of an air ejector and orifice plate was compared in terms of environmental performance, by conventional manufacturing and by SLM. Although the results showed that AM had higher impacts in more than half of the impact categories, the authors exalted the relevance in comparing AM and conventional manufacturing machines gate-to-gate, since the depreciation of machine tools for conventional production plays a major role in manufacturing processes.

In a broader analysis of the environmental performance of AM technologies, one research [33] elaborated an extensive review of eco-friendly AM processing of metal materials. The study conducted an analysis of energy efficiency and LCA of material production, product design and manufacturing, product distribution, usage and recycling stages. One of the main takeaways was that wire feedstock materials are more attractive than powder-based feedstock materials due to a faster printing rate. However, extrusion heads needed for wire feedstock are bigger than the ones needed for powder feedstock. Thus, it is crucial to include the impacts of the machinery when comparing technologies and even when comparing different feedstock materials.

More recently, Gouveia et al. [14] analyzed DED's capability of conducting repairing activities instead of producing new parts. The authors compared the environmental and cost performance of repairing a damaged mold using DED, with discarding and conventional production of a new mold. Here, the authors provided energy and material parameters for the DED operations, specifically for the H13 steel material. Although the LCI of the DED system was not provided, the environmental impacts of the DED production were considered in the final assessment of the case study.The results showed that the repairing process generated less environmental impacts and less costs when compared with convention manufacturing.

This paper presents the continuing work on the environmental analysis of the DED technology [14]. Specifically, the main goal is to provide a robust LCI of DED and to environmentally characterize the subsystems that compose this technology, in the circular activities enabled by AM. The purpose is to provide data that can be used in the future when analyzing the impacts of parts produced by DED. A case study for the refurbishment of an obsolete mold is presented to determine the potential environmental impact reduction that this technology can bring, in the context of a future (more) circular manufacturing industry.

Section 2 presents the gathering of data to build the LCI and the main case study of a circular application of the DED. First, a description of the equipment and the work conducted to select the main components of each subsystem component is presented (Section 2.1). Then, the approach utilized to collect and organize the life cycle data of the DED equipment per subsystem (Section 2.2) is conducted. The matching of the identified flows of energy and mass with the ecoinvent database is referenced in Appendix A. In addition, a mass representation per subsystem was analysed to ascertain the main contributions to each subsystem, on a material level. Then, a detailed description of the LCA case study is presented, together with an explanation of the applied refurbishment process (Section 2.3). Finally, the results are presented in Section 3. The environmental impacts of the DED system production were analysed, as well as the main impacts generated by each subsystem (Section 3.1). Subsequently, the life cycle environmental impacts of the refurbishment and the conventional production process were presented and compared (Section 3.2). Lastly, a discussion on the results is presented in Section 4, including a comparison with other studies in the literature. The final conclusions are drawn in Section 5.

2. Materials and Methods

2.1. DED Component Selection

The manufacturing process via DED is accomplished through the melting and projection of metallic powders, with the energy that triggers the process coming from a high-power laser beam. The following group of equipment refers to all the subsystems necessary for the functioning of this technology. Figures 1–3 present an overview of the subsystems that compose the DED.

2.1.1. Robot

In this system, a robotic arm (Figure 1a) with 6 degrees of freedom is used to perform the metallic powder deposition trajectories. Given the importance of the path followed during deposition, a high-precision KUKA industrial robot was selected, with the model number "KUKA KR 30 HA". It is characterized by a payload of up to 30 kg, a maximum reach radius of 2033 mm and repeatability of ±0.100 mm. The robot's control system is the KUKA KR C4.

2.1.2. Powder Feeder

The powder feeder (Figure 1b) has the specific function of transporting the metallic powder(s) to the printer head (located in the robot's terminal axis as seen in Figure 1f) with the desired mass flow. It is a vibrating platform-type device with its own controller. To protect the metallic powders from oxidation and to conduct their transport, the powder feeder uses an inert gas line. In this subsystem, Argon (Ar) is used as the inert gas. The powder feeder is from MEDICOAT, having two powder reservoirs and, consequently, two output lines.

2.1.3. Laser

The energy for the DED process is delivered by a high-energy laser source, depicted in Figure 2a. This laser acts as the source of energy for the fusion of metallic powders. The laser light is created by a ROFIN FL030, with a maximum power of 3 kW , which is guided to the process head by a 100 µm optical fiber cable. The laser source uses the manufacturer's controller to create the laser beam with a controllable duty cycle and power between 300 W and 3 kW.

2.1.4. Deposition Table

The system is designed to have a heated work surface (Figure 1c), to allow better control of the cooling of the deposited material and thus the quality of the final parts. The work surface is placed on a welding table with nominal dimensions of 2000 × 1000 mm. The table sits bellow a layer of insulating refractory fiber board. This insulation material acts as a thermal barrier between the table and the heaters. This is a set of 8 metal plates of equal size, evenly distributed on top of the insulation. In each of the heating plates, 12 electrical cartridge heaters are placed, each one with a maximum output power of 900 W.

It is intended that the heating system allows for a maximum and uniform 600 °C temperature over the entire work surface. In addition, the table system includes a metal sheet on top of the heaters to protect and isolate them from the process metallic powders. This metal shield also serves the purpose of enabling the collection of the waste powder left by the process.

2.1.5. Chiller

To ensure ideal operating temperatures of several components, the system has a water chiller. The chiller is pictured in Figure 2b. The water chiller is a LAUDA Ultracool UC-0180 with a total cooling capacity of 32.9 kW. Through a network of water hoses, the chilled water is pumped from the chiller unit to the internals of the laser source, to the optical fiber and tool head optics, the nozzle of the printer head and to the solid-state relays that control the output power of the heating table.

2.1.6. Security Cell

Taking into account the nature of the process and its equipment, the DED system design requires a prominent safety component. As such, the system is installed inside a metal cabin (Figure 2c), properly equipped with security elements. From a control point of view, the safety logic is implemented in a Beckhoff Programmable Logic Controller (PLC) with TwinSAFE safety terminals and programmed in TwinCAT 3 in the TwinSAFE environment. The PLC is pictured in Figure 3a.

Inside the metallic cabin, there is an electrical panel (Figure 1e) with safety functions. It has safety PLC terminals that communicate with the safety central PLC, where the respective logic is programmed. This electrical panel is equipped with an emergency button that can be activated inside the cell in an emergency, as well as a button to open the cabin door in case an operator is locked inside. The system is also equipped with a mobile safety console that has an emergency button, as well as buttons to control the locking/unlocking of the cabin door from the operator work station.

The system is equipped with a set of warning lights at strategic points so that the status of the system is intuitively detected by the operator and visible in the industrial area of the building. There are 3 sets of warning lights, two of which are located outside the cabin and one inside.

Each of the equipment that makes up the system has a safety circuit. In particular, the robot controller, the laser, and the powder feeder have internal and external safety circuits that are interconnected via the safety central PLC. Its installation was performed in such a way that if any of the equipment in the system is in an emergency, this state is propagated to the other equipment. This safety configuration makes it possible to use the robot and laser emergency stop button as an external emergency button for the entire system.

2.1.7. Structure

The structure of the cell is a metallic cabin, located in the industrial area of the building and corresponds to a large structure with a working volume of 6.5 × 5 × 3.4 m. The existence of this structure establishes a physical barrier between the place where the process occurs and the operator. Due to the high energy of the laser beam, it is not possible to carry out a print job with people inside the cabin, which thus acts as a fundamental safety element to protect humans from the laser light used. The metallic cabin has an access door to its interior. It is equipped with two door closing sensors, and an actuator that guarantees its locking. The control of the locking/unlocking of the door is performed from the safety PLC, properly programmed according to the state of the system.

The metallic cabin is equipped with a specific safety sensor for the laser. The Laser Spy (Figure 1d) corresponds to a set of sensors installed on the cabin walls that are linked together and form a redundant safety electrical circuit. Its function is to detect a possible breach of the cabin sheet metal by the laser beam and trigger the safety alert on the PLC that will immediately switch off the laser source.

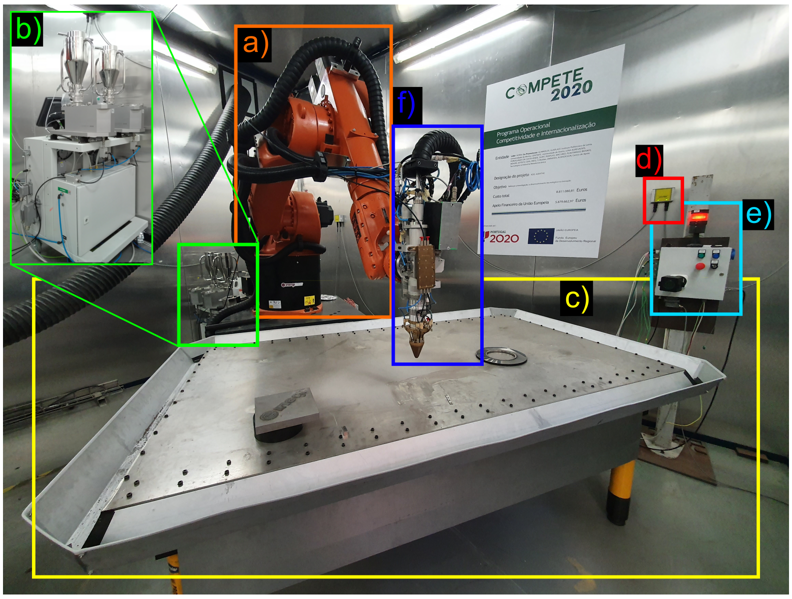

Figure 1. Inside view of the Security Cell. (**a**) Robot; (**b**) Powder Feeder; (**c**) Deposition Table; (**d**) Photosensitive Sensors; (**e**) Video Camera and electrical panel; (**f**) Printer Head.

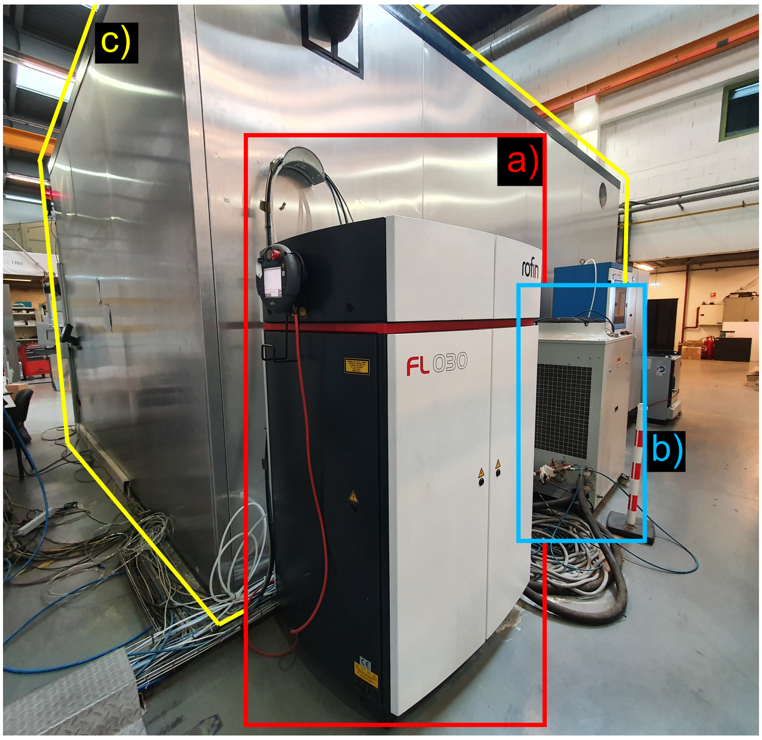

Figure 2. Outside back view of the Security Cell. (**a**) Laser; (**b**) Chiller; (**c**) Security Cell.

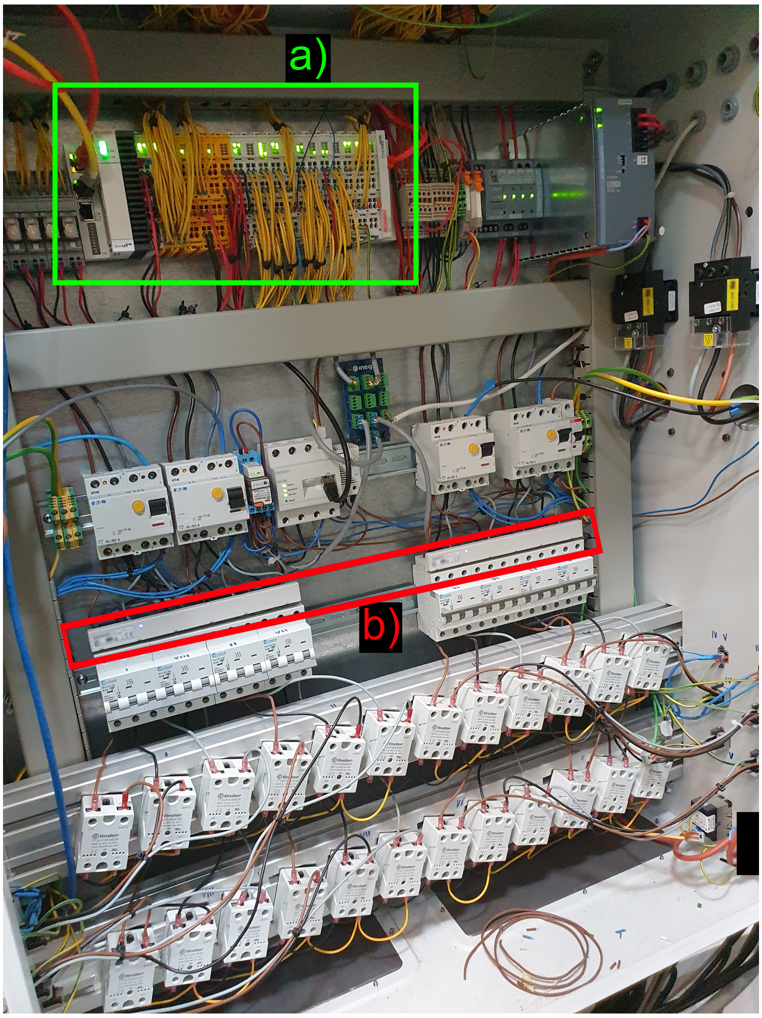

Figure 3. Inside view of the main control system electrical board. (**a**) Control PLC; (**b**) Electrical power sensors.

2.1.8. Control System

The central control point of the entire system is a Beckhoff PLC, pictured in Figure 3a. It establishes the communication between all the equipment, namely, between the process, safety, and auxiliary ones. The central PLC communicates via the EtherCAT protocol with the PLC inside the cabin, the robot controller and the powder feeder. Communication with the other components is performed by using the input and output terminals. The central PLC is installed in a central electrical panel, which also contains the solid-state relays that control the heating of the deposition surface. The information diagram of all equipment can be translated into a simplified schematic according to Figure 4.

The system has a video camera (Figure 1e) for real-time monitoring of the process from the outside of the security cell, as well as video recording for data analysis. It is a high-resolution camera with optical zoom from the manufacturer Abus. The camera is located inside the cabin and it gives the viewing point of the interior while deposition work is taking place. For this reason, the camera is exposed to laser radiation and must be equipped with a laser radiation filter that protects its lens and sensor from reflections of the laser beam. It is mounted on the electrical panel inside the cabin. Its data is sent via RTSP (Real Time Streaming Protocol) to the DED cell's internal network, from where it can be accessed to be transmitted by a video player.

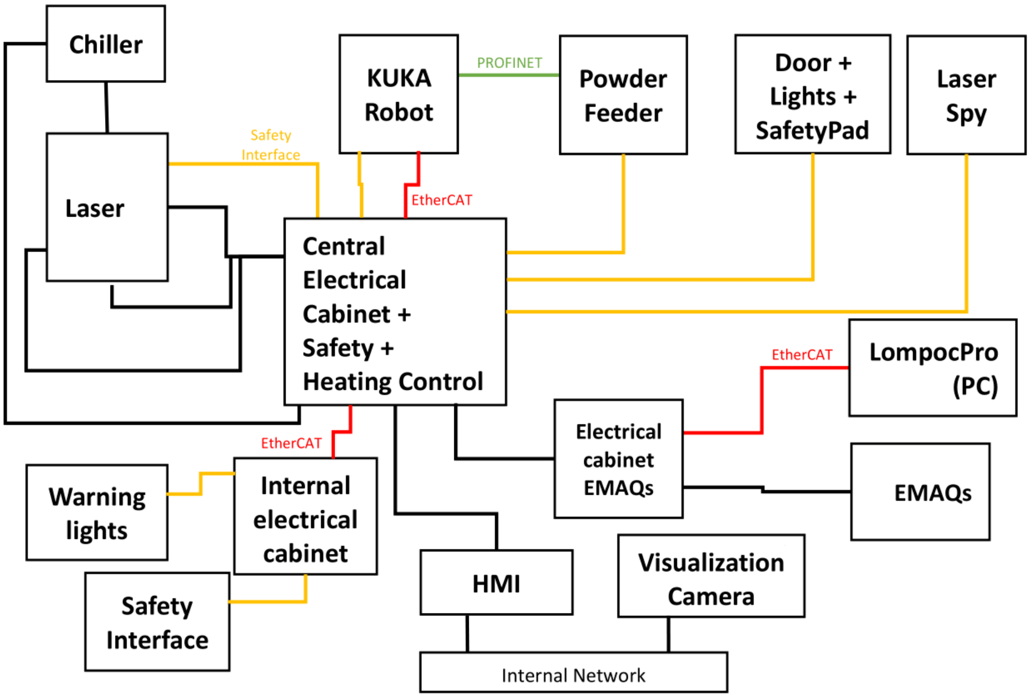

Figure 4. Schematic of the control interconnections for the DED system.

2.1.9. HMI

The system also includes an interface with the controller, which is depicted in Figure 5. It is an HMI (Human Machine Interface) where it is possible to establish communication with the various components of the system, being able to read their status and send commands. The HMI makes it possible to monitor the process variables of the different equipment in real time. This interface is implemented in a Beckhoff PC with a 23 inches monitor and is located next to the metallic cabin, on the outside.

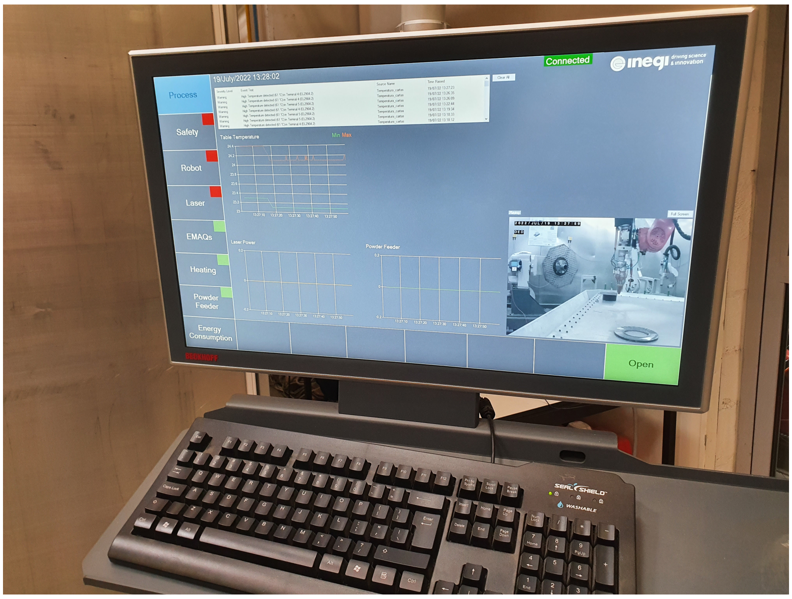

Figure 5. Humam Machine Interface of the DED system control system.

2.1.10. Printer Head

The printer head (Figure 1f) consists of a nozzle that conveys metal powder and inert gas to the deposition surface. The nozzle is model COAX12-V6 and is produced and marketed by Fraunhofer IWS. The laser, which contains optical fibers, enter the printer head in the collimator and passes through a set of optics that allow the laser beam to be focused, coaxially with the metallic powder, on the deposition surface. The ideal deposition point is located at a distance of 13 mm from the bottom of the printer head and corresponds to a laser beam focus of Ø1 mm.

The thermal camera installed on the printer head is the EMAQs camera system, developed by Fraunhofer IWS. This camera is tasked with measuring the temperature of the deposited material throughout the process. The camera system is controlled by a Beckhoff PLC. Inside the camera, there is a compressed air circuit to control a pneumatic actuator that enables an internal protection filter. The camera is mounted on the focusing optics assembly and can be integrated into an advanced temperature control system developed by the same manufacturer. LompocPro 8 software has a control algorithm that allows modulating the laser power as a function of the temperature of the deposited metallic powder, measured by the EMAQs camera. LompocPro 8 produces data files with measured temperature and/or laser power as a function of time, as well as camera images, for studying the process.

2.2. DED Life Cycle Inventory

The first step for the development of the study is related to the survey of the composition of the equipment referring to the DED system. Thus, it was necessary to collect information on the constitution of the machine at the component level, taking into account the total mass of each component and constituent materials, as well as manufacturing processes inherent to the production of the components themselves. It should be noted that the energy and mass flows that occur during the assembly of the DED machine were not considered. The DED machine was assembled and placed in the laboratory, where the study was conducted. As such, it was possible to organize field sessions to collect all the data necessary for the characterization of the equipment. Due to its complexity, the DED system was divided into several subsystems according to their function, and characterized at the component level within each of these subsystems, as shown in Figure 6.

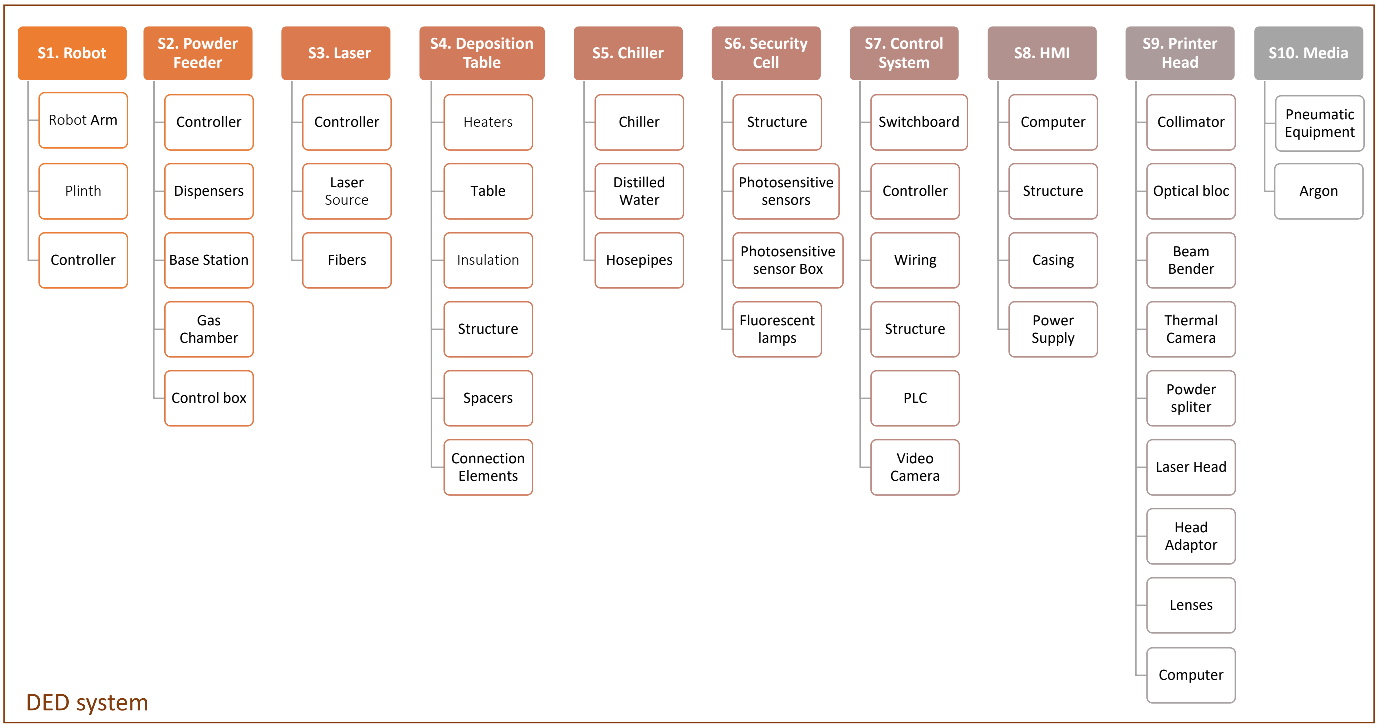

Figure 6. Composition of the DED subsystems.

The main data source came directly from the DED system development team. Through an exhaustive data collection, either in the collection of the references of the manufacturers of the components in situ or from the measurement of their dimensions, among other approaches, as well as through bibliographical research to define the material composition and respective mass quantities, it was possible to collect most of the information needed to build the DED system LCI. However, whenever there was a need to address the lack of information, the ecoinvent V3.7.1 database [34] and the existing literature were also consulted. For some components, it was not possible to collect enough information from the manufacturer, so it was necessary to search for similar components from other manufacturers that had the same function and apparent composition, to fill the lack of data. Thus, it was possible to build a DED machine inventory with high reliability and a similar level of detail for most subsystems.

In the case of the chiller subsystem, the information available in one paper for a chiller in an SLM system [31] was used (model SMC HRGC002-A). Through the analysis of this model, it was found that the underlying components were similar to the DED machine model LAUDA Ultracool UC -0060/0240. Thus, for the information in this inventory to be suitable for the DED system chiller, the quantities of the inventory components were adapted through a mass proportion, so that the total mass quantity of the original chiller inventory was equal to the total chiller mass of the DED system:

$$amount\ of\ component\ in\ the\ S5\ Chiller = \frac{amount\ of\ component\ in\ the\ literature\ Chiller \times weight\ of\ S5\ Chiller\ [\mathrm{kg}]}{weight\ of\ the\ literature\ Chiller\ [\mathrm{kg}]} \quad (1)$$

It should be noted that the inventory built for the DED system also includes most of the transformation processes in the production of each component, based on the approach present in Faludi et al. [31].

Taking into account the data collected for each subsystem, the life cycle data was uploaded into the SimaPro V.9.2.0.1 software [35]. Thus, for each material and manufacturing process, it was necessary to carry out the matching between the inventoried materials and manufacturing processes and those present in the ecoinvent V3.7.1 database. To avoid allocation within the transformation and treatment systems [15,16], the allocation library at the point of substitution (APOS) was selected. The efficiency of the system in terms of material deposition was determined by computing the relation between the amount of material that was deposited in the piece and the total amount that was provided by the powder feeder:

$$material\ deposition\ efficiency\ [\%] = \frac{material\ deposited\ [\mathrm{g}]}{material\ deposited\ [\mathrm{g}] + wasted\ powder\ [\mathrm{g}]} \quad (2)$$

To this end, both the powder feeder and the mold were weighed before and after the deposition. For the current case study, the material deposition efficiency of the system was 37.5%. With the imputation of the processes in Simapro and the corresponding matching, the initial acquisition of data was completed to characterize in detail the mass and energy flows underlying the production of the components that make up the systems of each of these technologies. Regarding the mass flows, it was possible to obtain a preliminary mass distribution by the DED equipment subsystems through the collected inventory, shown in Figure 7.

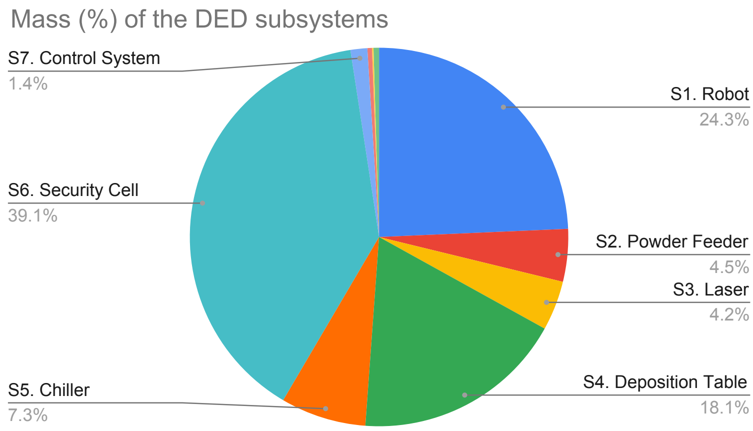

Figure 7. Mass characterization of the DED equipment subsystems.

As expected, the security cell (S6) is the subsystem with the highest mass contribution compared to the others, as it includes the steel of the surrounding structure of the machine that protects the employee from the effects of the laser when it is in operation. Next is the steel table system (S4), where the material deposition takes place, and the Robot (S1) which includes the cast iron robotic arm and the stainless-steel plinth. The printer head (S9) and Media (S10) do not make a significant contribution to the total mass of the DED system.

The analysis of the energy consumption (kWh) of this system was made possible with the installation of energy sensors connected to the robot, the laser head and the heating table. In parallel with the web service system in the robot controller, the monitoring system allowed a holistic approach to the production parameters, in terms of its visualization and monitoring in real-time, as well as its historical evaluation.

2.3. Case Study

The present work will follow the standardized methodology of LCA [15,16]. The main goal of this study is to compare the environmental performance of the refurbishment of an obsolete thermoplastic mold piece for new applications with the business-as-usual (BAU) scenario of disposal of the obsolete mold and conventional manufacturing of the new one. The scope will focus on a European context, and consider the main energy and mass flows that occur from extraction of raw materials, to transport and production of the mold, including the AM and conventional machinery production. Figure 8 presents the system boundaries of this study with the quantified energy and mass flows obtained at the laboratory, through the use of sensors, data acquisition equipment and measurement techniques made on-site. The functional unit is one fully functional mold piece with a life expectancy of 1 million cycles for the production of thermoplastic components. It is assumed that the refurbishment of the obsolete mold will produce a new useful mold, with the same durability as its counterpart from the conventional production process.

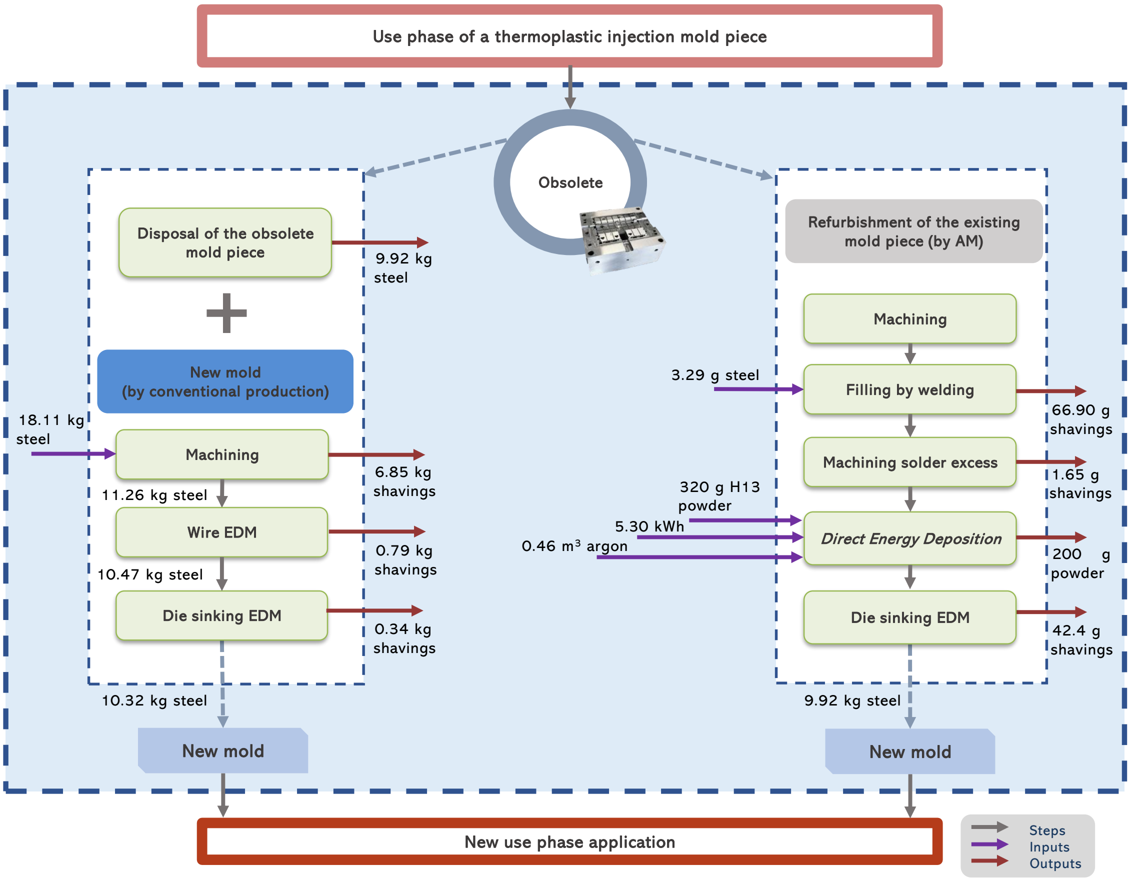

Figure 8. System boundaries.

The BAU scenario starts with the disposal of the obsolete mold for landfill. With this, it is necessary to manufacture a new mold part with the desired features. For this, the conventional process starts with the machining of an 18.11 kg block of steel to the approximate dimensions of the final part, generating steel scrap. Then, the block goes through two finishing processes of Electrical Discharge Machining (EDM), first through wire EDM, and after with die sinking EDM to obtain the mold piece in the final form with the required characteristics. The conventionally produced mold piece weighs 10.32 kg and is considered ready to go to the use stage.

The new circular scenario to handle the obsolete mold piece allows to take advantage of the existing piece as a basis and work on providing its new features through the AM. In the DED process, the laser used for the heat input is guided to the printer head by a optical fiber cable, where a series of optical elements focus it on the surface to be deposited. The feedstock material to be added is H13 powder, which is fed to the deposition head through a series of hoses. The printer head then focuses the powder in the area to be deposited. Alongside the H13 powder, Ar gas is introduced to shield the metal against oxidation.

The first step for the refurbishment via DED is to optimize the printing parameters according to the powder and the material where it will be deposited. A Design of Experiment (DOE) was performed on substrates using different ranges of laser power, speed, powder feed rate, carrier gas flow and shield gas flow as presented in Figure 9. This combination of parameters generates a specific layer height and width, and optimal hatch, which are important inputs for the deposition path. The optimal printing parameters used for the deposition can be found in Table 1.

Figure 9. DOEs of H13 powder on steel.

Table 1. Printing parameters used on the mold depositions.

Printing Parameters	Values
Laser Power	400 W
Speed	3 mm/s
Powder feeder rate	4 g/min
Carrier gas flow	3 L/min
Shield gas flow	35 L/min
Layer height	1.5 mm
Layer width	1.5 mm
Hatch spacing	0.85 mm

In general, the refurbishment process of a typical part has three main phases: (1) material removal, (2) material deposition, and (3) high-precision machining. In this case, between the material removal and the deposition, the cavities of the mold that had to be partially removed were filled with solder. Therefore, the material deposited on the top of the cavities would then stand and create a surface to cover them. An intermediate machining process was performed before the deposition to remove excess solder, as can be seen in Figure 10. After depositing the material, the mold is ready for the final machining process, which is normally performed using EDM due to tight tolerance requirements. Details of the main operations are given as follows.

The 3D models of the original mold and the final aimed geometry were provided by the project partners. First, a comparison between these two models was performed in SolidWorks® using the command "Compare Volume". From this command, it was possible to determine what material regions needed to be either removed or added.

Figure 11 represents the different models developed to define the manufacturing processes. Focusing on models (a) and (f), the original and final geometry of the mold respectively, it is clear that several cavities and slots were eliminated. On the other hand, the operation resulted in surface inclinations and grooves.

The definition of the first machining volume was based on the Z height of the slots to be eliminated and on making all the adding-material regions reachable by the deposition tool. By comparing the original model with the model after first machining (see Figure 11b), it was possible to obtain the volume that needed to be machined. This model was exported on a .step format, uploaded into the MasterCAM® software, and then the machining procedure was written into a .H file using a post processor.

To ensure the correct deposition of the powdered metal on the cavities, filler metal was soldered manually (highlighted in red in Figure 11c). Then, to machine the resulting soldered surface, the second machining 3D model (Figure 11d) was adopted and the surfaces were machined to the final height before deposition. As a result, complete and planar surfaces were obtained, which are very suitable for depositing the powdered metal.

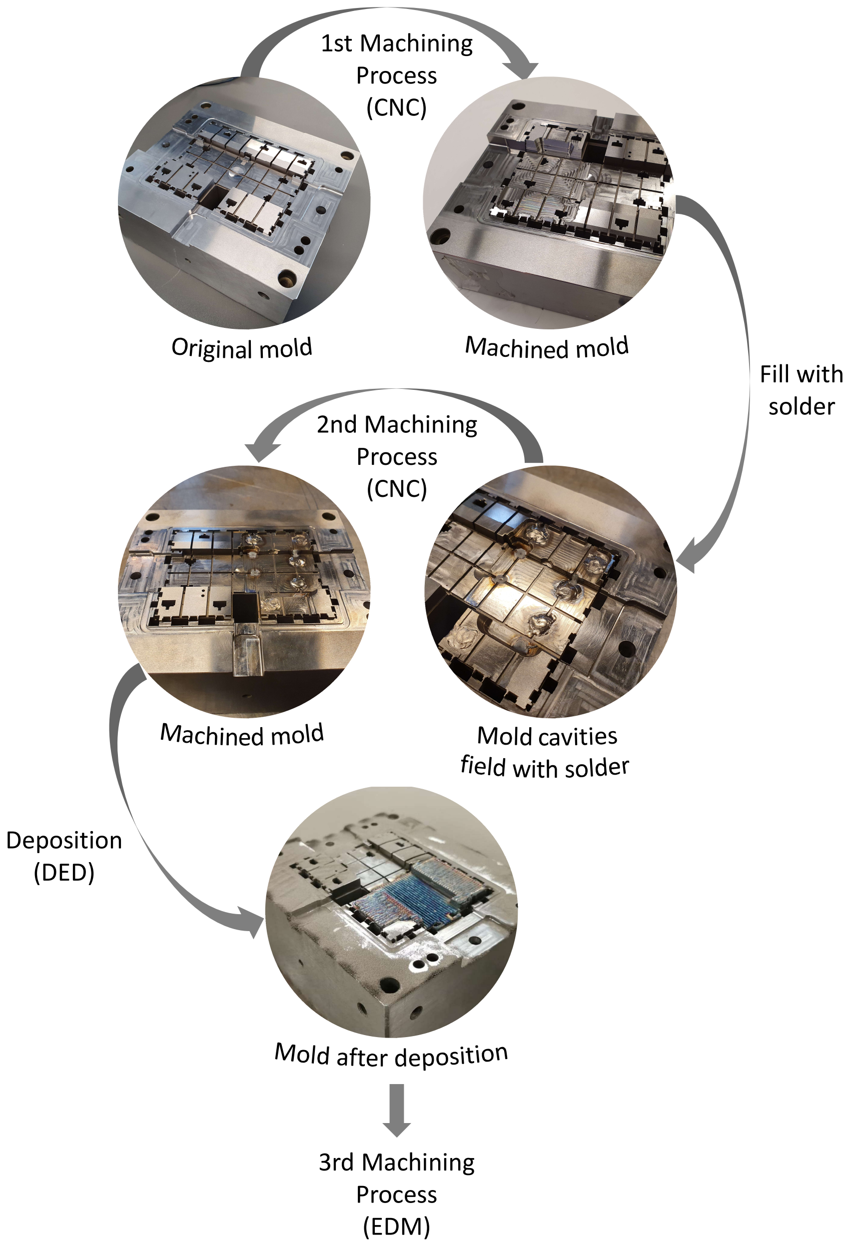

Figure 10. Different steps adopted throughout the mold refurbishment.

The deposition volume was defined based on the comparison between the model of intermediate machined mold and the model of the final aimed geometry (highlighted in blue in Figure 11e). After the deposition a final machining was still required, and as such, extra material was added to the deposition volume, i.e., the height was increased by 1 mm. The resulting volume was exported to a .stl file, uploaded into an open-source slicer software (Slic3r®), and then exported to a .gcode file. The .gcode file includes information about the robot's position and movements, but the actual process parameters are defined by a different post-processor.

Lastly, by comparing the deposited (Figure 11e) and the final models (Figure 11f), it was possible to obtain the new volume to be machined by EDM (using the .step file of the final geometry). Although the tool program had several complex paths with challenging perimeters, the deposition occurred without any problems. The deposited material had no visible cracks or major imperfections.

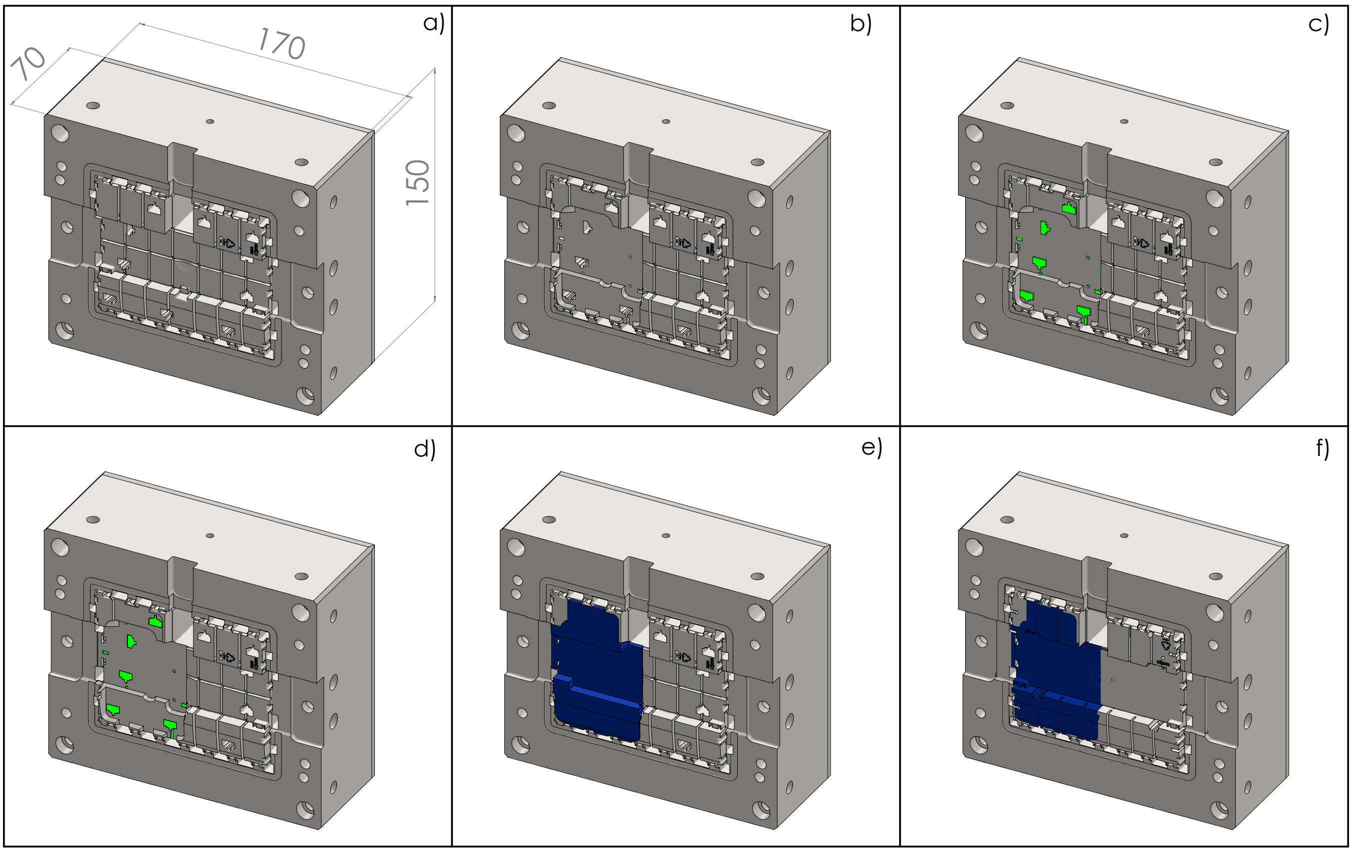

Figure 11. 3D models used on the different phases of the mold refurbishment: (**a**) original model; (**b**) mold after first machining process; (**c**) mold after filling cavities with solder; (**d**) mold after second machining process; (**e**) mold after deposition; (**f**) final mold geometry.

3. Results

The results regarding the potential environmental impacts of the production of the DED system, as well as the life cycle impact assessment comparison of the mold production by refurbishment and the BAU scenario are presented in this section. The quantification of the environmental impacts was conducted through the ReCiPe Endpoint (H) method [36] in the Simapro software. The results include impacts from infrastructure and do not consider the transformation processes for each component.

3.1. Environmental Impacts of the DED System Production

The main environmental impacts from the DED system are presented in Figure 12, with the total ecopoints (pt) for the production of one DED system, aggregated by impact category (Figure 12a), as well as the percentage in contribution from each category to the total DED impacts (Figure 12b).

The results of the environmental damage generated by the production of the DED system show that the main impact categories that contribute to the total impact damage are Human carcinogenic toxicity, HCTox (45%), Fine particulate matter formation, PM (23%), Human non-carcinogenic toxicity, HNCTox (19%) and Global Warming, GW (12%). The remaining categories (defined as "Others" in Figure 12) do not reach more than 1% of the total environmental impacts, whereas the highest only generates 0.3% of the total impacts (Fossil resource scarcity). A more detailed analysis was conducted to assess the source of the environmental hotspots for the most relevant categories for the environmental performance of the DED production. In Figure 13, the contributions from each subsystem of the DED equipment for the relevant categories are shown.

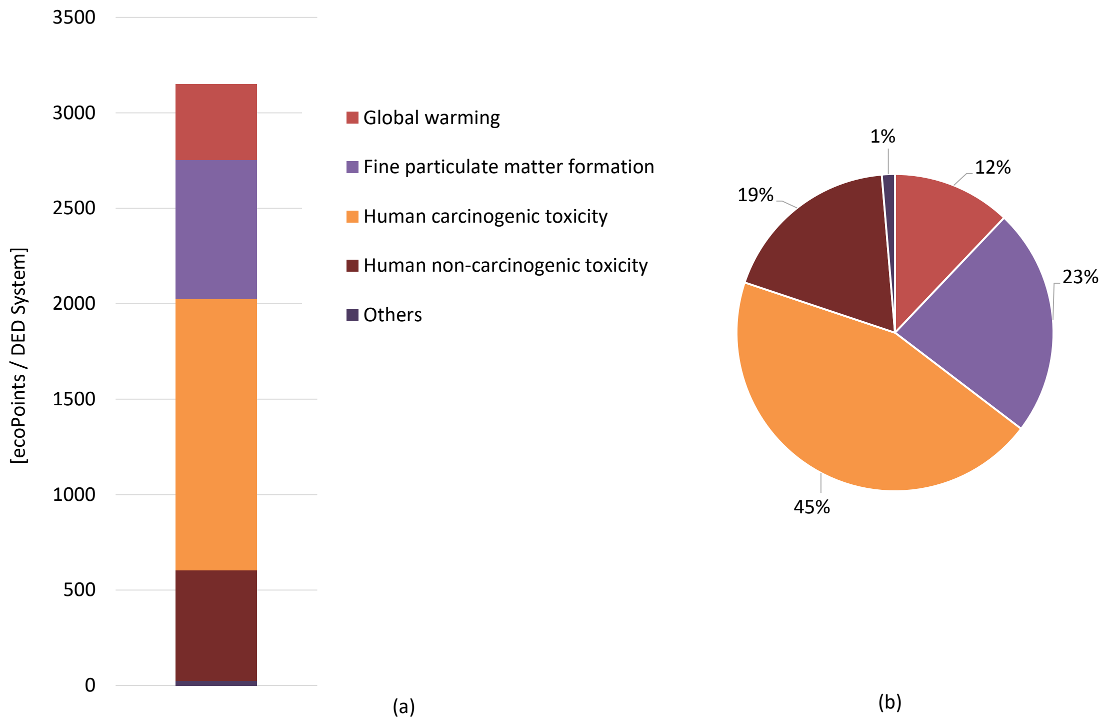

Figure 12. Total environmental damage from the DED system production per impact category, using the ReCiPe Endpoint (H) method: (**a**) in absolute values and (**b**) in percentage.

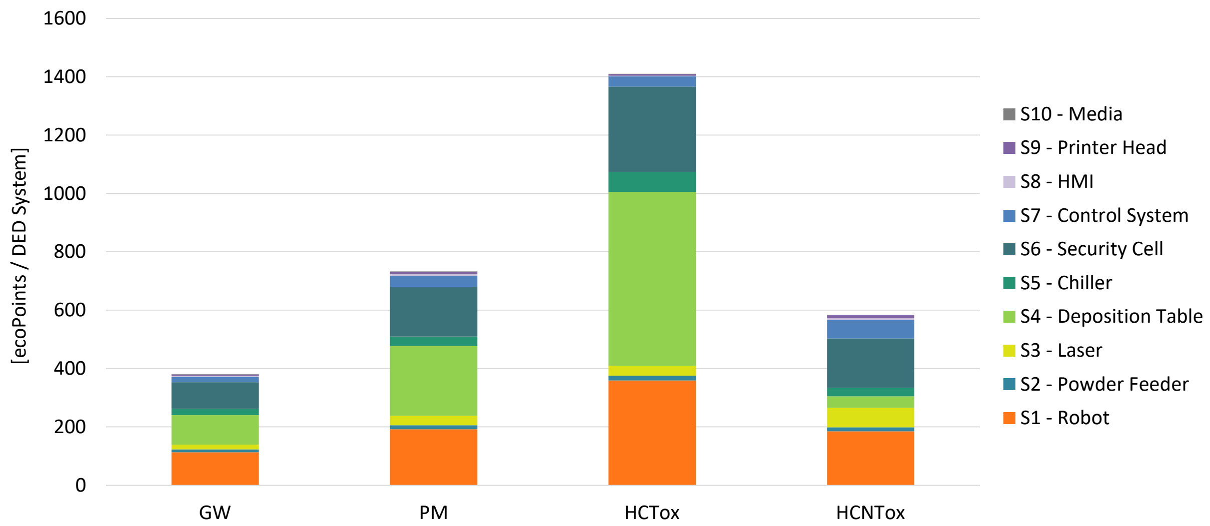

Figure 13. Contributions from each subsystem to the total environmental damages for the relevant impact categories, using the ReCiPe Endpoint (H) method.

In all categories, it is evident that the Robot (S1), the Deposition Table (S4) and the Security Cell (S6) are the most contributing subsystems to the total impacts generated during production. S1 generates 30% and 26% of the total impacts from the GW and the PM categories, respectively. This is mainly due to the electronic equipment within the controller (60% in GW and 54% for PM), namely the printed wiring board and integrated circuits that are mostly manufactured in countries highly dependent on fossil fuels for energy production. The manufacturing of the steel for the plinth and the cast iron for the robot arm also have significance in these categories, with 38% and 42% of the system's total impact in the GW and PM categories, respectively. These metals are the main drivers of the HCTox category, with almost 94% of S1's impact, because of the generated slag from the electric arc furnace during steel production, which is related to the presence of hazardous toxic metals which can leach into the ecosystem [37–40]. In the HNCTox category, the main impacts generated by S1 come from the copper and the gold present in the cables and in the integrated circuits existing in the robot arm and the controller, respectively, with a total of 32% of the DED system HNCTox impacts.

Regarding the other impact-relevant systems, the results show that the impacts generated by the S4 system in all categories are mostly related to the steel structure that composes the deposition table, specifically its production and associated energy consumption. This is especially relevant in the PM and HCTox categories, where the system contributes 33% and 42% to the total impacts, respectively. The S6 system contributes 24% to the total GW impacts. In this category, the production of the aluminum from the safety cell structure represents 58% of S6 contributions, followed by the production of the tin plate steel rails with 37%. In the PM category these materials are responsible for 95% of the total impacts. In both of these categories, the production of these materials has higher contributions due to the high level of energy consumption, which is mostly derived from fossil fuel resources. Regarding the HCTox category, the tin plate steel rails are responsible for 68% of the system's contributions (because of the toxic metal sludge generated during production), whereas the aluminum structure generates 30%. However, this material is responsible for 89% of the S6 total impacts in the HNCTox category due to the sulfidic tailings (that contain sulfide minerals, a combination of sulfide with metals such as iron, copper, nickel, lead and zinc) [41] generated in the extraction of raw materials through mining operations, which can leach acid to the soil and groundwater if not properly handled. Other systems, such as S3 and S7, have also some relevant contributions in the HNCTox category, with 11.5% and 10.8%, respectively. This is mostly due to the production and refining of the copper present in the wiring.

Overall, the results indicate that the main drivers of the DED machine production impacts are the extraction and processing of steel and aluminum, as well as the production of electronic components, mostly due to the generation of toxic waste and the combustion of fossil fuels for energy purposes. The total impacts for the production of one DED machine are 3149.65 pt, from which 3107.64 pt are derived from these four categories. The total damage points will be integrated into the assessment of the case study, considering the amount of usage during the lifetime of the machine. For this, a 10-year lifetime scenario was considered, with a daily operation of 4 h, during which one refurbishment takes 45 min to be completed and one minute for it to be exchanged to start a new process. With this, a total of 12,650 refurbishment processes were estimated. This number was used to include the environmental impacts of the DED system for one refurbishment process in the case study.

3.2. Environmental Impacts — Conventional Production vs Refurbishment using DED technology

The environmental impact comparison between the conventional production of a new mold piece and the refurbishment of the obsolete piece are presented in Figure 14. The results are presented in ecopoints (pts), aggregating all of the environmental effects from the analyzed activities that are within the previously established system boundaries. European conditions were assumed and the electricity generation was adjusted for the Portuguese 2020 electricity mix, using data from national entities [42,43].

The results show that there is a significant reduction (98%) in environmental damage when the mold piece is refurbished with the DED technology, instead of being discarded and a new mold piece being produced. In both scenarios, there is a clear influence of the four major categories previously mentioned: GW, PM, HCTox and HNCTox. The remaining categories (marked as "Others") do not contribute more than 2% in the BAU scenario and 3% in the refurbishment. In the conventional production, the HCTox contributes with more than 50% of the total damage, whereas in the refurbishment this category contributes with 47%. This is mostly due to the electric arc furnace slag formed during steel production of the new mold (around 74% of HCTox impacts in the conventional production are due to the production of the initial block) and, in the refurbishment scenario, these impacts are due to powder waste treatment (in this case landfill was selected).

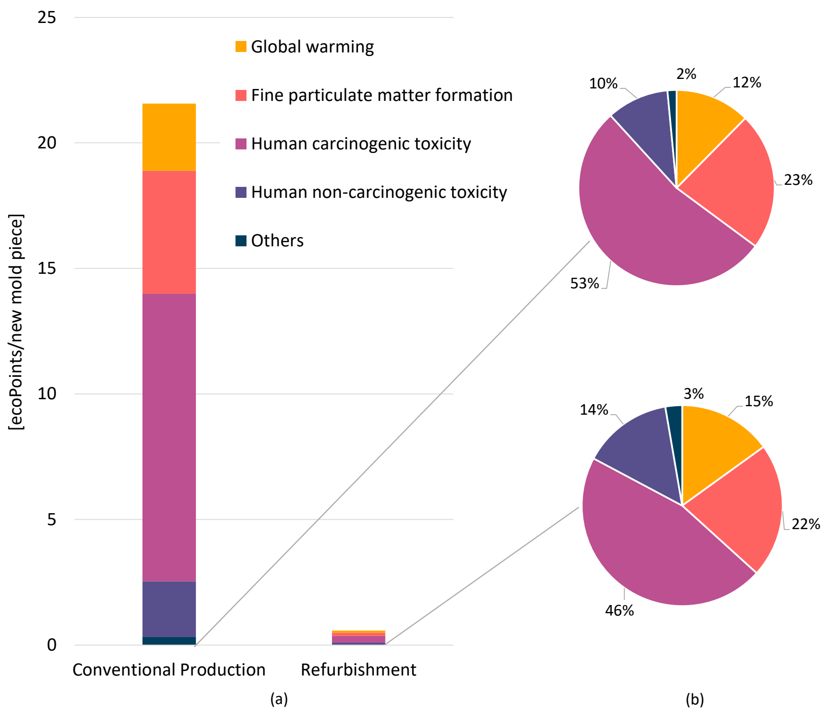

Figure 14. Total environmental damage comparison between conventional production of a new mold piece and the refurbishment of the obsolete version via DED, using ReCiPe Endpoint (H): (**a**) in absolute values and (**b**) in percentage.

The second most relevant category in these activities is the PM, with 23% of total damage in the conventional production and 21% in the refurbishment. In the conventional production, the main drivers of these impacts are the atmospheric emissions from the steel production of the new mold, whereas, in the refurbishment, this category has mainly contributions from the argon and Portuguese electricity consumption during the DED process. In these results, GW is the third most relevant category, with 12% of total impacts in the conventional production, due to steel production and its additives, together with the resins present in the EDM wiring processes. In the refurbishment scenario, this category represents 17% of total environmental damage, mostly generated by the argon and electricity consumption in the DED, similarly to the PM category. Finally, in the HNCTox category, most impacts are due to consumables with copper and electronic components, in the wiring EDM in the conventional production (10% of total damages). In the refurbishment (12% of the total damages), the production and end-of-life treatment of the H13 powder is the main contributor to this category, followed by argon consumption during deposition.

4. Discussion

The results of the LCA study for the refurbishment application clearly show a high level reduction in environmental impacts when compared with the conventional process. This indicates that AM can have a significant role in the future circular manufacturing industry. In all analyzed categories, the environmental damage reduction was over 90%. When analyzing current literature, in one study [7], the comparison between conventional repairing and DED repairing (using also H13 powder) resulted in similar results as this paper, but had a high-level of uncertainty due to lack of information, a proper LCI of the DED system and the use of estimates from the industry. In this study, the reliability of the results provide from a robust LCI data acquisition process, mainly the on-site measurements for this specific process. The resulted LCI can be useful to researchers to validate their previous studies and conduct a more solid investigation on the life cycle of this technology. Other repairing studies [14], reach the same conclusion, even considering that the repaired mold only reaches one-third of the conventional lifetime of cycles. In other studies [13,26], the authors compare conventional manufacturing with DED processes. Although the scope is different, the authors also come to the same conclusion that the 3D printed product has less environmental impacts, although this relation is not always clear when comparing production processes due to the different levels of technology development.

The decision to opt for the traditional route or DED technology depends on the degree of confidence and reliability that the final finish of the part corresponds to the necessary specifications, or that guarantees beneficial sustainability for the end user. Moreover, additional studies must be conducted regarding the technical performance of the refurbished mold piece to ensure that it is up to par with the conventionally produced mold. Up until the conclusion of this study, the characterization of the refurbished mold piece had not yet been conducted. With the number of cycles to determine the comparability for the use stage, the results for the refurbishment would be adapted to match the number of cycles of the BAU scenario (as conducted in [14]) in a future study, together with other relevant mechanical performance features that may differ from the conventionally produced mold piece in finishing or treatment processes, as well as in the use stage. Nonetheless, a recent study [7] of a similar process, using the same technology and the same material, concluded that the durability of the mold is equivalent to the mold produced by a conventional process, and as such, the comparison made in this study is very plausible.

5. Conclusions

The main goal of this study was to create life cycle models for the production and use of the DED system, from a circular economy perspective, to measure the environmental performance of the additive manufacturing system in a real-life application. To do so, a mapping of materials and components was conducted to create a reliable LCI for the machine system and its subsystems.

The inventory was built using foreground data from laboratory measurements, invoices, and sensors with a high level of reliability. The first step consisted of describing the systems into which the machine can be divided to facilitate the data collection. The second step involved the description of all components for each defined system. The third step consisted of allocating the components to the life cycle impact assessment software processes. This was a complex process that involved large amounts of data. The data collection was possible in a detailed manner since the DED system was built in the laboratory, through the purchase and assembly of various parts and components. Thus, it was possible to collect information about the description of most of the components. Overall, the study successfully measured and obtained detailed data regarding the main components and materials that compose each subsystem of the DED. It is expected that the built LCI can provide LCA researchers and the scientific community with important life cycle information for this AM technology.

The built LCI provided a clear picture of the material demand and resource consumption for the production of these systems, where the Security Cell (S6), the Deposition Table (S4) and the Robot (S1) had the highest quantity. When analyzing the environmental impacts of the production of the DED, most of the environmental damage derives from the emissions of toxic compounds, particulate matter and GHG during the production of the constituting metal and electronic components.

The case study referred to the refurbishment of an obsolete thermoplastic injection mold into a new geometry. Yet, for repairing processes, for example, a mold with cracking problems, the process may involve fewer resources than the traditional processes, and translate into lower environmental impacts. The refurbishment process of the mold included machining processes (CNC and EDM), manual solder application and DED. There were not any major problems during the processes, and the material was machined effectively and deposited with no visible cracks. The complex tool path with challenging borders was performed successfully and the deposition process was a success in terms of providing the obsolete mold piece with the desired features for new applications. Future studies will conduct a characterization of the refurbished mold to confirm its equivalency to the conventionally produced pieces, together with an economic and social assessment to assess other relevant parameters, such as operation time and production costs, and the overall sustainability of the process. Concluding, the quantified environmental performance of this refurbishment has great potential in reducing the environmental footprint of the tooling industry. As such, this study showed that there is a high potential for repairing processes using AM technology in the circularity sphere.

Author Contributions: Conceptualization, J.R.G., S.M.P. and S.C.; methodology, J.R.G. and S.M.P.; software, J.R.G., S.M.P., S.C., J.R.M. and C.C.; validation, J.R.M., L.O. and S.E.; formal analysis, J.R.G., S.M.P. and S.C.; resources, L.O. and S.E.; writing—original draft preparation, J.R.G., S.M.P., S.C., J.R.M. and C.C.; writing—review and editing, T.A.D.; L.O. and S.E.; funding acquisition, S.E. All authors have read and agreed to the published version of the manuscript.

Funding: The present work was performed and funded under the scope of the project Add. Additive—add additive manufacturing to Portuguese industry (ANI | P2020 | POCI-01-0247-FEDER-024533), co-funded by Portugal 2020 and FEDER, through COMPETE 2020-Operational Program for Competitiveness and Internationalization. The authors would also like to thank the project LEVEL-UP—Protocols and Strategies for extending the useful Life of major capital investments and Large Industrial Equipment (project nº 869991), supported by the European Commission, under the frame of Horizon 2020.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data gathered to be applied in this study are available in Appendix A.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AM	Additive Manufacturing;
DED	Directed Energy Deposition;
GTAW	Gas Tungsten Arc Welding;
LCA	Life Cycle Assessment;
LCI	Life Cycle Inventory;
CNC	Computer Numeric Control;
CED	Cumulative Energy Demand;
HIPS	High Impact Polystyrene;
CFRP	Carbon Fiber-Reinforced Plastic;
SLM	Selective Laser Melting;
Ar	Argon;
PLC	Programmable Logic Controller;
RTSP	Real Time Streaming Protocol;
HMI	Human–Machine Interface;
APOS	Allocation Library at the Point of Substitution;
BAU	Business-as-Usual;
EDM	Electrical Discharge Machining;
DOE	Design of Experiment;
HCTox	Human Carcinogenic Toxicity;
PM	Fine Particulate Matter Formation;
HNCTox	Human Non-Carcinogenic Toxicity;
GW	Global Warming;
GHG	Greenhouse Gas.

Appendix A

Table A1. System 1—Matching Ecoinvent v3.7.1 database with S1 components.

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Robot Arm	Wiring	1	Cast iron {GLO} | market for | APOS, U	21.6000	kg
	Robot	1	Cable, unspecified {GLO} | market for | APOS, U	643.4000	kg
Plinth	Base	1	Steel, chromium steel 18/8 {GLO} | market for | APOS, U	334.8126	kg
Controller	Single Phase Circuit Breaker	2	Steel, unalloyed {GLO} | market for | APOS, U	0.0372	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0009	kg
			Ethylene vinyl acetate copolymer {RER} | market for ethylene vinyl acetate copolymer | APOS, U	0.0002	kg
			Zinc {GLO} | market for | APOS, U	0.0008	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0007	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0163	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0014	kg
			Polyphenylene sulfide {GLO} | market for | APOS, U	0.0019	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} | market for | APOS, U	0.0005	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} | market for | APOS, U	0.0005	kg
			Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0299	kg
			Polycarbonate {GLO} | market for | APOS, U	0.0012	kg
	Three Phase Circuit Breaker	1	Steel, unalloyed {GLO} | market for | APOS, U	0.1256	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0030	kg
			Ethylene vinyl acetate copolymer {RER} | market for ethylene vinyl acetate copolymer | APOS, U	0.0007	kg
			Zinc {GLO} | market for | APOS, U	0.0027	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0024	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0550	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0047	kg
			Polyphenylene sulfide {GLO} | market for | APOS, U	0.0064	kg
			Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.1009	kg
			Polycarbonate {GLO} | market for | APOS, U	0.0041	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} | market for | APOS, U	0.0017	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} | market for | APOS, U	0.0017	kg
	Lead-Acid Battery	2	Lead {GLO} | market for | APOS, S	0.1625	kg
			lead concentrate {GLO} | zinc mine operation | APOS, U	0.2275	kg
			Polypropylene, granulate {GLO} | market for | APOS, S	0.0650	kg
			Sulfuric acid {RER} | market for sulfuric acid | APOS, S	0.0650	kg
			Flat glass, uncoated {RER} | market for flat glass, uncoated | APOS, S	0.0130	kg
			Antimony {GLO} | market for | APOS, S	0.0065	kg

Table A1. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Source 24V-5A	1	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0065	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.2568	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.1633	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0414	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} | market for | APOS, U	0.0183	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} | market for | APOS, U	0.0183	kg
			Bronze {GLO} | market for | APOS, U	0.0008	kg
			Electronic component, passive, unspecified {GLO} | market for | APOS, U	0.1942	kg
			Polyphenylene sulfide {GLO} | market for | APOS, U	0.0390	kg
	Block Terminal	8	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0594	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0114	kg
			Brass {CH} | market for brass | APOS, U	0.0420	kg
	Fuse holder Fuse	4	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0422	kg
			Polycarbonate {GLO} | market for | APOS, U	0.0011	kg
			Steel, unalloyed {GLO} | market for | APOS, U	0.0180	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0123	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0013	kg
	Switch type 1	1	Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	0.0002	kg
			Activated silica {GLO} | market for | APOS, U	0.0006	kg
			Polyethylene, low density, granulate {GLO} | market for | APOS, U	0.0029	kg
			Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	0.0058	kg
			Glass fibre {GLO} | market for | APOS, U	0.0129	kg
			Cobalt {GLO} | market for | APOS, U	0.0003	kg
			Iron ore concentrate {GLO} | market for iron ore concentrate | APOS, U	0.0003	kg
			Nickel, class 1 {GLO} | market for nickel, class 1 | APOS, U	0.0005	kg
			Aluminium hydroxide {GLO} | market for | APOS, U	0.0044	kg
			Aluminium oxide, non-metallurgical {RoW} | market for aluminium oxide, non-metallurgical | APOS, S	0.0006	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0073	kg
			Tin {GLO} | market for | APOS, U	0.0065	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0163	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0093	kg
			Single-Si wafer, for electronics {GLO} | market for | APOS, U	5.7034	cm^2
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0004	kg
			Polymethyl methacrylate, sheet {GLO} | market for | APOS, U	0.0029	kg
			Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0242	kg
			Acrylonitrile-butadiene-styrene copolymer {GLO} | market for | APOS, U	0.0702	kg

Table A1. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Switch type 2	1	Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	0.0001	kg
			Activated silica {GLO} | market for | APOS, U	0.0004	kg
			Polyethylene, low density, granulate {GLO} | market for | APOS, U	0.0020	kg
			Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	0.0039	kg
			Glass fibre {GLO} | market for | APOS, U	0.0088	kg
			Cobalt {GLO} | market for | APOS, U	0.0002	kg
			Iron ore concentrate {GLO} | market for iron ore concentrate | APOS, U	0.0002	kg
			Nickel, class 1 {GLO} | market for nickel, class 1 | APOS, U	0.0004	kg
			Aluminium hydroxide {GLO} | market for | APOS, U	0.0030	kg
			Aluminium oxide, non-metallurgical {RoW} | market for aluminium oxide, non-metallurgical | APOS, S	0.0004	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0049	kg
			Tin {GLO} | market for | APOS, U	0.0044	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0111	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0063	kg
			Single-Si wafer, for electronics {GLO} | market for | APOS, U	3.8824	cm^2
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0002	kg
			Polymethyl methacrylate, sheet {GLO} | market for | APOS, U	0.0020	kg
			Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0165	kg
			Acrylonitrile-butadiene-styrene copolymer {GLO} | market for | APOS, U	0.0478	kg
Controller	Coupler	1	Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	0.0003	kg
			Activated silica {GLO} | market for | APOS, U	0.0009	kg
			Polyethylene, low density, granulate {GLO} | market for | APOS, U	0.0044	kg
			Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	0.0087	kg
			Glass fibre {GLO} | market for | APOS, U	0.0195	kg
			Cobalt {GLO} | market for | APOS, U	0.0005	kg
			iron ore concentrate {GLO} | market for iron ore concentrate | APOS, U	0.0005	kg
			nickel, class 1 {GLO} | market for nickel, class 1 | APOS, U	0.0008	kg
			Aluminium hydroxide {GLO} | market for | APOS, U	0.0067	kg
			Aluminium oxide, non-metallurgical {RoW} | market for aluminium oxide, non-metallurgical | APOS, S	0.0009	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0110	kg
			Tin {GLO} | market for | APOS, U	0.0098	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0246	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0140	kg
			Single-Si wafer, for electronics {GLO} | market for | APOS, U	8.6238	cm^2
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0006	kg
			Polymethyl methacrylate, sheet {GLO} | market for | APOS, U	0.0044	kg
			Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0366	kg
			Acrylonitrile-butadiene-styrene copolymer {GLO} | market for | APOS, U	0.1062	kg

Table A1. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	PCB	0.2 (m^2)	Printed wiring board, for through-hole mounting, Pb free surface {GLO} | market for | APOS, S	0.5000	m^2
			Printed wiring board, for surface mounting, Pb free surface {GLO} | market for | APOS, U	0.5000	m^2
	Motor driver	2	Aluminium alloy, AlLi {GLO} | market for | APOS, U	6.7492	kg
			Copper, cathode {GLO} | market for | APOS, U	0.2603	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} | market for | APOS, U	0.0607	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} | market for | APOS, U	0.0607	kg
			Steel, unalloyed {GLO} | market for | APOS, U	0.5032	kg
			Zinc {GLO} | market for | APOS, U	0.1041	kg
			Polycarbonate {GLO} | market for | APOS, U	1.0931	kg
			Polypropylene, granulate {GLO} | market for | APOS, S	0.1562	kg
			Polyphenylene sulfide {GLO} | market for | APOS, U	0.1041	kg
			Cable, unspecified {GLO} | market for | APOS, U	0.4164	kg
			Tube insulation, elastomere {GLO} | market for | APOS, U	0.1041	kg
			Printed wiring board, mounted mainboard, laptop computer, Pb free {GLO} | market for | APOS, U	4.9274	kg

Table A2. System 2—Matching Ecoinvent v3.7.1 database with S2 components.

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Dispensers (Flowmotion 2.5 L)	-	1	Steel, chromium steel 18/8 {GLO} | market for | APOS, U	334.8126	kg
Base Station (Flowmotion)	-	1	Steel, unalloyed {GLO} | market for | APOS, U	36.6000	kg
Control Box	-	1	Steel, unalloyed {GLO} | market for | APOS, U	18.7800	kg
Gas Chamber	-	1	Steel, unalloyed {GLO} | market for | APOS, U	15.4000	kg

Table A2. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Power supply unit	1	Power supply unit, for desktop computer {GLO} | market for | APOS, U	0.5333	p
	U Profile 1	1	Steel, unalloyed {GLO} | market for | APOS, U	29.9539	kg
	U Profile 2	1	Steel, unalloyed {GLO} | market for | APOS, U	64.1870	kg
	Two Phase Circuit Breaker	1	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0862	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0024	kg
			Polycarbonate {GLO} | market for | APOS, U	0.0051	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0024	kg
			Polyphenylene sulfide {GLO} | market for | APOS, U	0.0073	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0016	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0085	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} | market for | APOS, U	0.0014	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} | market for | APOS, U	0.0014	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0024	kg
			Steel, unalloyed {GLO} | market for | APOS, U	0.0591	kg
			Zinc {GLO} | market for | APOS, U	0.0096	kg
	Three Phase Circuit Breaker	2	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.1293	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0037	kg
			Polycarbonate {GLO} | market for | APOS, U	0.0076	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0037	kg
			Polyphenylene sulfide {GLO} | market for | APOS, U	0.0110	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0024	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0128	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} | market for | APOS, U	0.0021	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} | market for | APOS, U	0.0021	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0037	kg
			Steel, unalloyed {GLO} | market for | APOS, U	0.0887	kg
			Zinc {GLO} | market for | APOS, U	0.0143	kg

Table A2. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Breaker	1	Polycarbonate {GLO} | market for | APOS, U	0.2841	kg
			Polyethylene, low density, granulate {GLO} | market for | APOS, S	0.0054	kg
			Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0375	kg
			Polyester resin, unsaturated {RER} | market for polyester resin, unsaturated | APOS, U	2.0100	kg
			Zinc {GLO} | market for | APOS, U	0.0107	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.1072	kg
			Copper, cathode {GLO} | market for | APOS, U	1.1363	kg
			Steel, unalloyed {GLO} | market for | APOS, U	1.5598	kg
	Switch type 3	1	Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	0.0010	kg
			Activated silica {GLO} | market for | APOS, U	0.0020	kg
			Polyethylene, low density, granulate {GLO} | market for | APOS, U	0.0090	kg
			Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	0.0170	kg
			Glass fibre {GLO} | market for | APOS, U	0.0390	kg
			Cobalt {GLO} | market for | APOS, U	0.0010	kg
			iron ore concentrate {GLO} | market for iron ore concentrate | APOS, U	0.0010	kg
			nickel, class 1 {GLO} | market for nickel, class 1 | APOS, U	0.0020	kg
			Aluminium hydroxide {GLO} | market for | APOS, U	0.0130	kg
			Aluminium oxide, non-metallurgical {RoW} | market for aluminium oxide, non-metallurgical | APOS, S	0.0020	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0220	kg
			Tin {GLO} | market for | APOS, U	0.0200	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0490	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0280	kg
			Single-Si wafer, for electronics {GLO} | market for | APOS, U	17.1790	cm^2
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0010	kg
			Polymethyl methacrylate, sheet {GLO} | market for | APOS, U	0.0090	kg
			Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0730	kg
			Acrylonitrile-butadiene-styrene copolymer {GLO} | market for | APOS, U	0.2120	kg
	Solid State Relay	3.7500	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0120	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0200	kg
			Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	0.0800	kg

Table A2. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Controller Drivers	2	Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.1530	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0059	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} | market for | APOS, U	0.0014	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} | market for | APOS, U	0.0014	kg
			Steel, unalloyed {GLO} | market for | APOS, U	0.0114	kg
			Zinc {GLO} | market for | APOS, U	0.0024	kg
			Polycarbonate {GLO} | market for | APOS, U	0.0248	kg
			Polypropylene, granulate {GLO} | market for | APOS, S	0.0035	kg
			Polyphenylene sulfide {GLO} | market for | APOS, U	0.0024	kg
			Cable, unspecified {GLO} | market for | APOS, U	0.0094	kg
			Tube insulation, elastomere {GLO} | market for | APOS, U	0.0024	kg
			Printed wiring board, mounted mainboard, laptop computer, Pb free {GLO} | market for | APOS, U	0.1117	kg
	Terminal Block	0.6275 (kg)	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.4825	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0930	kg
			Brass {CH} | market for brass | APOS, U	0.3409	kg
	Valve Controller	3	Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.2071	kg
			Synthetic rubber {GLO} | market for | APOS, U	0.0230	kg
	Solenoid Valve	2	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0060	kg
			Aluminium, primary, cast alloy slab from continuous casting {GLO} | market for | APOS, U	0.0260	kg
			Steel, unalloyed {GLO} | market for | APOS, U	0.0060	kg
			Synthetic rubber {GLO} | market for | APOS, U	0.0020	kg
	Solenoid Valve Positively Actuated	3	Brass {CH} | market for brass | APOS, U	2.7000	kg
			Synthetic rubber {GLO} | market for | APOS, U	0.3000	kg
	Metalic connectors	1	Aluminium, primary, cast alloy slab from continuous casting {GLO} | market for | APOS, U	0.6698	kg
			Polycarbonate {GLO} | market for | APOS, U	0.4199	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0692	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0316	kg
			Lead {GLO} | market for | APOS, U	0.0010	kg
			Glass fibre reinforced plastic, polyester resin, hand lay-up {GLO} | market for | APOS, U	0.0186	kg
			Zinc {CA-QC} | primary production from concentrate | APOS, U	0.0876	kg

Table A2. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	PLC	1	Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0157	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0090	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0081	kg
			Electronic component, passive, unspecified {GLO} | market for | APOS, U	0.5494	kg
			Polycarbonate {GLO} | market for | APOS, U	0.3675	kg
			Polyethylene, low density, granulate {GLO} | market for | APOS, U	0.0223	kg
			Ethylene vinyl acetate copolymer {RER} | market for ethylene vinyl acetate copolymer | APOS, U	0.0127	kg
	Pinch valve	1	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0191	kg
			Aluminium, primary, cast alloy slab from continuous casting {GLO} | market for | APOS, U	0.0827	kg
			Steel, unalloyed {GLO} | market for | APOS, U	0.0191	kg
			Synthetic rubber {GLO} | market for | APOS, U	0.0064	kg

Table A3. System 3—Matching Ecoinvent v3.7.1 database with S3 components.

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Fiber Optic Cable	-	10 (m)	Germanium	1.10×10^{-6}	kg
			Activated silica {GLO} | market for | APOS, S	2.64×10^{-5}	kg
			Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	0.0002	kg
			Activated silica {GLO} | market for | APOS, S	0.0004	kg
			Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0003	kg
			Polyethylene, low density, granulate {GLO} | market for | APOS, S	0.0023	kg
			Extrusion, plastic pipes {RER} | extrusion, plastic pipes | APOS, S	0.0023	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.1372	kg

Table A3. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Power Supply	1	Power supply unit, for desktop computer {GLO} | market for | APOS, S	0.0933	p
	Transformer	1	Transformer, low voltage use {GLO} | market for | APOS, S	17.0000	kg
	Computer	1	Computer, desktop, without screen {GLO} | market for | APOS, U	1	p
	Laptop	1	Computer, laptop {GLO} | market for | APOS, U	1	p
	Cables	1	Cable, unspecified {GLO} | market for | APOS, U	27.9252	kg
	Switch (8 doors)	0.32 (kg)	Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	0.0001	kg
			Activated silica {GLO} | market for | APOS, U	0.0004	kg
			Polyethylene, low density, granulate {GLO} | market for | APOS, U	0.0020	kg
			Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	0.0039	kg
			Glass fibre {GLO} | market for | APOS, U	0.0088	kg
			Cobalt {GLO} | market for | APOS, U	0.0002	kg
			iron ore concentrate {GLO} | market for iron ore concentrate | APOS, U	0.0002	kg
			nickel, class 1 {GLO} | market for nickel, class 1 | APOS, U	0.0004	kg
			Aluminium hydroxide {GLO} | market for | APOS, U	0.0030	kg
			Aluminium oxide, non-metallurgical {RoW} | market for aluminium oxide, non-metallurgical | APOS, S	0.0004	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0049	kg
			Tin {GLO} | market for | APOS, U	0.0044	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0111	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0063	kg
			Single-Si wafer, for electronics {GLO} | market for | APOS, U	3,8824	cm^2
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0002	kg
			Polymethyl methacrylate, sheet {GLO} | market for | APOS, U	0.0020	kg
			Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0165	kg
			Acrylonitrile-butadiene-styrene copolymer {GLO} | market for | APOS, U	0.0478	kg
	Double Deck Terminal Block	0.82 (kg)	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.4825	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0930	kg
			Brass {CH} | market for brass | APOS, U	0.3409	kg

Table A3. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Terminal Block 1	0.39 (kg)	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.4825	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0930	kg
			Brass {CH} ∣ market for brass ∣ APOS, U	0.3409	kg
	Terminal Block 2	0.18 (kg)	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.4825	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0930	kg
			Brass {CH} ∣ market for brass ∣ APOS, U	0.3409	kg
	Solid State Relay 1	0.47 (kg)	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.0120	kg
			Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.0200	kg
			Epoxy resin insulator, SiO_2 {GLO} ∣ market for ∣ APOS, U	0.0800	kg
	Safety Relay	6	Nylon 6 {RER} ∣ market for nylon 6 ∣ APOS, S	0.2667	kg
			Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.1308	kg
			Polycarbonate {GLO} ∣ market for ∣ APOS, U	0.1176	kg
			Polypropylene, granulate {GLO} ∣ market for ∣ APOS, S	0.0182	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.1954	kg
			Zinc {GLO} ∣ market for ∣ APOS, U	0.0696	kg
			Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.0248	kg
			Tin {GLO} ∣ market for ∣ APOS, U	0.0166	kg
			Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.0050	kg
			Glass fibre {GLO} ∣ market for ∣ APOS, S	0.0928	kg
			Epoxy resin insulator, SiO_2 {GLO} ∣ market for ∣ APOS, U	0.0712	kg
			Silica sand {RoW} ∣ production ∣ APOS, S	0.0248	kg
	Solid State Relay 2	6	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.0120	kg
			Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.0200	kg
			Epoxy resin insulator, SiO_2 {GLO} ∣ market for ∣ APOS, U	0.0800	kg
	Timer Relay	1	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.0157	kg
			Polycarbonate {GLO} ∣ market for ∣ APOS, U	0.0403	kg
			Electronic component, passive, unspecified {GLO} ∣ market for ∣ APOS, U	0.0428	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0052	kg
			Steel, unalloyed {GLO} ∣ market for ∣ APOS, U	0.0138	kg
			Polymethyl methacrylate, sheet {GLO} ∣ market for ∣ APOS, S	0.0008	kg
			Ethylene vinyl acetate copolymer {RER} ∣ market for ethylene vinyl acetate copolymer ∣ APOS, U	0.0015	kg

Table A3. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Time Counter Equipment	1	Steel, unalloyed {GLO} | market for | APOS, U	0.0142	kg
			Brass {CH} | market for brass | APOS, U	0.0054	kg
			Electronic component, passive, unspecified {GLO} | market for | APOS, U	0.0326	kg
			Polycarbonate {GLO} | market for | APOS, U	0.0305	kg
			Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0161	kg
			Ethylene vinyl acetate copolymer {RER} | market for ethylene vinyl acetate copolymer | APOS, U	0.0011	kg
			Polymethyl methacrylate, sheet {GLO} | market for | APOS, S	0.0002	kg
	Single Phase Circuit Breaker	8	Steel, unalloyed {GLO} | market for | APOS, U	0.0372	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0009	kg
			Ethylene vinyl acetate copolymer {RER} | market for ethylene vinyl acetate copolymer | APOS, U	0.0002	kg
			Zinc {GLO} | market for | APOS, U	0.0008	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0007	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0163	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0014	kg
			Polyphenylene sulfide {GLO} | market for | APOS, U	0.0019	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} | market for | APOS, U	0.0005	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} | market for | APOS, U	0.0005	kg
			Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0299	kg
			Polycarbonate {GLO} | market for | APOS, U	0.0012	kg
	Three Phase Circuit Breaker	6	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.1293	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0037	kg
			Polycarbonate {GLO} | market for | APOS, U	0.0076	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0037	kg
			Polyphenylene sulfide {GLO} | market for | APOS, U	0.0110	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0024	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0128	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} | market for | APOS, U	0.0021	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} | market for | APOS, U	0.0021	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0037	kg
			Steel, unalloyed {GLO} | market for | APOS, U	0.0887	kg
			Zinc {GLO} | market for | APOS, U	0.0143	kg

Table A3. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Breaker	1	Polycarbonate {GLO} ∣ market for ∣ APOS, U	0.2841	kg
			Polyethylene, low density, granulate {GLO} ∣ market for ∣ APOS, S	0.0054	kg
			Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.0375	kg
			Polyester resin, unsaturated {RER} ∣ market for polyester resin, unsaturated ∣ APOS, U	2.0100	kg
			Zinc {GLO} ∣ market for ∣ APOS, U	0.0107	kg
			Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.1072	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	1.1363	kg
			Steel, unalloyed {GLO} ∣ market for ∣ APOS, U	1.5598	kg
	Cooler	1	Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.0043	kg
			Brass {CH} ∣ market for brass ∣ APOS, S	0.1936	kg
	Motor Contactor	2	Steel, unalloyed {GLO} ∣ market for ∣ APOS, U	0.8698	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.3725	kg
			Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.0051	kg
			Brass {CH} ∣ market for brass ∣ APOS, U	0.0051	kg
			Bronze {GLO} ∣ market for ∣ APOS, U	0.0053	kg
			Brass {CH} ∣ market for brass ∣ APOS, U	0.0078	kg
			Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.0059	kg
			Bronze {GLO} ∣ market for ∣ APOS, U	0.0020	kg
			Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.4719	kg
			Polyester resin, unsaturated {RER} ∣ market for polyester resin, unsaturated ∣ APOS, S	0.0332	kg
			Polycarbonate {GLO} ∣ market for ∣ APOS, U	0.0020	kg
	Metalic Connectors	3	Aluminium, primary, cast alloy slab from continuous casting {GLO} ∣ market for ∣ APOS, U	0.6698	kg
			Polycarbonate {GLO} ∣ market for ∣ APOS, U	0.4199	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0692	kg
			Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.0316	kg
			Lead {GLO} ∣ market for ∣ APOS, U	0.0010	kg
			Glass fibre reinforced plastic, polyester resin, hand lay-up {GLO} ∣ market for ∣ APOS, U	0.0186	kg
			Zinc {CA-QC} ∣ primary production from concentrate ∣ APOS, U	0.0876	kg
	Contactors	2	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.0120	kg
			Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.0200	kg
			Epoxy resin insulator, SiO_2 {GLO} ∣ market for ∣ APOS, U	0.0800	kg

Table A3. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Power Supply 24V-3,3A	1	Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.1251	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0017	kg
			Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.0075	kg
			Steel, unalloyed {GLO} ∣ market for ∣ APOS, U	0.0505	kg
			Polycarbonate {GLO} ∣ market for ∣ APOS, U	0.0063	kg
			Polypropylene, granulate {GLO} ∣ market for ∣ APOS, S	0.0023	kg
			Tetrafluoroethylene {GLO} ∣ market for ∣ APOS, S	0.0011	kg
			Printed wiring board, mounted mainboard, laptop computer, Pb free {GLO} ∣ market for ∣ APOS, U	0.3054	kg
	Power Supply 24V-20A	1	Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.2963	kg
			Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.1884	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0478	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} ∣ market for ∣ APOS, U	0.0211	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} ∣ market for ∣ APOS, U	0.0211	kg
			Bronze {GLO} ∣ market for ∣ APOS, U	0.0009	kg
			Electronic component, passive, unspecified {GLO} ∣ market for ∣ APOS, U	0.2241	kg
			Polyphenylene sulfide {GLO} ∣ market for ∣ APOS, S	0.0450	kg
			Polyethylene, high density, granulate {GLO} ∣ market for ∣ APOS, U	0.0131	kg
			Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.0075	kg
	Filter	1	Polyvinylchloride, emulsion polymerised {GLO} ∣ market for ∣ APOS, U	0.0175	kg
			Epoxy resin insulator, SiO_2 {GLO} ∣ market for ∣ APOS, U	0.0044	kg
			Capacitor, electrolyte type, <2 cm height {GLO} ∣ market for ∣ APOS, U	0.1374	kg
			Printed wiring board, mounted mainboard, laptop computer, Pb free {GLO} ∣ market for ∣ APOS, U	0.0393	kg
			Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.3272	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.1178	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} ∣ market for ∣ APOS, U	0.4440	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} ∣ market for ∣ APOS, U	0.4440	kg
			Steel, unalloyed {GLO} ∣ market for ∣ APOS, U	0.6436	kg
Controller	Fiber Optic Cable	3 (m)	Germanium	1.10×10^{-6}	kg
			Activated silica {GLO} ∣ market for ∣ APOS, S	2.64×10^{-5}	kg
			Epoxy resin insulator, SiO_2 {GLO} ∣ market for ∣ APOS, U	0.0002	kg
			Activated silica {GLO} ∣ market for ∣ APOS, S	0.0004	kg
			Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.0003	kg
			Polyethylene, low density, granulate {GLO} ∣ market for ∣ APOS, S	0.0023	kg
			Extrusion, plastic pipes {RER} ∣ extrusion, plastic pipes ∣ APOS, S	0.0023	kg

Table A4. System 4—Matching Ecoinvent v3.7.1 database with S4 components.

Components	Parts / Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Heater cartridge with thermocouple	-	1	Resistor, auxilliaries and energy use {GLO} ∣ market for ∣ APOS, U	10.5600	kg
Steel Plate	-	1	Tin plated chromium steel sheet, 2 mm {GLO} ∣ market for ∣ APOS, U	37.2800	m^2
Retractors/Spacers	-	1	Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	7.2000	kg
Bolts	-	1	Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.3500	kg
Nuts	-	1	Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.0088	kg
Table	-	1	Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	629.7300	kg
Insulation	-	15.50 (kg)	Activated silica {GLO} ∣ market for ∣ APOS, U Stone wool {RoW} ∣ stone wool production ∣ APOS, S Aluminium hydroxide {CN} ∣ aluminium hydroxide production ∣ APOS, U (Adjusted for alumina)	0.6500 1.0000 0.3500	kg kg kg

Table A5. System 5—Matching Ecoinvent v3.7.1 database with S5 components.

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Distilled Water	-	1	water, deionised {Europe without Switzerland} ∣ market for water, deionised ∣ APOS, U	100	kg
Hosepipes	-	1	Polyurethane, rigid foam {RER} ∣ production ∣ APOS, U (Adjusted)	0.9286	kg
Chiller	-	1	Chiller adaptado de Faludi [31]	210	kg

Table A6. System 6—Matching Ecoinvent v3.7.1 database with S6 components.

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Structure	Rail	1	Steel, low-alloyed, hot rolled {GLO} ∣ market for ∣ APOS, U	15.2000	kg
	Steel Plate	1	Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, S	1263.7848	kg
	Cables	1	Cable, unspecified {GLO} ∣ market for ∣ APOS, U	1.3963	kg
	Profile	1	Tin plated chromium steel sheet, 2 mm {GLO} ∣ market for ∣ APOS, U	24.9965	m^2
Photosensitive sensors	-	1	Electronic component, passive, unspecified {GLO} ∣ market for ∣ APOS, U	0.0570	kg
Photosensitive sensors box	-	1	Light emitting diode {GLO} ∣ market for ∣ APOS, U	0.9600	kg
Fluorescent Lamps	-	1	Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	13.5800	kg

Table A7. System 7—Matching Ecoinvent v3.7.1 database with S7 components.

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Structure	Aluminium profile	1	Aluminium alloy, AlLi {GLO} | market for | APOS, U	5.2161	kg
	Steel Box	1	Steel, chromium steel 18/8 {GLO} | market for | APOS, U	52.0000	kg
Switchboard	Structure	1	Tin plated chromium steel sheet, 2 mm {GLO} | market for | APOS, U	0.1328	m^2
	EMAQS	0.370 (kg)	Electronic component, passive, unspecified {GLO} | market for | APOS, U	0.3771	kg
			Polycarbonate {GLO} | market for | APOS, U	0.2754	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0161	kg
			Ethylene vinyl acetate copolymer {RER} | market for ethylene vinyl acetate copolymer | APOS, U	0.0074	kg
	Fuse Terminal	3	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0791	kg
			Copper, cathode {GLO} | market for | APOS, S	0.0152	kg
			Brass {CH} | market for brass | APOS, U	0.0559	kg
	Terminal Block	0.047 (kg)	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.4825	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0930	kg
			Brass {CH} | market for brass | APOS, U	0.3409	kg
	Cable glands	2	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0079	kg
	Screw Terminal	1	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0060	kg
			Copper, cathode {GLO} | market for | APOS, S	0.0070	kg
			Brass {CH} | market for brass | APOS, U	0.0043	kg
	RJ45 connector	1	Nylon 6-6, glass-filled {RER} | market for nylon 6-6, glass-filled | APOS, S	0.0520	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0120	kg
			Polyester resin, unsaturated {RER} | market for polyester resin, unsaturated | APOS, S	0.0040	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0120	kg
Controller	Solid State Relays	24	Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0120	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.0200	kg
			Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	0.0800	kg
	Relays	0.0499 (kg)	Steel, unalloyed {GLO} | market for | APOS, U	0.0038	kg
			Brass {CH} | market for brass | APOS, U	0.0031	kg
			Cast iron {GLO} | market for | APOS, U	0.0005	kg
			Bronze {GLO} | market for | APOS, U	0.0003	kg
			Silver {GLO} | market for | APOS, S	8.42×10^{-5}	kg
			Tin {GLO} | market for | APOS, U	5.61×10^{-5}	kg
			Electronic component, passive, unspecified {GLO} | market for | APOS, U	0.0032	kg
			Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0121	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, U	0.0012	kg
			Polycarbonate {GLO} | market for | APOS, U	0.0005	kg
			Epoxy resin insulator, SiO_2 {GLO} | market for | APOS, U	5.61E-05	kg

Table A7. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Four Phase Circuit Breaker	4	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.1723	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} ∣ market for ∣ APOS, U	0.0049	kg
			Polycarbonate {GLO} ∣ market for ∣ APOS, U	0.0102	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} ∣ market for ∣ APOS, U	0.0049	kg
			Polyphenylene sulfide {GLO} ∣ market for ∣ APOS, U	0.0146	kg
			Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.0033	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0171	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} ∣ market for ∣ APOS, U	0.0028	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} ∣ market for ∣ APOS, U	0.0028	kg
			Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.0049	kg
			Steel, unalloyed {GLO} ∣ market for ∣ APOS, U	0.1183	kg
			Zinc {GLO} ∣ market for ∣ APOS, U	0.0191	kg
	Three Phase Circuit Breaker	8	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.1293	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} ∣ market for ∣ APOS, U	0.0037	kg
			Polycarbonate {GLO} ∣ market for ∣ APOS, U	0.0076	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} ∣ market for ∣ APOS, U	0.0037	kg
			Polyphenylene sulfide {GLO} ∣ market for ∣ APOS, U	0.0110	kg
			Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.0024	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0128	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} ∣ market for ∣ APOS, U	0.0021	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} ∣ market for ∣ APOS, U	0.0021	kg
			Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.0037	kg
			Steel, unalloyed {GLO} ∣ market for ∣ APOS, U	0.0887	kg
			Zinc {GLO} ∣ market for ∣ APOS, U	0.0143	kg
	Single Phase Circuit Breaker	1	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.0431	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} ∣ market for ∣ APOS, U	0.0012	kg
			Polycarbonate {GLO} ∣ market for ∣ APOS, U	0.0025	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} ∣ market for ∣ APOS, U	0.0012	kg
			Polyphenylene sulfide {GLO} ∣ market for ∣ APOS, U	0.0037	kg
			Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.0008	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0043	kg
			Ferrochromium, high-carbon, 68% Cr {GLO} ∣ market for ∣ APOS, U	0.0007	kg
			Ferromanganese, high-coal, 74.5% Mn {GLO} ∣ market for ∣ APOS, U	0.0007	kg
			Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.0012	kg
			Steel, unalloyed {GLO} ∣ market for ∣ APOS, U	0.0296	kg
			Zinc {GLO} ∣ market for ∣ APOS, U	0.0048	kg

Table A7. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Metalic connectors	5	Aluminium, primary, cast alloy slab from continuous casting {GLO} ∣ market for ∣ APOS, U	0.6698	kg
			Polycarbonate {GLO} ∣ market for ∣ APOS, U	0.4199	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0692	kg
			Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.0316	kg
			Lead {GLO} ∣ market for ∣ APOS, U	0.0010	kg
			Glass fibre reinforced plastic, polyester resin, hand lay-up {GLO} ∣ market for ∣ APOS, U	0.0186	kg
			Zinc {CA-QC} ∣ primary production from concentrate ∣ APOS, U	0.0876	kg
	Plug A	4	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.0251	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0036	kg
	Plug B	8	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.0526	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0048	kg
	Plug C	4	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.5740	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0060	kg
	Plug D	1	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.0790	kg
	Plug E	2	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.0280	kg
	Switch Ethernet	1	Epoxy resin insulator, SiO_2 {GLO} ∣ market for ∣ APOS, U	0.0001	kg
			Activated silica {GLO} ∣ market for ∣ APOS, U	0.0004	kg
			Polyethylene, low density, granulate {GLO} ∣ market for ∣ APOS, U	0.0020	kg
			Epoxy resin insulator, SiO_2 {GLO} ∣ market for ∣ APOS, U	0.0039	kg
			Glass fibre {GLO} ∣ market for ∣ APOS, U	0.0088	kg
			Cobalt {GLO} ∣ market for ∣ APOS, U	0.0002	kg
			Iron ore concentrate {GLO} ∣ market for iron ore concentrate ∣ APOS, U	0.0002	kg
			Nickel, class 1 {GLO} ∣ market for nickel, class 1 ∣ APOS, U	0.0004	kg
			Aluminium hydroxide {GLO} ∣ market for ∣ APOS, U	0.0030	kg
			Aluminium oxide, non-metallurgical {RoW} ∣ market for aluminium oxide, non-metallurgical ∣ APOS, S	0.0004	kg
			Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.0049	kg
			Tin {GLO} ∣ market for ∣ APOS, U	0.0044	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0111	kg
			Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.0063	kg
			Single-Si wafer, for electronics {GLO} ∣ market for ∣ APOS, U	3.8824	cm^2
			Polyethylene terephthalate, granulate, amorphous {GLO} ∣ market for ∣ APOS, U	0.0002	kg
			Polymethyl methacrylate, sheet {GLO} ∣ market for ∣ APOS, U	0.0020	kg
			Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.0165	kg
			Acrylonitrile-butadiene-styrene copolymer {GLO} ∣ market for ∣ APOS, U	0.0478	kg

Table A7. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Safety Relay	0.2515 (kg)	Nylon 6 {RER} ∣ market for nylon 6 ∣ APOS, S	0.2667	kg
			Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.1308	kg
			Polycarbonate {GLO} ∣ market for ∣ APOS, U	0.1176	kg
			Polypropylene, granulate {GLO} ∣ market for ∣ APOS, S	0.0182	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.1954	kg
			Zinc {GLO} ∣ market for ∣ APOS, U	0.0696	kg
			Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.0248	kg
			Tin {GLO} ∣ market for ∣ APOS, U	0.0166	kg
			Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.0050	kg
			Glass fibre {GLO} ∣ market for ∣ APOS, S	0.0928	kg
			Epoxy resin insulator, SiO_2 {GLO} ∣ market for ∣ APOS, U	0.0712	kg
			Silica sand {RoW} ∣ production ∣ APOS, S	0.0248	kg
	PLC	1	Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.0157	kg
			Steel, chromium steel 18/8 {GLO} ∣ market for ∣ APOS, U	0.0090	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0081	kg
			Electronic component, passive, unspecified {GLO} ∣ market for ∣ APOS, U	0.5494	kg
			Polycarbonate {GLO} ∣ market for ∣ APOS, U	0.3675	kg
			Polyethylene, low density, granulate {GLO} ∣ market for ∣ APOS, U	0.0223	kg
			Ethylene vinyl acetate copolymer {RER} ∣ market for ethylene vinyl acetate copolymer ∣ APOS, U	0.0127	kg
	Terminal Block	0.2256 (kg)	Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S	0.4825	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0930	kg
			Brass {CH} ∣ market for brass ∣ APOS, U	0.3409	kg
	Power Supply 1	0.22 (kg)	Phenolic resin {RER} ∣ market for phenolic resin ∣ APOS, S	0.0037	kg
			Polyethylene, low density, granulate {GLO} ∣ market for ∣ APOS, U	0.0039	kg
			Epoxy resin insulator, SiO_2 {GLO} ∣ market for ∣ APOS, U	0.0166	kg
			Acrylonitrile-butadiene-styrene copolymer {GLO} ∣ market for ∣ APOS, U	0.0200	kg
			Polycarbonate {GLO} ∣ market for ∣ APOS, U	0.0831	kg
			Electrolyte, KOH, LiOH additive {GLO} ∣ market for ∣ APOS, U	0.0074	kg
			Triphenyl phosphate {GLO} ∣ market for triphenyl phosphate ∣ APOS, U	0.0100	kg
			Glass fibre {GLO} ∣ market for ∣ APOS, U	0.0229	kg
			Tin {GLO} ∣ market for ∣ APOS, U	0.0074	kg
			Copper, cathode {GLO} ∣ market for ∣ APOS, U	0.0134	kg
			Ferrite {GLO} ∣ market for ∣ APOS, U	0.0142	kg
			Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.0145	kg
			Polyethylene terephthalate, granulate, amorphous {GLO} ∣ market for ∣ APOS, U	0.0029	kg

Table A7. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Controller	Power Supply 2	1.50 (kg)	Printed wiring board, mounted mainboard, laptop computer, Pb free {GLO} | market for | APOS, U	0.9162	kg
			Tetrafluoroethylene {GLO} | market for | APOS, S	0.0034	kg
			Polypropylene, granulate {GLO} | market for | APOS, S	0.0069	kg
			Polycarbonate {GLO} | market for | APOS, U	0.0189	kg
			Steel, unalloyed {GLO} | market for | APOS, U	0.1516	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.0224	kg
			Copper, cathode {GLO} | market for | APOS, U	0.0052	kg
			Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.3754	kg
	Breaker	1.06 (kg)	Polycarbonate {GLO} | market for | APOS, U	0.2841	kg
			Polyethylene, low density, granulate {GLO} | market for | APOS, S	0.0054	kg
			Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S	0.0375	kg
			Polyester resin, unsaturated {RER} | market for polyester resin, unsaturated | APOS, U	2.0100	kg
			Zinc {GLO} | market for | APOS, U	0.0107	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.1072	kg
			Copper, cathode {GLO} | market for | APOS, U	1.1363	kg
			Steel, unalloyed {GLO} | market for | APOS, U	1.5598	kg
	PCB	0.0047 (m^2)	Printed wiring board, for through-hole mounting, Pb containing surface {GLO} | market for | APOS, S	0.5000	m^2
			Printed wiring board, for surface mounting, Pb containing surface {GLO} | market for | APOS, S	0.5000	m^2
Wiring	-	1	Cable, unspecified {GLO} | market for | APOS, U	16.7551	kg
			Cable, 18 nucleos PVC (unspecified {GLO} | production) | APOS, U (Adjusted)	12.4100	kg

Table A7. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Video Camera	-	0.67 (kg)	Aluminium, cast alloy {GLO} | market for | APOS, S	0.01625	kg
			Silicon, metallurgical grade {RoW} | production | APOS, S	0.00223	kg
			Cast iron {RER} | production | APOS, S	0.00008	kg
			Polyethylene terephthalate, granulate, amorphous {RER} | production | APOS, S	0.00034	kg
			Glass fibre {RER} | production | APOS, S	0.00004	kg
			Injection moulding {RER} | processing | APOS, S	0.00038	kg
			Brass {CH} | market for brass | APOS, S	0.00031	kg
			Gold {GLO} | market for | APOS, S	0.0000003	kg
			Printed wiring board, surface mounted, unspecified, Pb free {GLO} | market for | APOS, S	0.00903	kg
			Printed wiring board, for surface mounting, Pb free surface {GLO} | production | APOS, S	1285	mm^2
			Mounting, surface mount technology, Pb-free solder {GLO} | market for | APOS, S	1285	mm^2
			Capacitor, for surface-mounting {GLO} | market for | APOS, S	0.00112	kg
			Diode, glass-, for surface-mounting {GLO} | market for | APOS, S	0.00014	kg
			Electric connector, peripheral component interconnect buss {GLO} | market for | APOS, S	0.00140	kg
			Integrated circuit, logic type {GLO} | market for | APOS, S	0.00100	kg
			Light emitting diode {GLO} | market for | APOS, S	0.00004	kg
			Resistor, surface-mounted {GLO} | market for | APOS, U	0.00080	kg
			Transistor, surface-mounted {GLO} | market for | APOS, S	0.00035	kg
			Aluminium, cast alloy {GLO} | market for | APOS, S	0.00219	kg
			Silicon, metallurgical grade {RoW} | production | APOS, S	0.00024	kg
			Flat glass, coated {RER} | production | APOS, S	0.00486	kg
			Adhesive, for metal {DE} | production | APOS, S	0.00100	kg
			Steel, chromium steel 18/8 {GLO} | market for | APOS, S	0.00100	kg
			Wire drawing, steel {RER} | processing | APOS, S	0.00100	kg
			Copper, cathode {GLO} | market for | APOS, S	0.00051	kg
			Nickel, class 1 {GLO} | market for nickel, class 1 | APOS, S	0.00017	kg
			Zinc {GLO} | market for | APOS, S	0.00025	kg
			Sheet rolling, copper {RER} | processing | APOS, S	0.00092	kg
			Silicone product {RER} | production | APOS, S	0.00013	kg
			Adhesive, for metal {DE} | production | APOS, S	0.00100	kg

Table A8. System 8—Matching Ecoinvent v3.7.1 database with S8 components.

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Small Laptop	-	1	Computer, laptop {GLO} | market for | APOS, U (Adjusted)	1	p
Structure and Casing	Steel Structure	1	Tin plated chromium steel sheet, 2 mm {GLO} | market for | APOS, U	6.8611	cm^2
	Railway	1	Aluminium alloy, AlLi {GLO} | market for | APOS, U	2.0000	kg
	HPDE	1	Polyethylene, high density, granulate {RER} | production | APOS, U	0.2000	kg
	Rubber	1	Synthetic rubber {GLO} | market for | APOS, U	0.0500	kg
Power Supply Unit	-	1	Power supply unit, for desktop computer {GLO} | market for | APOS, U	1	p
Ethernet Cable	-	1	Polycarbonate {GLO} | market for | APOS, S Nylon 6-6 {RER} | market for nylon 6-6 | APOS, S Steel, chromium steel 18/8 {GLO} | market for | APOS, S Copper, cathode {GLO} | market for | APOS, S Steel, unalloyed {GLO} | market for | APOS, S Polyethylene terephthalate, granulate, amorphous {GLO} | market for | APOS, S Injection moulding {GLO} | market for | APOS, S Metal working, average for chromium steel product manufacturing {GLO} | market for | APOS, S Wire drawing, copper {GLO} | market for | APOS, S Metal working, average for steel product manufacturing {GLO} | market for | APOS, S	0.0024 0.0200 0.0019 0.0032 0.0132 0.0054 0.0278 0.0019 0.0032 0.0132	kg kg kg kg kg kg kg kg kg kg

Table A9. System 9—Matching Ecoinvent v3.7.1 database with S9 components.

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Optical Components	Collimator	1	flat glass, coated {RER} | market for flat glass, coated | APOS, U Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.3900 0.9100	kg kg
	Beam bender	1	Aluminium alloy, AlLi {GLO} | market for | APOS, U Steel, chromium steel 18/8 {GLO} | market for | APOS, U flat glass, coated {RER} | market for flat glass, coated | APOS, U	0.2000 0.7000 0.3000	kg kg kg
	Focusing Unit	0.60 (kg)	Aluminium alloy, AlLi {GLO} | market for | APOS, U flat glass, coated {RER} | market for flat glass, coated | APOS, U	0.4200 0.1800	kg kg
	Spacer	0.23 (kg)	Aluminium alloy, AlLi {GLO} | market for | APOS, U	0.2300	kg
	Optical Window	0.36 (kg)	Steel, chromium steel 18/8 {GLO} | market for | APOS, U flat glass, coated {RER} | market for flat glass, coated | APOS, U	0.3500 0.0097	kg kg
	Collimating Unit Holder	0.40 (kg)	Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.4000	kg
	Focusing Unit Holder	0.40 (kg)	Steel, chromium steel 18/8 {GLO} | market for | APOS, U	0.4000	kg

Table A9. *Cont.*

Components	Parts/Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Nozzle	-	2 (kg)	Brass {CH} ∣ market for brass ∣ APOS, U Bronze {CH} ∣ production ∣ APOS, U Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.7000 0.7000 0.6000	kg kg kg
Computer	-	1	Computer, desktop, without screen {GLO} ∣ market for ∣ APOS, U	1	p
Powder Spliter	-	0.40 (kg)	Brass {CH} ∣ market for brass ∣ APOS, S	0.4000	kg
Head Adapter	-	2.00 (kg)	Aluminium removed by milling, average {RER} ∣ aluminium milling, average ∣ APOS, U	2.0000	kg

Table A10. System 10—Matching Ecoinvent v3.7.1 database with S10 components.

Components	Parts Materials	No. of Parts (#)	Ecoinvent Processes	Amount/Part	Units
Pneumatic Equipment	Filter MS4	1	Aluminium, primary, cast alloy slab from continuous casting {GLO} ∣ market for ∣ APOS, U Nylon 6-6 {RER} ∣ market for nylon 6-6 ∣ APOS, S Ethylene vinyl acetate copolymer {RER} ∣ market for ethylene vinyl acetate copolymer ∣ APOS, U Polycarbonate {GLO} ∣ market for ∣ APOS, U Aluminium, wrought alloy {GLO} ∣ market for ∣ APOS, U Polyethylene, high density, granulate {RER} ∣ production ∣ APOS, U Synthetic rubber {GLO} ∣ market for ∣ APOS, U Steel, unalloyed {GLO} ∣ market for ∣ APOS, U	0.0495 0.0550 0.0413 0.0275 0.0275 0.0275 0.0055 0.0413	kg kg kg kg kg kg kg kg
	Tube	0.67 (kg)	Polyurethane, rigid foam {RER} ∣ production ∣ APOS, U (Adjusted)	0.6736	kg
	Water Tube	1.62 (kg)	Polyurethane, rigid foam {RER} ∣ production ∣ APOS, U (Adjusted)	1.6166	kg
	Sensor	0.19 (kg)	Aluminium, primary, cast alloy slab from continuous casting {GLO} ∣ market for ∣ APOS, U	0.1940	kg
	Filter and Condenser	1	Zinc {CA-QC} ∣ primary production from concentrate ∣ APOS, U Polycarbonate {GLO} ∣ market for ∣ APOS, U	2.2100 0.3900	kg kg
	Flow Control Valve GRLA	1	Brass {CH} ∣ market for brass ∣ APOS, U Zinc {CA-QC} ∣ primary production from concentrate ∣ APOS, U Aluminium, wrought alloy {GLO} ∣ market for ∣ APOS, U Synthetic rubber {GLO} ∣ market for ∣ APOS, U	0.0044 0.0077 0.0088 0.0011	kg kg kg kg
	Flow Control Valve SMC	1	Polyethylene terephthalate, granulate, amorphous {GLO} ∣ market for ∣ APOS, U Brass {CH} ∣ market for brass ∣ APOS, U	0.0044 0.0176	kg kg
	Thicc Hose	14 (kg)	Synthetic rubber {GLO} ∣ market for ∣ APOS, U	14.0000	kg
	Distribution Block	0.56 (kg)	Aluminium alloy, AlLi {GLO} ∣ market for ∣ APOS, U	0.5619	kg

References

1. Leunda, J.; Soriano, C.; Sanz, C.; Navas, V.G. Laser Cladding of Vanadium-Carbide Tool Steels for Die Repair. *Phys. Procedia* **2011**, *12*, 345–352. [CrossRef]
2. Lestan, Z.; Milfelner, M.; Balic, J.; Brezocnik, M.; Karabegovic, I. Laser deposition of Metco 15E, Colmony 88 and VIM CRU 20 powders on cast iron and low carbon steel. *Int. J. Adv. Manuf. Technol.* **2013**, *66*, 2023–2028. [CrossRef]
3. Kattire, P.; Paul, S.; Singh, R.; Yan, W. Experimental characterization of laser cladding of CPM 9V on H13 tool steel for die repair applications. *J. Manuf. Process.* **2015**, *20*, 492–499. [CrossRef]
4. Leino, M.; Pekkarinen, J.; Soukka, R. The Role of Laser Additive Manufacturing Methods of Metals in Repair, Refurbishment and Remanufacturing—Enabling Circular Economy. *Phys. Procedia* **2016**, *83*, 752–760. [CrossRef]
5. Ahn, D.G.; Lee, H.J.; Cho, J.R.; Guk, D.S. Improvement of the wear resistance of hot forging dies using a locally selective deposition technology with transition layers. *CIRP Ann.* **2016**, *65*, 257–260. [CrossRef]
6. Lourenço, J.M.; Sun, S.D.; Sharp, K.; Luzin, V.; Klein, A.N.; Wang, C.H.; Brandt, M. Fatigue and fracture behavior of laser clad repair of AerMet® 100 ultra-high strength steel. *Int. J. Fatigue* **2016**, *85*, 18–30. [CrossRef]
7. Bennett, J.; Garcia, D.; Kendrick, M.; Hartman, T.; Hyatt, G.; Ehmann, K.; You, F.; Cao, J. Repairing Automotive Dies With Directed Energy Deposition: Industrial Application and Life Cycle Analysis. *J. Manuf. Sci. Eng.* **2018**, *141*, 021019. [CrossRef]
8. Saboori, A.; Aversa, A.; Marchese, G.; Biamino, S.; Lombardi, M.; Fino, P. Application of Directed Energy Deposition-Based Additive Manufacturing in Repair. *Appl. Sci.* **2019**, *9*, 3316. [CrossRef]
9. Oh, W.J.; Lee, W.J.; Kim, M.S.; Jeon, J.B.; Shim, D.S. Repairing additive-manufactured 316L stainless steel using direct energy deposition. *Opt. Laser Technol.* **2019**, *117*, 6–17. [CrossRef]
10. Rahito; Wahab, D.A.; Azman, A.H. Additive Manufacturing for Repair and Restoration in Remanufacturing: An Overview from Object Design and Systems Perspectives. *Processes* **2019**, *7*, 802. [CrossRef]
11. Oh, W.J.; Son, Y.; Do Sik, S. Effect of in-situ heat treatments on deposition characteristics and mechanical properties for repairs using laser melting deposition. *J. Manuf. Process.* **2020**, *58*, 1019–1033. [CrossRef]
12. Ahn, D.G. Directed Energy Deposition (DED) Process: State of the Art. *Int. J. Precis. Eng. Manuf.-Green Technol.* **2021**, *8*, 703–742. [CrossRef]
13. Stieberova, B.; Broumova, M.; Matousek, M.; Zilka, M. Life Cycle Assessment of Metal Products Produced by Additive Manufacturing: A Metal Mold Case Study. *ACS Sustain. Chem. Eng.* **2022**, *10*, 5163–5174. [CrossRef]
14. Gouveia, J.R.; Pinto, S.M.; Campos, S.; Matos, J.R.; Sobral, J.; Esteves, S.; Oliveira, L. Life Cycle Assessment and Cost Analysis of Additive Manufacturing Repair Processes in the Mold Industry. *Sustainability* **2022**, *14*, 2105. [CrossRef]
15. *ISO 14040*; Environmental Management—Life Cycle Assessment—Principles and Framework; ISO: Geneva, Switzerland, 2006.
16. *ISO 14044*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines; ISO: Geneva, Switzerland, 2006.
17. Botejara-Antúnez, M.; González-Domínguez, J.; García-Sanz-Calcedo, J. Comparative analysis of flat roof systems using life cycle assessment methodology: Application to healthcare buildings. *Case Stud. Constr. Mater.* **2022**, *17*, e01212. [CrossRef]
18. Annibaldi, V.; Cucchiella, F.; Rotilio, M. Economic and environmental assessment of thermal insulation. A case study in the Italian context. *Case Stud. Constr. Mater.* **2021**, *15*, e00682. [CrossRef]
19. Zago Barbosa, M.; De, J.; Dias, O.; Teixeira Marvila, M.; De Azevedo, A.R.G. Life cycle approach applied to the production of ceramic materials incorporated with ornamental stone wastes. *Environ. Sci. Pollut. Res.* **2022**, *29*, 9957–9970. [CrossRef]
20. Pinto, S.M.; Campos, S.; Oliveira, L.; Atilano, J.; Barros, L.; Pereira, e.C. Environmental and economic assessment of food additive production from mushroom bio-residues. *Clean. Environ. Syst.* **2022**, *6*, 100083. [CrossRef]
21. Gouveia, J.; Mendes, A.; Monteiro, R.; Mata, T.; Caetano, N.; Martins, A. Life cycle assessment of a vanadium flow battery. *Energy Rep.* **2020**, *6*, 95–101. [CrossRef]
22. Gouveia, J.R.; Silva, E.; Mata, T.M.; Mendes, A.; Caetano, N.S.; Martins, A.A. Life cycle assessment of a renewable energy generation system with a vanadium redox flow battery in a NZEB household. *Energy Rep.* **2020**, *6*, 87–94. [CrossRef]
23. Gouveia, J.R.; Gonçalves, M.; Rocha, R.; Baptista, A.J.; Monteiro, H. Efficiency framework to assess aeronautic composite panel production: Tracking environmental and process performance. *Sustain. Prod. Consum.* **2022**, *31*, 419–431. [CrossRef]
24. Yoon, H.S.; Lee, J.Y.; Kim, H.S.; Kim, M.S.; Kim, E.S.; Shin, Y.J.; Chu, W.S.; Ahn, S.H. A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study. *Int. J. Precis. Eng. Manuf.-Green Technol.* **2014**, *1*, 261–279. [CrossRef]
25. Islam, F. *Sustainability Assessment of Direct Energy Deposition (DED) based Hybrid Manufacturing Using Life Cycle Assessment (LCA) Method*; West Virginia University: Morgantown, WV, USA, 2021.
26. Landi, D.; Zefinetti, F.C.; Spreafico, C.; Regazzoni, D. Comparative life cycle assessment of two different manufacturing technologies: Laser additive manufacturing and traditional technique. *Procedia CIRP* **2022**, *105*, 700–705. [CrossRef]
27. Ehmsen, S.; Yi, L.; Aurich, J.C. Process Chain Analysis of Directed Energy Deposition: Energy flows and their influencing factors. *Procedia CIRP* **2021**, *98*, 607–612. [CrossRef]
28. Kafara, M.; Süchting, M.; Kemnitzer, J.; Westermann, H.H.; Steinhilper, R. Comparative Life Cycle Assessment of Conventional and Additive Manufacturing in Mold Core Making for CFRP Production. *Procedia Manuf.* **2017**, *8*, 223–230. [CrossRef]
29. Cerdas, F.; Juraschek, M.; Thiede, S.; Herrmann, C. Life Cycle Assessment of 3D Printed Products in a Distributed Manufacturing System: LCA-Distributed Manufacturing System. *J. Ind. Ecol.* **2017**, *21*, S80–S93. [CrossRef]

30. Saade, M.R.M.; Yahia, A.; Amor, B. How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies. *J. Clean. Prod.* **2020**, *244*, 118803. [CrossRef]
31. Faludi, J.; Baumers, M.; Maskery, I.; Hague, R. Environmental Impacts of Selective Laser Melting: Do Printer, Powder, Or Power Dominate? *J. Ind. Ecol.* **2016**, *21*, S144–S156. [CrossRef]
32. Výtisk, J.; Honus, S.; Kočí, V.; Pagáč, M.; Hajnyš, J.; Vujanovic, M.; Vrtek, M. Comparative study by life cycle assessment of an air ejector and orifice plate for experimental measuring stand manufactured by conventional manufacturing and additive manufacturing. *Sustain. Mater. Technol.* **2022**, *32*, e00431. [CrossRef]
33. Gao, C.; Wolff, S.; Wang, S. Eco-friendly additive manufacturing of metals: Energy efficiency and life cycle analysis. *J. Manuf. Syst.* **2021**, *60*, 459–472. [CrossRef]
34. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The ecoinvent database version 3 (part I): Overview and methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. [CrossRef]
35. PRé Consultants. What's new in SimaPro 9.0; Technical Report. 2019. Available online: https://simapro.com/wp-content/uploads/2019/02/SimaPro90WhatIsNew.pdf (accessed on 8 July 2022).
36. Huijbregts, M.; Steinmann, Z.J.N.; Elshout, P.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; van Zelm, R. *ReCiPe 2016: A harmonized Life Cycle Impact Assessment Method at Midpoint and Enpoint Level—Report 1: Characterization*; Technical Report; National Institute for Public Health and the Environment: Utrecht, The Netherlands, 2016.
37. Bayless, E.R.; Greeman, T.K.; Harvey, C. Hydrology and geochemistry of a slag-affected aquifer and chemical characteristics of slag-affected ground water, northwestern Indiana and northeastern Illinois. *Water-Resour. Investig. Rep.* **1998**, *97*, 4198.
38. Mayes, W.M.; Younger, P.L.; Aumônier, J. Buffering of alkaline steel slag leachate across a natural wetland. *Environ. Sci. Technol.* **2006**, *40*, 1237–1243. [CrossRef] [PubMed]
39. Mayes, W.M.; Younger, P.L.; Aumônier, J. Hydrogeochemistry of alkaline steel slag leachates in the UK. *Water Air Soil Pollut.* **2008**, *195*, 35–50. [CrossRef]
40. Singh, S.K.; Vashistha, P.; Chandra, R.; Rai, A.K. Study on leaching of electric arc furnace (EAF) slag for its sustainable applications as construction material. *Process Saf. Environ. Prot.* **2021**, *148*, 1315–1326. [CrossRef]
41. Ye, M.; Li, G.; Yan, P.; Ren, J.; Zheng, L.; Han, D.; Sun, S.; Huang, S.; Zhong, Y. Removal of metals from lead-zinc mine tailings using bioleaching and followed by sulfide precipitation. *Chemosphere* **2017**, *185*, 1189–1196. [CrossRef]
42. Direção-Geral de Energia e Geologia (DGEG). Produção Anual e Potência Instalada. 2019. Available online: https://www.dgeg.gov.pt/pt/estatistica/energia/eletricidade/producao-anual-e-potencia-instalada/ (accessed on 8 July 2022).
43. APREN. Balanço da Produção de Eletricidade de Portugal Continental (agosto de 2020); 2020. Available online: https://www.apren.pt/pt/energias-renovaveis/producao (accessed on 8 July 2022).