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CAD Assistant for Evaluating the Economic and Ecological Sustainability of Products

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Abstract

The greatest influence on the economic and ecological sustainability of a product can be exerted in the early stages of product development. However, limited knowledge about the product makes it difficult to make decisions based on a solid data base. For this purpose, it is required to provide the necessary information for an economic and ecological evaluation as well as decision support during the design in the CAD system. This raises the question of how a sustainability assessment for the raw material and production phase can be carried out based on a 3D CAD model and the requirements for a part. For this purpose, this paper presents a methodology to generate feasible and assessable material and manufacturing process chain combinations. Furthermore, a methodology for automatic economic and ecological evaluation of the 3D CAD model is implemented. The result is a CAD assistant that enables decisions to be made directly within the CAD system based on economic and ecological criteria. A suitable database structure is developed to provide the necessary information. The CAD assistant is then demonstrated with two case studies, which show the possibilities of the developed tool.

Keywords: sustainable development; sustainable manufacturing; CAD model; decision support

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1. Introduction

In the past, companies focused on economic sustainability. Their main focus was to balance costs, delivery time, and product quality to stay successful. With legal regulations, like the Corporate Sustainability Reporting Directive (CSRD) and the European Green Deal, and an increased environmental awareness among customers, the importance of ecological sustainability has increased [1,2]. It follows that both economic and ecological criteria must be included in the decision-making process in product development. The evaluation factors should cover the whole ecological life cycle with the raw material phase, production phase, usage phase, and end-of-use phase [3]. The presented methodology in this paper supports decision-making from the perspective of the raw material and production phase. But before the start of the ecological product life cycle, the product move through the product development process [4]. The challenge here is that 80% of the resulting economic and ecological impact is defined during the early stages of product design, but there is little knowledge available about the product, and the impacts occur in later phases of the life cycle [5]. For this reason, suitable models and the provision of information are of great importance in development.

A special challenge in the machine and plant engineering industry is the engineer-to-order character of the product development. This means that products are developed, produced, and delivered according to customer specifications [6].

Through these aspects, parts are produced in small quantities, and decisions from an economic and ecological perspective need to be made project-specific. This requires an evaluation of solutions that is specific to the project, as well as the provision of information that is specific to the use case. Currently, the evaluation of economic sustainability is often undertaken by communication between the designer and the production engineer, who analyzes the expected costs by use of their personal experience and knowledge. Furthermore, in the literature are several well-known approaches to estimate the manufacturing costs based on the known product design [7]. The assessment of ecological sustainability is often neglected. The reasons for this are a lack of modeling experience and missing data regarding the expected impacts.

A very common methodology to evaluate the ecological sustainability of a product is the life cycle assessment (LCA), which is described in DIN EN ISO 14040 [8] and DIN EN ISO 14044 [9]. The LCA requires identifying and modeling the required manufacturing processes and requires a proper database for a good analysis. In product design, the database is often unavailable, or the modeling is too time-consuming. For this reason, the methodology is often used after the first products have been produced to identify improvement potentials for later product generations. To integrate ecological sustainability into the decision-making during product design, it is necessary to make the evaluation easier and reduce the required time for modeling and data acquisition. But it is not only the ecological evaluation that requires improvement; the interaction between product design and production engineering also needs to be made easier. Often, inconsistent models are used, which makes communication difficult [10].

To integrate production engineering efficiently into the product design process, it is necessary to establish a common modeling language for product design and production engineering. A solution approach is the usage of Model-Based Systems Engineering (MBSE) in both domains with a similar structure [10].

Considering the idea of MBSE, Scholz et al. [11] present a systematic development process based on the VDI 2206 [12], integrating the material and production from the beginning of the product development process into decision-making. The focus of the process is on lightweight design. It uses cost, CO_2, and weight as decision criteria. While the integration of manufacturing and material clearly demonstrates potential, there is a lack of tools capable of efficiently generating the necessary information on materials and manufacturing directly from the product model. Furthermore, it was identified that a geometric model of the part is very important to identify the manufacturing processes or materials. Integrating a tool that provides manufacturing and material information directly in the CAD environment and enables the automatic generation of manufacturing and material evaluation will close this gap [11].

For this reason, the focus is set on Computer Aided Design (CAD) as a central model for evaluating products during the raw material phase and in the production phase. Therefore, the engineer should be supported in evaluating the design directly in their working environment. Furthermore, it must be possible to determine the best possible combination of design, material, and manufacturing process chains, considering economic and ecological sustainability.

To guide the engineer during the design phase, several Design for X (DfX) approaches exist. The most relevant one for this paper is Design for Manufacturing (DfM), which guides the engineer towards suitable designs for specific manufacturing processes. This is an established research domain. In the context of DfM, different approaches are presented. The handbook in [13] presents a collection of manufacturing process-specific design rules to ensure manufacturability and reduced costs. Approaches like [14] formalized manufacturing in an ontology to provide the knowledge and information required to analyze the manufacturing of parts.

Connecting the DfM guidelines with the CAD model can support the engineer during design with hints. For this purpose, it is necessary to separate the CAD model in features to describe the geometry of the part [15].

However, these approaches have limitations in supporting decision making for different solutions. To overcome this issue, cost and time estimation models, as well as multi-criteria decision-making tools, were integrated into the DfM approaches [16]. Although approaches to support the decision-making process by providing a targeted methodology for data collection have been developed, generating data and identifying possible manufacturing variants is very time-consuming.

To overcome this issue, a feature recognition approach to identify manufacturing-specific features in the CAD model are used. For the DfM analysis, the user selects a production process and describes the part with quality information. The manufacturing and raw material opportunities are described in a database, which also includes cost models. The database enables a rule-based manufacturability evaluation of the part with the selected process and an automatic cost evaluation is executed. The methodology is able to select the best possible product design [17,18]. The tool enables the user to analyze specified manufacturing process chains. However, it is not capable of generating alternative permissible manufacturing process chains and evaluating them.

All of the approaches described above also have in common the fact that they mainly consider conventional manufacturing processes and do not include additive manufacturing methods. Another limiting factor is the manual selection of the manufacturing processes that are analyzed. In addition, the approaches lack an expansion of the evaluation criteria with regard to ecological sustainability, as these are currently very strongly focused on costs.

At the end of the product development process, an established tool for several manufacturing processes is Computer Aided Manufacturing (CAM), which generates tool paths for production machines based on the CAD model and enables the identification of collisions before the start of production. This can also be used for simulating the required manufacturing time or process parameters. These process parameters and especially the manufacturing time are important input variables for an LCA. Due to the high level of detail, the LCA is very manufacturing process-specific. This requires the prior selection of a feasible process and an appropriate machine. Furthermore, it requires expert knowledge, and it is time-consuming to enable a usable CAM model [19].

Although the usage of CAM simulation clearly shows great potential to be established to generate input data for an LCA, the application is too complex and too specific to be used during early product design by a developer. Furthermore, running a CAM simulation for every single combination of (geometric) design, material, and production will be very time-consuming.

In [20] a commercial solution for an LCA in a CAD system is used. The commercial solution enables the environmental analysis of parts directly in the CAD system and visualizes the environmental impact. Nevertheless, the calculation strongly depends on the selected material. Furthermore, it is necessary to manually select the manufacturing process. The impact of the manufacturing process is calculated based on a reference process model, which mainly depends on the part volume. A feasibility check of the material and manufacturing process selection is not included in the tool. This could lead to non-feasible manufacturing process chains.

The several investigations undertaken regarding integrating costs and ecological evaluation in the product development process show the need for integration. The main barriers for the implementation of the tools and methods are the specific knowledge regarding LCAs and the usage of the tools, as well as time pressure during development. This brings the main focus on functionality and cost aspects. Furthermore, many specialized tools are available and need to be connected. Another problem is the scarcity of available data [21].

The challenges involved in evaluation also represent obstacles to the establishment of lightweight construction. Due to limited time and evaluation knowledge, the potential advantages during the complete life cycle of a lightweight solution are often not utilized. The lighter solution is not considered due to the higher costs during manufacturing compared to conventional solutions. In addition, methods that enable early analysis of potential, such as König's Functional Lifecycle Energy Analysis [22], are only used to a limited extent due to a lack of data and the time required for evaluation.

To address the outlined challenges, the following research questions (RQ) need to be answered:

- RQ1: How can a 3D CAD model be converted into a model for the economic and ecological evaluation of the raw material and manufacturing phase?
- RQ2: Is it possible to automatically select feasible combinations of design, material, and manufacturing process chains in the target conflict of economic and ecological sustainability?

To answer these two research questions, this paper presents a CAD assistant for the economic and ecological evaluation of products in the CAD system, whose function is roughly illustrated in Figure 1.

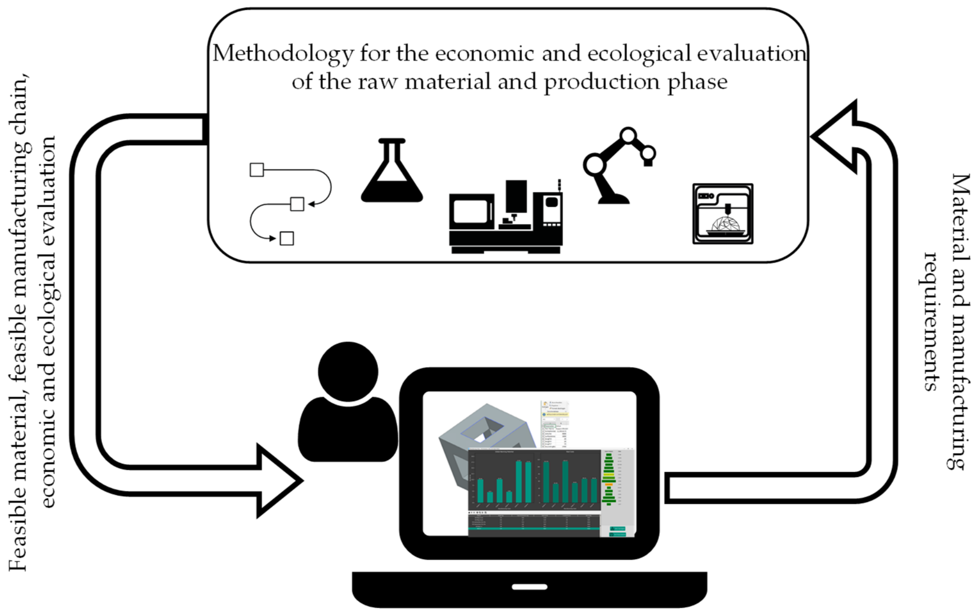


Figure 1. Overview of the presented CAD assistant.

To overcome the limitations of cost-focused DfM tools and the necessity to manually select the considered manufacturing processes, this paper presents a CAD assistant to select the best possible combination of design, manufacturing process chain, and raw material from a raw material and manufacturing perspective. Based on an automated extraction of manufacturing features combined with a manual description of the quality and mechanical requirements of the part, feasible raw material and manufacturing process chain combinations are generated automatically. The information for the manufacturing process chain generation and raw material selection is provided by different databases. Additionally, the generated solutions are evaluated from an economic and ecological sustainability perspective.

First, this paper presents the methodological background of the CAD assistant, including its classification within the current state of the art, in Section 2. Based on the theoretical structure, the implementation of the CAD assistant is presented in Section 3. The functionality of the CAD assistant is then demonstrated in Section 4 using two parts of a handling system. Section 5 shows the conclusions of the research. This paper closes with an outlook on further research directions in Section 6.

2. Materials and Methods

For ecological assessment, LCA is a very common tool. The procedure for an LCA is defined in the DIN EN ISO 14040 [8] and DIN EN ISO 14044 [9]. The first step is the definition of the scope. In the presented paper, the scope of the LCA needs to be set in accordance with the life cycle of the considered product [8]. The life cycle with the considered system boundary is visualized using the example of machine and plant engineering in Figure 2.

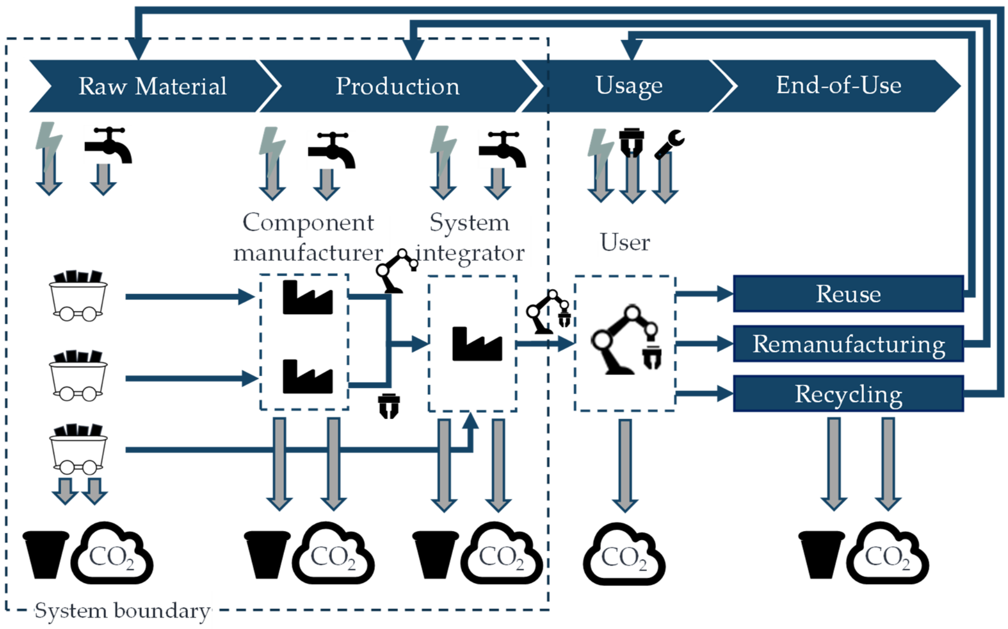


Figure 2. System boundaries in the life cycle for the CAD assistant adapted with permission from [23].

The goal of the CAD assistant is to support the engineer directly in the CAD system, evaluating the designed product from an economic and ecological perspective during the raw material and production phase. For this purpose, the system boundary is set to the raw material and the production phase. This means that the incoming raw materials with the resulting emissions, as well as the energy consumption and the consumption of other substances in manufacturing, need to be considered. In the case of the visualized life cycle of a machine, the component manufacturer or the system integrator is the potential user of the developed CAD assistant.

The execution of an LCA requires the execution of a life cycle inventory (LCI). During this step, each process inside the product system is described by its input flows and output flows. In the example in Figure 2, the process on a very high level is the component manufacturing by the component manufacturer. The inputs are the raw material, as well as energy, and consumables. The outputs are the manufactured part and waste, as well as emissions to the environment. A product system is the "Summary of process modules, elementary flows, and product flows that model the life cycle of a product and fulfill one or more specified functions" [8].

For evaluation of the environmental performance of the products, Midpoint Impact Categories are used. Compared to Endpoint Impact Categories, fewer assumptions are required. Furthermore, the number of indicators is reduced compared to the direct evaluation of the LCI results. Additionally, the Midpoint Indicators are representative of the reporting directives, like the CSRD [2]. Each Midpoint Indicator requires a corresponding characterization model. For this study, the Environmental Footprint 3.1 (EF 3.1) Midpoint Indicators with the corresponding characterization models are selected to evaluate the ecological sustainability of the product [24]. For example, the Midpoint Indicator of climate change is the Global Warming Potential (GWP_{100}), which is measured in kg CO_2-eq. and indicates all the climate gases that are emitted through the raw material and production phase. It represents the average warming effect over 100 years. For reasons of clarity, the GWP_{100} is consistently used as the sole sustainability indicator in the following sections. However, the environmental assessment within the CAD assistant considers all indicators defined in EF 3.1.

For the assessment of costs, it is helpful to use a similar approach to that used for ecological assessment. The assessment of costs is therefore carried out by DIN EN ISO 14051 [25]. This approach enables a bottom-up calculation like that presented in Figure 3.

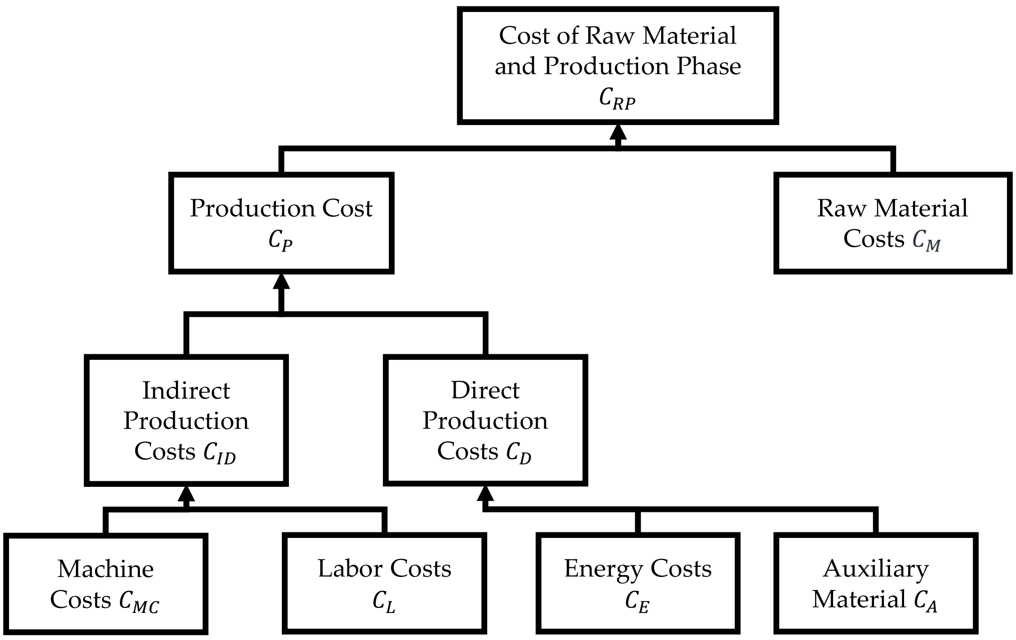


Figure 3. Structure of the economic evaluation by [25].

The costs are separated into production and raw material costs and are further classified according to their cause. This is a similarity with the ecological assessment. For the calculations, the machine is described with an hourly machine rate that includes the machine costs. Labor costs are calculated based on an hourly rate, and direct production costs are calculated based on power consumption. The same data are generated in the LCI, which is required for the ecological midpoint impact categories, and can be used for cost calculation.

To carry out an LCI, the product needs to be modeled with processes along its life cycle inside the system boundaries. The manufacturing processes can be structured in accordance with DIN 8580, which sorts the manufacturing processes into six main groups. The first main group is the primary shaping, which is the start of every manufacturing process chain. The main groups, two to five, transforming, separating, joining, and coating, are the changing of the shape. These are collected as shaping processes in this paper. The main group, separating, is also part of the finishing group in this paper. The sixth main group is changing the material properties [26].

Based on this structure, the identification of feasible combinations of materials and manufacturing process chains is required. A description with technology chains is too rough, because technology chains just describe the manufacturing processes without an application to a machine [27]. From ecological and economic perspectives, average values are used for evaluation, meaning the influence of machines on the assessment is neglected. Nevertheless, existing Technology Chain Planning Methodologies show great potential to be integrated into the CAD assistant. The actual state of the art for technology chain or manufacturing process chain planning is summarized in Figure 4 [27,28].

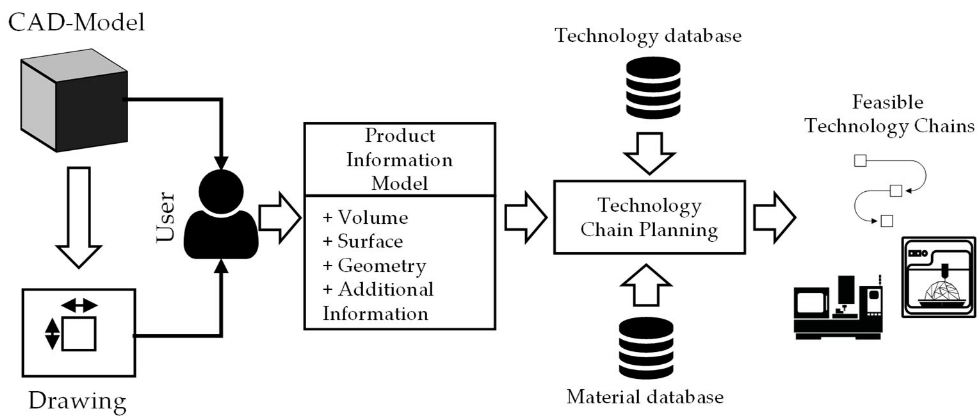


Figure 4. State of the art regarding technology chain planning with manually generated product information model.

Before the technology chain planning, the product is modeled by an engineer as a 3D CAD model. For manufacturing, the 3D CAD model is converted into drawings. With this information, the production engineer, described as user, generates a Product Information Model, which is the standardized description model of the component for the Technology Chain Planning [28,29]. Generating the product description model is very time-consuming. Furthermore, the geometry of the part is described very roughly with form elements like cylindrical shapes or uneven shapes. Functional geometric elements are not described adequately.

This leads to a rough modeling of costs compared to the feature-based manufacturing cost estimation by Jung [30]. This approach breaks down the component into machining features, which describe geometrical elements of the part. Four classes of features are used: rotational features, prismatic features, slab features, and revolving features. For each feature, the machining time is determined, and the overall manufacturing costs are calculated. This leads to a more detailed evaluation of the parts and a more precise allocation of manufacturing costs to geometric elements, which is especially important in lightweight design, as it is a key technology for improving resource efficiency

Considering the approaches from the literature for technology chain planning, as well as the potential of a feature-based description, the product information model used for the CAD assistant is shown in Table 1.

Table 1. Description of the data model generated from the 3D CAD model, including a classification into data sources; the X indicates where the information is included.

Parameter	Included in the 3D CAD Model	Detailed Analysis of 3D CAD Model	Not in 3D CAD Model
Length in X-direction	X		
Length in Y-direction	X		
Length in Z-direction	X		
Volume	X		
Part surface area	X		
Min. wall thickness		X	
Avg. wall thickness		X	
Max. wall thickness		X	
Complexity		X	
IsFlat		X	
IsExtrudable		X	
Has channels		X	
Support structures		X	
Required tensile strength			X
Required yield strength			X
Electrical conductivity			X
Quantity			X
Tolerances			X
Surface roughness			X
Feature types		X	
Feature properties		X	

The information in the product information model is classified according to its availability in the 3D CAD model. Information regarding the part dimensions are directly accessible in the 3D CAD model. Their extraction does not require any further deep analysis of the 3D CAD model. The information regarding material requirements, as well as tolerances and surface roughness, are not included in the 3D CAD model. This information must be entered manually via a user interface despite the existence of a direct data interface to the CAD system. The information for "IsFlat" describes whether the part is flat by using a Boolean variable. This means the part just has features on one level, which, for example, enables manufacturing with laser cutting. Furthermore, the part is checked if it is rotationally symmetrical and if it has several rotational and revolving features on the dominant rotational axis. This is the hint that each revolving or rotational feature on the dominant rotational axis can be manufactured by turning. Furthermore, each feature is described by its surface area and the volume that needs to be removed during manufacturing. For revolving features, this equals the volume of the hole. In contrast, for rotational features, the feature's volume is not cut. Therefore, the subtracted volume $V_{Subtracted,\ Rev}$ is calculated by Equation (1). The volume of the bounding box of the feature V_{F-BB} is multiplied with the factor 1.1, which is just a small correction factor for the raw material. The feature volume $V_{Rev.F.}$ is subtracted from this product.

$$V_{Subtracted,\ Rev} = (V_{F-BB} \times 1.1) - V_{Rev.F.} \tag{1}$$

The information that is allocated to the column of detailed analysis of the 3D CAD model is generated based on the geometry elements of the boundary representation scheme (B-Rep). This is the commonly used description model for 3D CAD models in modern CAD systems. Using this information as a basis, rather than identifying CAD system-specific definitions of drilling holes, has the advantage of being independent of the engineer's design process. Even 3D CAD models converted to a neutral data format, such as STEP (Standard for the Exchange of Product model data), can be analyzed using this methodology.

The B-Rep describes the 3D CAD model as a triple B = (K, E, F) with K = {Set of edges}, E = {Set of vertices}, and F = {Set of faces} [31]. The sets of the triplets are low-level features, which are combined to form high-level features like manufacturing features. The identification of the features is undertaken by logical analysis of the low-level features. For this purpose, an Application Programming Interface (API) is used to read the information from the CAD system. This procedure enables the semi-automatic generation of more detailed product information models for technology chain planning based on 3D CAD models. The procedure is summarized in a flow chart in Figure 5.

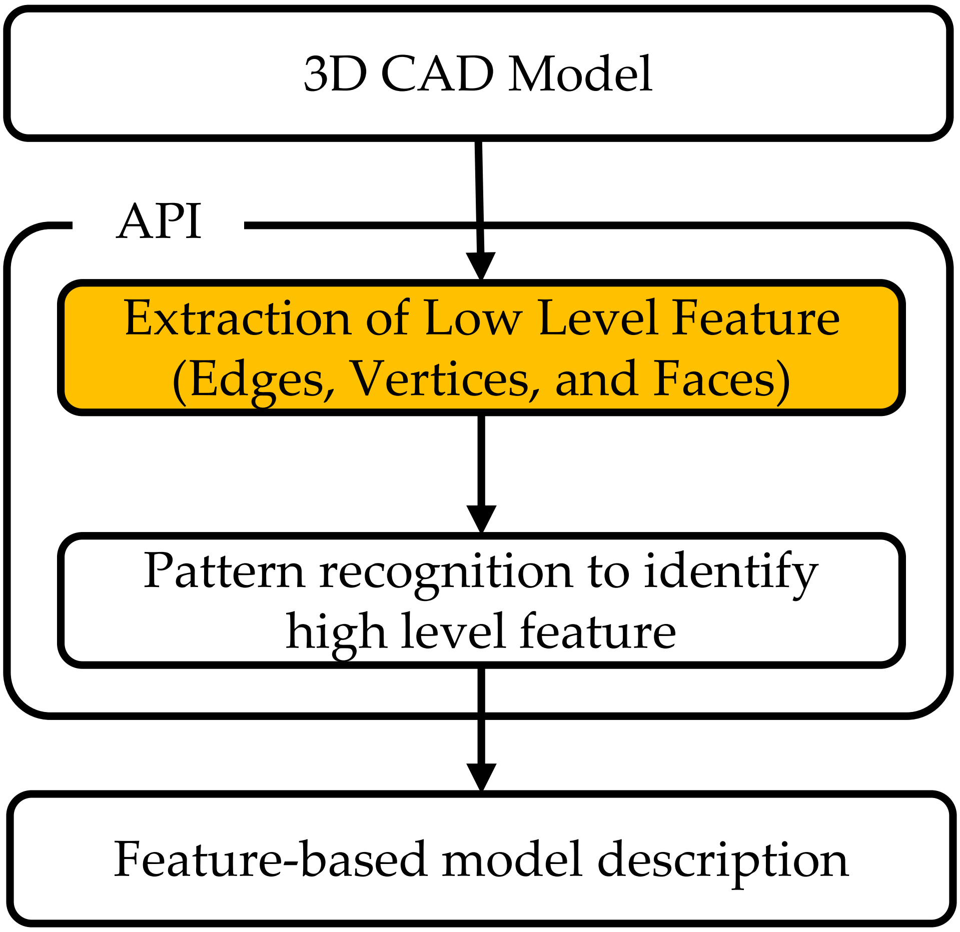


Figure 5. Flow chart for high-level feature extraction; the CAD kernel-specific part is highlighted in orange.

The entire feature recognition procedure has been implemented in the API. Based on the CAD kernel's specific notation, edges, vertices, and faces are extracted. Furthermore, pieces of information such as directions, positions, and dimensions are extracted. This is also CAD kernel-specific. Patterns for the high-level features can then be recognized based on this extracted information. Since the 3D CAD model has been broken down into its low-level features, this step is CAD kernel-independent.

Similarly to the existing Technology Chain Planning Approaches databases with the capabilities of materials, processes and machines are required. A machine is described as a resource that is able to carry out a process to generate a geometry element or property of the part to be manufactured.

A skill database is created to enable processes to be carried out on different machines. In the context of the Product–Process–Resource approach, a skill describes the ability of a machine to perform a process. However, the process is specified by specific process parameters and feasible workpiece dimensions or materials [32]. Each process can be executed by several machines, and a machine can execute several processes. The skill database combines the machine database with the process database. The machine database contains all relevant machine-specific data, while the process database encompasses essential process-related information. To construct the skill database, an expert must assign machines to corresponding processes—or vice versa. This assignment relies on the information provided by both databases.

However, the mapping procedure remains a manual task and requires the domain expertise of the user. Due to the high degree of manual effort involved, this development step entails considerable potential for errors. This is particularly critical because the current methodology does not include an automated validation mechanism for the compatibility of machine–process combinations, making expert knowledge indispensable.

Consequently, the generation of these databases must be carried out with meticulous care. Supporting the expert through methodological enhancements should therefore be a key objective of future research. To enable automated assistance in the assignment process, the machine and process databases could be extended with data describing fundamental machine capabilities and process requirements. This enriched data structure would allow for algorithmic evaluation of compatibility between machines and processes, thereby potentially reducing manual workload and minimizing error rates. However, if the user creates valid skills in the database, the CAD assistant is able to generate permissible manufacturing process chains. Nevertheless, integrating the knowledge from the skill database is a key lever for improving the economic and ecological sustainability of products [33].

For the manufacturing process chain generation, the skill database and the material database are compared to the product information model. The procedure for the generation and evaluation of the manufacturing process chains is summarized in Figure 6.

First of all, the feasible materials are selected from the material database. The requirements for the material are defined in the product information model. Afterward, feasible skills are selected from the skill database for each material. The criterion for the feasibility selection is the ability of the skill to manufacture a feature with the necessary tolerances. The information regarding the manufacturable tolerance is provided by the process of the skill. In the case that the tolerances can be met but the surface quality cannot, the database also contains processes that are categorized as “finishing” processes. These are also selected from the skill database and considered in the list of feasible skills. To identify feasible skills, the boundary conditions of the skills regarding part size and weight are checked.

Each manufacturing process chain starts with a primary shaping skill [27]. It is then checked which feature can be manufactured with the necessary tolerances by the primary forming skill. When features cannot be manufactured with the necessary tolerance or are not manufacturable with the primary forming skill, an additional shaping skill is assigned. If all features can be manufactured and the tolerances are reached, the reachable surface quality is checked. If the required surface quality is not reached, finishing processes are assigned to the features. If a material can be manufactured with several primary forming skills for each primary forming skill, a new manufacturing process chain variant is generated. The purchase of raw materials as a starting stock for milling processes is also a permissible primary shaping process in this context.

The generation of manufacturing process chains is followed by the generation of product systems for the ecological evaluation and the calculation of costs. The resulting tree structure of the manufacturing process chain process generation, which is the input to the last two steps in Figure 6, is visualized in Figure 7.

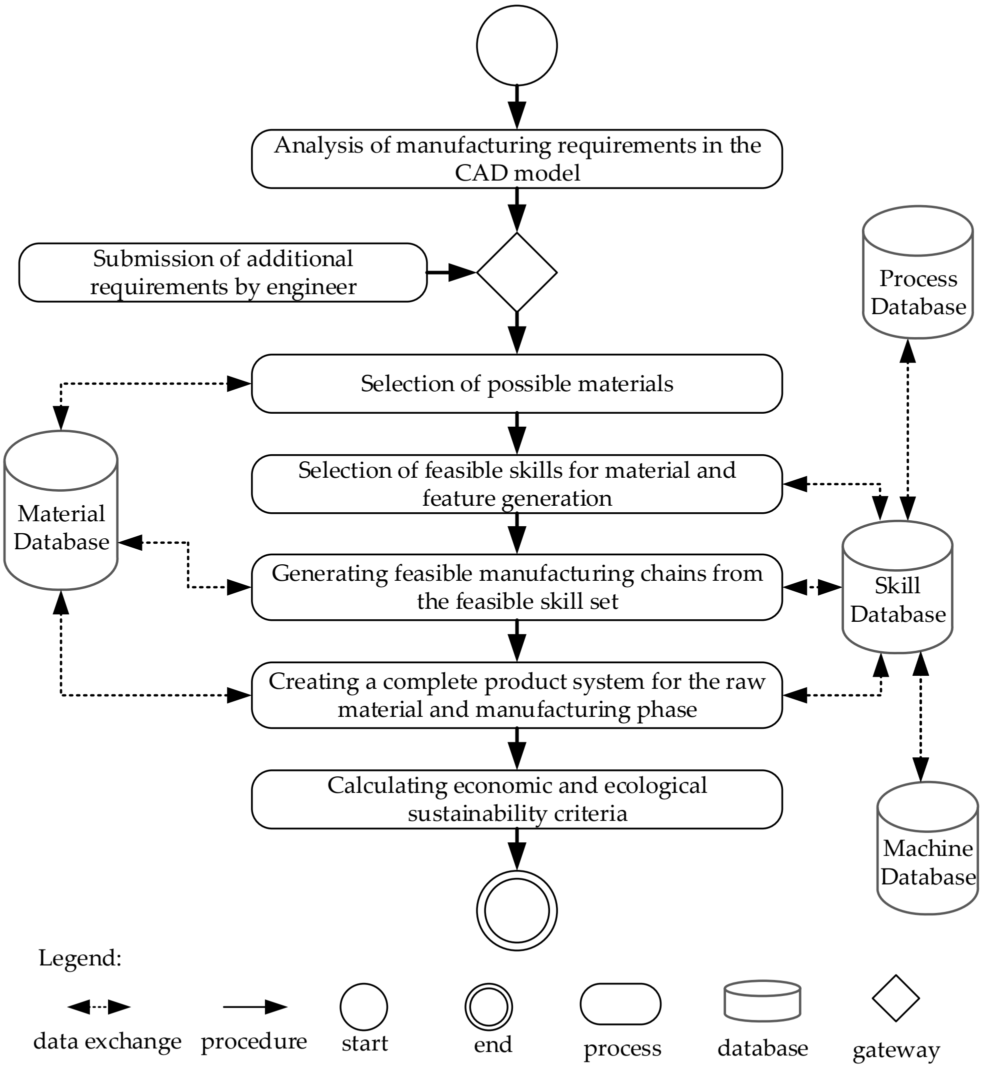


Figure 6. Procedure for manufacturing process chain generation and evaluation.

The root of the tree is the part, which can be realized by using different materials. These materials set different requirements regarding the feasible skills to fulfill the manufacturing requirements of the part. Each path through the tree represents a possible realization of the part from the raw material phase until the end of production.

The resulting descriptions enable the necessary LCI to evaluate the solutions from ecological and economic perspective. Each skill includes a process, which is described by its parameters, and a time model to calculate the manufacturing time of the skill's process. The time model can be assigned to the analytical models of the manufacturing cost estimation [7]. Furthermore, each machine is described by its machine costs per time period, as well as the required energy and the required consumables per time, like gases or liquids. The information can be gathered by analyzing machine documentation or integrating a measurement setup into the machine, as presented in [34].

With the time model and the machine model, the input flows of the skills can be calculated. These input flows are transformed into the costs from Figure 4, with a database including the costs per amount for the input flows. For the ecological evaluation, the input flows are separated into the elementary flows. For this purpose, ecological databases like ecoinvent [35] can provide the elementary flows. Furthermore, the elementary flows are assigned to the impact categories for evaluation. The characterization models for the assignment to the impact categories are generally included in the ecological databases.

After the evaluation step, the part is described with the economic and ecological evaluation for several realization possibilities regarding material and manufacturing process chains. To decide between different solutions, a multicriteria decision-making approach like Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) can be used.

To compare different part designs, a connection to the function of the part is required. Especially in the context of lightweight design, several functions are integrated into one part. To compare an integral solution with a differential solution, the methodology enables the assignment of several parts to a function. This allows us to decide between these two design approaches based on the results of the CAD assistant.

The methodology enables an automatic generation of material and manufacturing alternatives through the coupling of existing manufacturing process chain planning approaches with the 3D CAD model of the part. Furthermore, the alternatives are evaluated regarding economic and ecological sustainability. To demonstrate how the method is applied, the implementation of the CAD assistant is explained below.

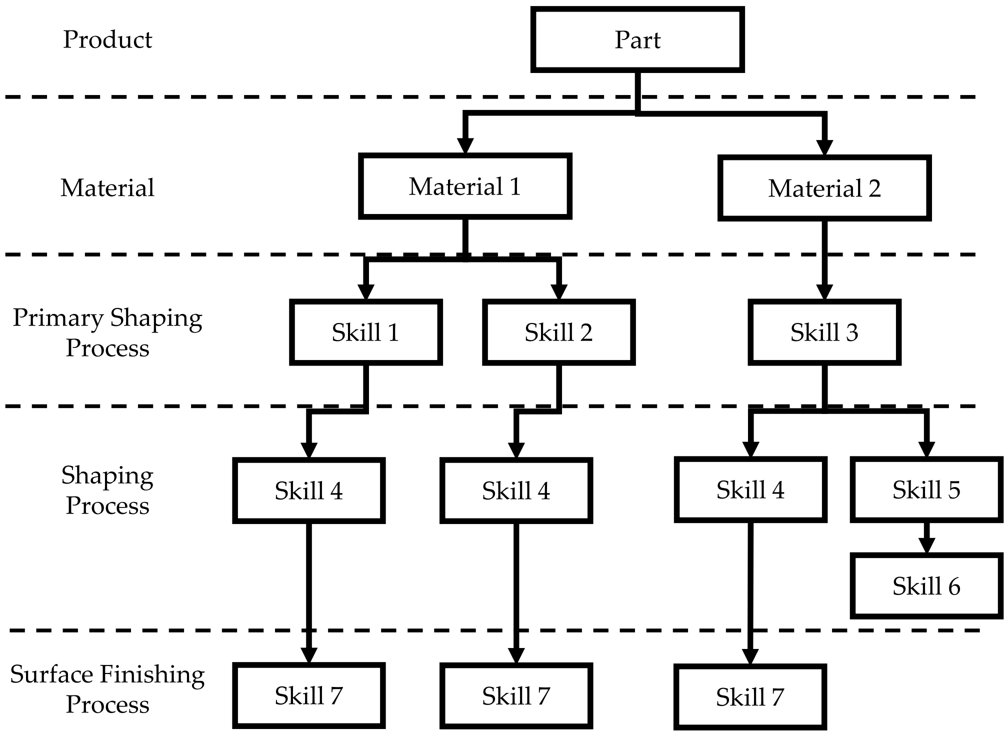


Figure 7. Tree-based description of a part after the manufacturing process chain generation.

3. Implementation of the CAD Assistant

Based on the previously presented methodology, the CAD assistant is implemented with four modules in Python 3.11. The four main modules and their functions are listed in Table 2.

Table 2. Summary of the implemented modules of the CAD assistant and the related functions of the modules.

Module	Name	Function
Module 1	CAD-Wrapper	Generation of the product information model
Module 2	Evaluation Module	Generation of manufacturing process chains, evaluation, and visualization
Module 3	Databases	Provision of databases and interaction with databases
Module 4	Ecological Assessment	Creation of the product system and implementation of the LCA

The four central modules are the so-called CAD-Wrapper, the evaluation module, the ecological assessment, and the databases. The evaluation module and the database module are fully standalone. The CAD-Wrapper, which generates the product information model, is based on the CAD system Siemens NX 1980. The only requirement for the CAD system is that it has an API. This makes it possible to implement the CAD wrapper for other systems as well. If the CAD system provides a feature recognition tool, this can also be used, and the resulting description can be linked to the other modules. However, the CAD wrapper must be implemented specifically for each system because the access via the API depends on the system used. Nevertheless, the product information model provides a standardized interface for the evaluation module, which is the key module of the CAD assistant.

The standardized description of the manufacturing process chains using input and output flows also enabled the creation of a standardized interface for ecological assessment. The determination of elementary flows based on input and output flows is already implemented in several commercial tools for LCA. These software tools integrate commercial LCA databases for the calculation of the ecological impact of the product systems. For the implementation, OpenLCA 2.1 is used [36]. This tool provides an API that enables automatic connection with the other modules, as well as the integration of many different existing databases. As a database, the ecoinvent database [35] is used. To select the required input and output flows from the ecoinvent database, the ecoinvent IDs are stored in the material and machine databases. With this information combined with the generated manufacturing process chains, the required product system for the LCA is generated fully automatically. This provides the additional advantage of the tool using the generated product system as a starting point for retrospective LCAs after the production of the part. The values of the midpoint impact categories are generated by this module. The implementation of the evaluation module is specific to OpenLCA 2.1 but can be adjusted to every other type of LCA software based on the description model generated by the CAD assistant.

The material, process, machine, and skill databases are implemented by using SQLite 3.46.0 databases. For the interaction with production and material expert, standardized user interfaces for the databases are implemented to add or adjust information in the database. The information from the databases is accessed by the evaluation module. Furthermore, the database module is able to save different part variants to evaluate them against each other.

In the evaluation module, the manufacturing process chains are generated, and the input flows and output flows are calculated for the ecological assessment module. Furthermore, the economic evaluation is performed based on the information in the machine database. Additionally, this module visualizes the results of the evaluation and provides the decisions based on economic and ecological assessment.

The whole structure of the CAD assistant, with the different modules and the interaction between them, is summarized in a software architecture diagram in Figure 8.

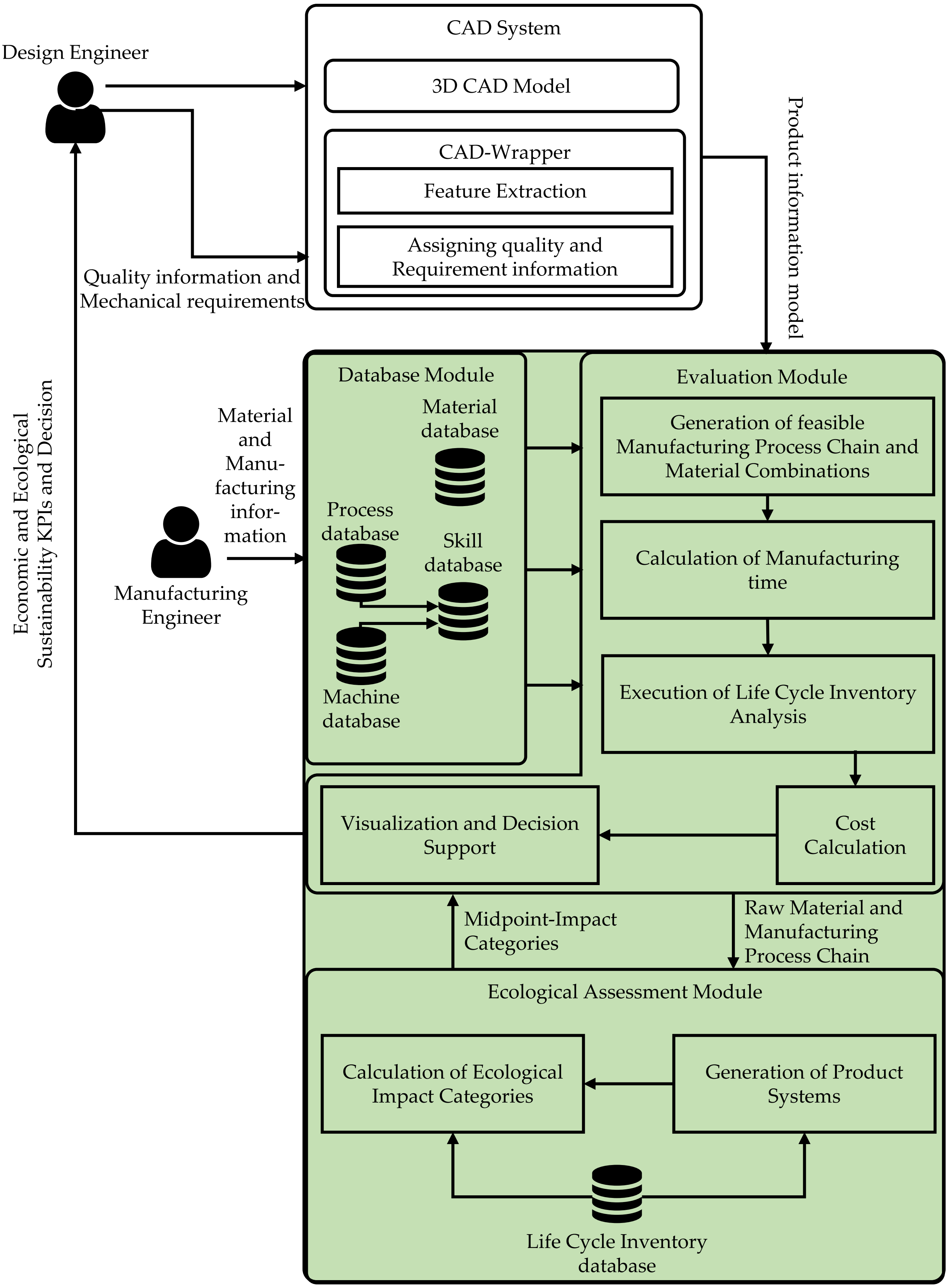


Figure 8. Software architecture of the CAD assistant and the interaction with the user; the main development focus is highlighted in green.

4. Case Studies

4.1. Introduction and Setup of the Case Studies

A handling system is used to demonstrate the functionality of the CAD assistant. Its functional structure and the logical parts required to implement the functions are shown in Figure 9.

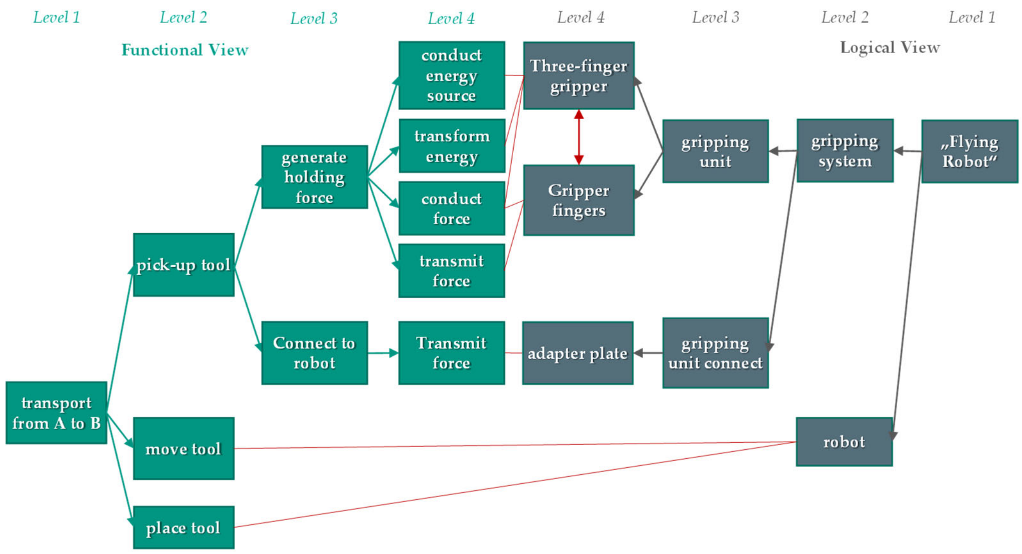


Figure 9. Functional and logical structure of the handling system under consideration in accordance to [37]; red lines show the correlation between the functions and their implementation.

The focus of the case studies is on the logical elements, "gripper finger" and "adapter plate". The adapter flange will serve as the first case study and the gripper fingers as the second one. The whole gripper system is visualized in Figure 10.

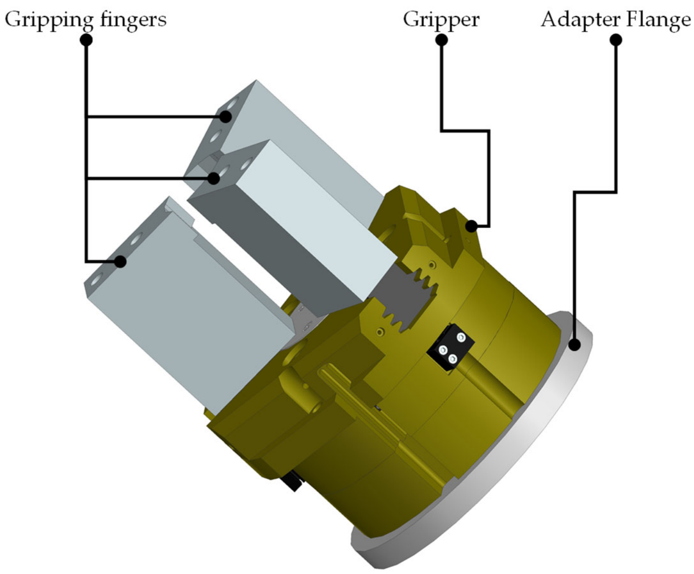


Figure 10. Visualization of the gripping system under consideration.

The gripper fingers transmit the force from the gripper to the handling object. The handling object has a cylindrical shape and a mass of 10 kg. The distance from the center of mass to the gripper finger equals 250 mm. The fingers are mounted to the gripper. The gripper itself is mounted to the adapter flange. The adapter flange is then mounted to the robot and transmits the forces between the robot and the gripper. The three-finger gripper will be purchased and is not part of the presented analysis.

For the case study, the material database is filled with the materials in Table 3.

Table 3. Summary of the materials used for the case study; "x" indicates the attribute is true.

Material Name	AlSi10Mg	Stainless Steel 316L	AlZnMgCu1.5	16MnCr5
Type	Metal	Metal	Metal	Metal
Form	Powder	Powder	Block	Block
Density [g/cm^3]	2.7	8	2.81	7.81
Tensile strength [N/mm^2]	460	530	480	640
Yield strength [N/mm^2]	230	410	380	400
Cost [€/t]	50,000	25,000	17,000	6059
Is cuttable	x	x	x	x
Is SLM-printable	x	x		
econinvent process	Adjusted process of 99b49a4d-45ce-4a45-a740-85693e19bc4c	268af6e4-ee44-4888-8fad-fff1c2009bd1	Adjusted process of 99b49a4d-45ce-4a45-a740-85693e19bc4c	a974153e-aa66-4518-89af-70548e04d87c

The attributes "Is cuttable" and "Is SLM printable" store the information on which manufacturing processes are possible for the material. As the processes in the ecoinvent database are not available for each material, an existing process for alloyed aluminum has been adjusted for the considered alloy. The output of the processes is a solid ingot, which needs to be atomized during powder production. The atomization process is modeled as well, as is recommended in the literature [38]. The database also includes primary processes for the materials. These are stored as primary processes and assigned to a specific material. For the AlSi10Mg, the process data from [39], and for Stainless Steel 316L, the data from [40] are used. These processes are just used for the ecological evaluation, as it is assumed that the prices already include these processes. The form block shows that a form-giving process is not necessary. The material can be used as an input material for milling processes.

The process database includes, for the case study, the processes from Table 4.

Table 4. Modeled processes in the database for the case study (X—possible).

Process Name	SLM	Milling	Milling
Category	Primary forming	Separating	Separating
Subcategory	Additive	Rough	Finishing
Minimal realizable tolerance [mm]	0.3	0.2	0.1
Minimal realizable surface roughness [Ra, µm]	8	2	3
Rotational feature	X	X	X
Revolving feature	X	X	X
Slab feature	X	X	X
Prismatic feature	X	X	X
Manufacturing quantity over time	10 mm^3/s	33.3 mm^3/s [41]	2.78 mm^2/s [41]

The first category of processes in the database is Selective Laser Melting (SLM), which is a metallic additive manufacturing process. The input material is metallic powder. A laser melts the contour of the layer. After the layer is finished, the powder for the next layer is provided. Then, layer by layer, the part is built up.

Milling processes are divided into roughing and finishing in the database. Due to the resulting quality properties, different cutting speeds are possible. During roughing, the speed can be substantially higher than during finishing. Furthermore, finishing does not separate huge volumes. For this reason, the manufacturing quantity is modeled with surface per time.

As presented in Table 4, all processes can manufacture every manufacturing feature. To execute these processes, suitable machines are necessary. Furthermore, the used machine has a major impact on the cost and ecological criteria of a part. The modeled machines are summarized in Table 5.

Table 5. Modeled resources for the case study.

Name	EOS M290 [42]	DMU 50 3rd
Manufacturer	EOS (Munich, Germany)	DMG (Pfronten, Germany)
Type	SLM printer	Milling
Building space [mm^3]	250 × 250 × 325	650 × 520 × 475
Buying cost [€]	400,000	350,000
Depreciation duration [year]	8	8
Average utilization	0.8	0.8
Estimated operation time (h/year)	2000	2000
Power consumption [kW]	3.2	14.5
Power consumption Finishing [kW]	-	10
Space requirements	6.2 m^2	9.40 m^2
Number of workers	0.5	0.5
Required fluids	Argon, 19.98 m^3/h [43]; compressed air 20.32 m^3/h	

The buying costs are transformed into a machine hour rate based on the depreciation duration and the average utilization. The operation time for the machine is estimated to be 2000 h per year. The power requirements are described in two stages. The SLM printer is modeled with just one power consumption. Although energy consumption varies depending on the process, it does not vary as greatly as with a milling machine. The milling machine is modeled with its power consumption during rough milling and its power consumption during finishing. Each process has an attribute, "finishing". If this is true and the milling machine is used, the power consumption for finishing will be used for calculations. For the ecological evaluation of the energy consumption, the energy mix of Germany is used with the market for electricity, the medium voltage process on the ecoinvent database [44].

Furthermore, the CAD assistant makes it possible to assign process fluids to the machine. The usage is given by the amount per time. This enables the calculation of the fluid consumption based on the calculated manufacturing time. Each fluid has an assigned ecoinvent flow ID, as well as an ecoinvent process ID. This is necessary for including the fluids in the ecological assessment.

The entries in the process and machine databases are manually combined into skills. During the manufacturing planning, the skills are connected to manufacturing process chains. For this case study, the skill database includes the following three skills. The SLM process on the EOS M290, the milling rough on the DMU 50 3rd, and the milling finishing on the DMU 50 3rd.

4.2. Results

This section presents the results obtained from the application of the CAD assistant, including the optimization and analysis of both the adapter flange (Case Study 1) and the gripper finger (Case Study 2).

4.2.1. Case Study 1: Adapter Flange

First of all, the CAD assistant is applied to the adapter flange, which is designed as a simple flat disk. The major functional features are shown in Figure 11.

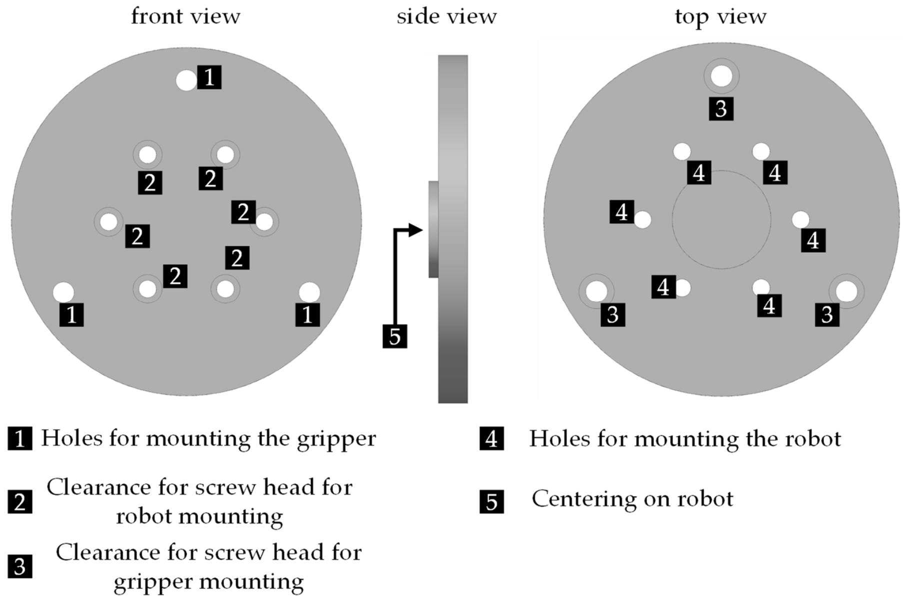


Figure 11. Description of the used adapter flange.

The adapter flange is analyzed by the CAD-Wrapper. This leads to the description shown in Table 6.

Table 6. Description model of the adapter flange based on the CAD-Wrapper.

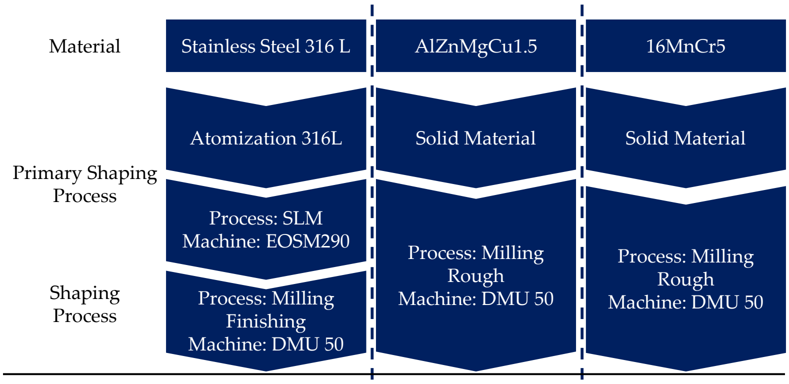
Attribute	Value
Dimensions Bounding Box	180 × 180 × 20 mm
Volume	370,381.68 mm^3
Surface	64,635.44 mm^3
Tensile Strength	470 N/mm^2
Yield Strength	300 N/mm^2
Tolerance	0.35 mm
Surface Roughness [Ra]	3.2 µm

As the information regarding mechanical properties and quality information is not stored in the 3D CAD model, this information is added manually. The description in Table 6 is supplemented by the features in Table 7.

Table 7. Description of the features detected with the CAD-Wrapper.

Feature Classification	Design Feature	Amount	Tolerance [mm]	Surface Roughness Ra [µm]	Volume [mm^3]	Surface [mm^2]
Revolving	1	3	0.2	3	399.14	145.14
Revolving	2	6	0.2	3	1555.09	414.69
Revolving	3	3	0.2	3	2748.27	610.73
Revolving	4	6	0.2	3	394.43	175.3
Rotational	5	1	0.2	3	12,500	2748.89
Prismatic	Topface	1	0.2	3	2410.15	24,101.51
Prismatic	Backface	1	0.2	3	2233.829	22,338.29

The feature classification and the volume are identified automatically by the CAD-Wrapper. The quality information regarding tolerances and surface roughness is added manually. Although this is not undertaken automatically, through the automatic identification, the user is asked specifically for this information regarding the detected features. This reduces the time for describing the product to enable the material and manufacturing selection. The results of the generated manufacturing process chains and the selected materials are shown in Figure 12.



Mass [kg]	2.96	1.04	2.89
Manufacturing Time [h]	12.91	3.35	3.35
Material Cost [€]	80.27	30.95	30.66
Total Cost [€]	585.05	107.71	107.42
Energy Consumption [kWh]	41.6	41.38	41.38

Figure 12. Resulting manufacturing process chains and material solutions for the adapter flange.

The AlSi10Mg cannot be considered for this use case, because it does not fulfill the required mechanical properties. For further ecological investigations, the corresponding product system is generated in OpenLCA 2.1.

The results of the ecological assessment, as well as the costs, are visualized for the engineer as shown in Figure 13.

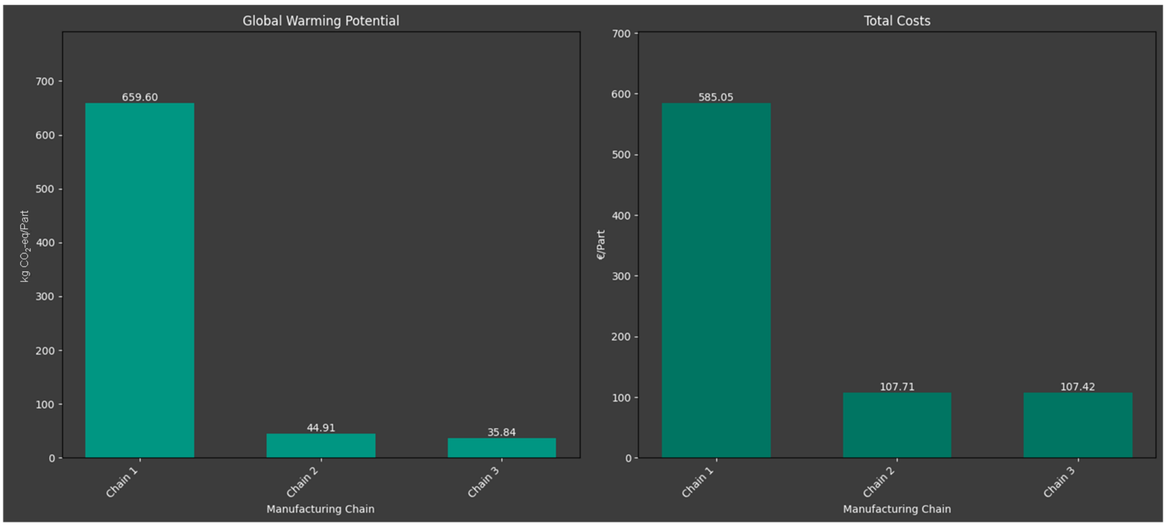


Figure 13. Visualization of the GWP and the total cost of the generated material solutions and manufacturing process chains.

The visualization clearly shows the difference in costs between the additive manufacturing solution and the conventional manufacturing. The GWP_{100} is very similar to the costs across all solutions. Based on these results, considering the total costs and GWP_{100}, the decision to use chain three is clear because it has the lowest values in both categories. The small difference in costs for the chain 2 and the chain 3 results from the similarity in the manufacturing process chain and the small differences in the material costs. Considering the weight of the solutions chain, chain two shows great potential for the usage phase of the part. The poor performance of additive manufacturing can be explained by the fact that the design freedom offered by additive manufacturing was not exploited during the part design phase. For this reason, the second case study will consider topology-optimized variants of the part.

4.2.2. Case Study 2: Gripper Fingers

The second case study is based on the gripper fingers. The use of the CAD assistant is slightly different in this context from that in the previous case study. Topology optimization is an effective tool for designing lightweight parts. It allows different variants of a part to be generated. In this case study, two topology optimizations were performed on the reference part to reduce the volume by 10% and 5%, respectively. The three variants are shown in Figure 14.

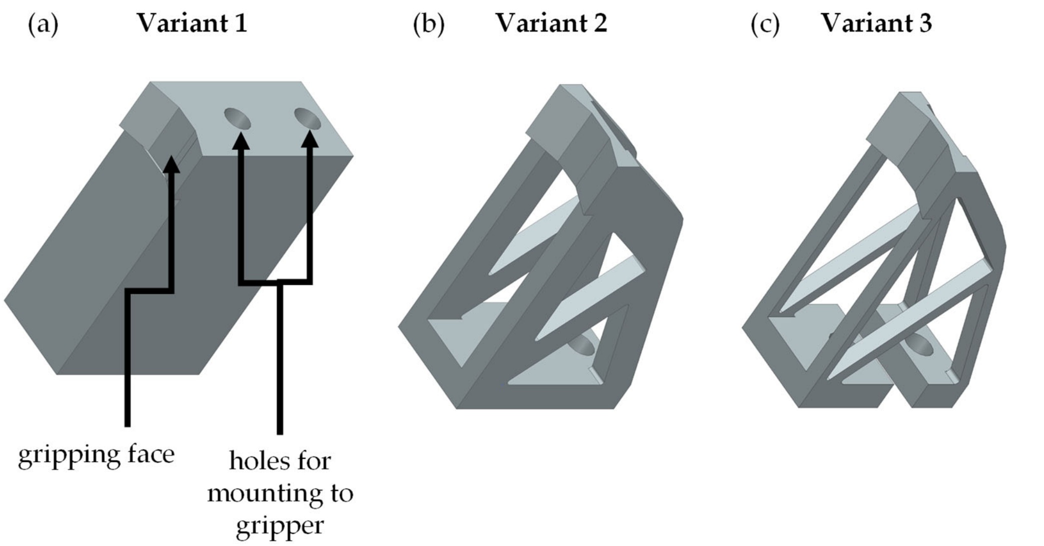


Figure 14. Considered gripper finger variants in the case study: (**a**) reference geometry with volume V_{Ref}; (**b**) topology optimized to $0.1 \times V_{Ref}$; (**c**) topology optimized to $0.05 \times V_{Ref}$.

The main design features of the finger are the gripping face and the two holes for mounting to the gripper. These faces were defined as non-design spaces for the topology optimization. After the topology optimization, the designs were manually adjusted. Then, all of these variants were analyzed by the CAD-Wrapper. Not only must a decision be made regarding which combination of materials and manufacturing processes is the best, but the three geometric variants also offer a further degree of freedom. This means the best geometric design variant has to be chosen as well. The feasible manufacturing process chains and material solutions are similar for each of the variants. For this reason, only four solutions are shown in Figure 15. However, these are applicable to all three variants.

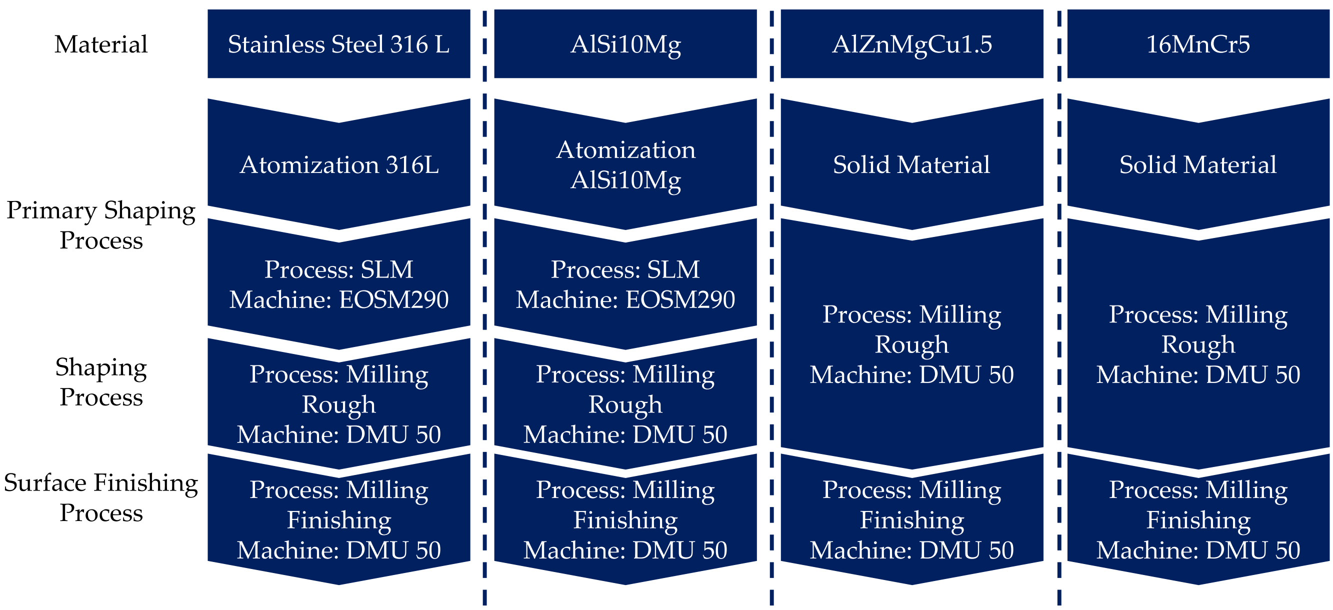


Figure 15. Generated material solutions and manufacturing process chains for the gripper fingers.

Compared to the previous case study, the requirements regarding the surface roughness of the holes and the gripping face are higher than what the rough milling or the SLM process are capable of. Therefore, a milling finishing process must be added. Based on the extracted part information, the manufacturing times as well as the costs, energy consumption, and fluid consumption can be calculated.

With the help of a product system in OpenLCA 2.1, the ecological impact can be calculated. Figure 16 presents the results for the GWP_{100} for each variant grouped into the four feasible manufacturing process chains.

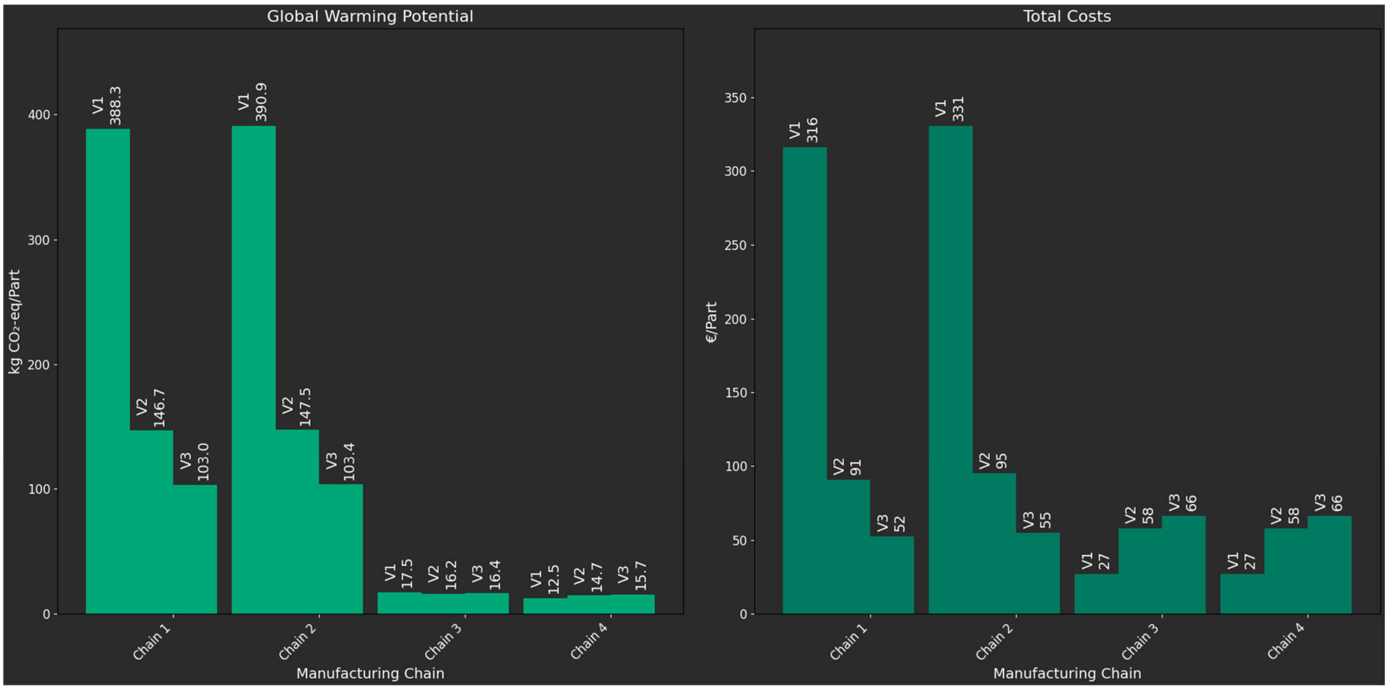


Figure 16. Dashboard for the expected GWP_{100} and total costs for the variants of the part for each feasible manufacturing process chain.

The results show a huge impact of the part design regarding the costs and the GWP_{100}. Furthermore, it can be seen that additive manufacturing has higher costs than conventional manufacturing until the part volume is just 5% of the reference volume in variant 3. Again, it can be seen that if the design freedom is not used, the conventional manufacturing process chains are the best choices. Additionally, for variant three, the best manufacturing process chain from a cost perspective is the first additive manufacturing process chain, but it is still more expensive than conventional manufacturing process chains three and four for variant one. If a TOPSIS in combination with the weights shown in Table 8 is applied, the order in Table 9 results.

Table 8. Category weights for the applied TOPSIS.

Evaluation Criteria	Weight
Cost	0.36
Climate change	0.04
Ecotoxicity freshwater	0.04
Energy resources	0.04
Eutrophication marine	0.04
Eutrophication terrestrial	0.04
Eutrophication freshwater	0.04
Human toxicity carcinogenic	0.04
Human toxicity non-carcinogenic	0.04
Ionizing radiation	0.04
Land use	0.04
Material resources	0.04
Ozone depletion	0.04
Particulate pattern formation	0.04
Photochemical oxidant	0.04
Water use	0.04

Table 9. Results of the TOPSIS.

Rank	Material and Manufacturing Process Chain Combination	Design Variant
1	Chain 3	Variant 1
2	Chain 4	Variant 1
3	Chain 4	Variant 2
4	Chain 3	Variant 2
5	Chain 4	Variant 3
6	Chain 3	Variant 3
7	Chain 1	Variant 3
8	Chain 2	Variant 3
9	Chain 1	Variant 2

The weighting sets the focus on the costs. Nevertheless, conventional chains are preferred. This is because the other environmental criteria, similarly to GWP_{100}, also perform much worse with SLM as the primary manufacturing technology than conventional production chains.

If the GWP_{100} is analyzed in more detail, as shown in Figure 17, a high impact of the used argon can be identified.

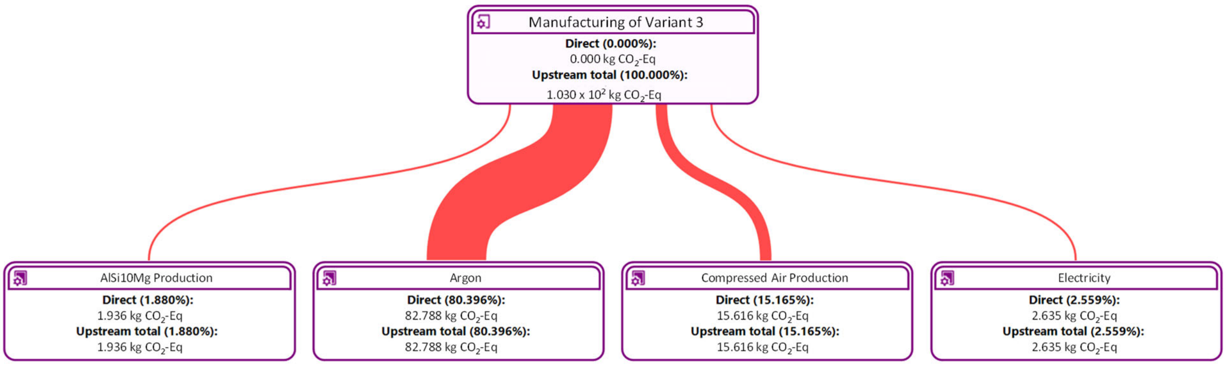


Figure 17. Sankey diagram of design variant 3 and manufacturing process chain 1 shows the high impact of the argon consumption on the GWP_{100}.

This influence of argon is similar to the other ecological evaluation categories. To demonstrate the sensitivity toward manufacturing process or machine optimization, the argon consumption is reduced by 20%. If the results are included in the ranking from Table 9, variant three with chain 2 will be ranked in fifth place.

4.3. Discussion of the Case Study Findings

The generated description combining the features, quality information, and mechanical requirements of the components enabled the description of the 3D CAD models by feasible combinations of raw materials and manufacturing process chains. The evaluation of the case studies by economic and ecological criteria has proven the ability to use this description for economically and ecologically sustainable decision-making.

For the adapter flange, conventional milling proved both economically and ecologically superior, as the design did not exploit the advantages of additive manufacturing. In contrast, the gripper finger analysis showed that topology optimization significantly affects cost and ecological performance, yet additive manufacturing remains disadvantaged due to high energy and argon consumption. Overall, the results underline that the benefits of additive manufacturing can only be realized when design freedom is systematically exploited, while conventional processes remain more efficient for standard geometries. The results of the case study also show that improvements to machines or processes can impact the evaluation of economic and ecological sustainability.

5. Conclusions

The previous section presented the application of the CAD assistant with two case studies, which are part of a gripping system. Based on the presented functional structure, the engineer needs to design solutions and decide between different solutions, as presented in the second case study. The aim of RQ1 of this paper was to find out how a 3D CAD model can be transformed into a model that can be used to model the economic and ecological sustainability of a product. Through analysis of the literature, it was determined that the geometric and quality characteristics, as well as the mechanical requirements, must be transferred to a combination of material and production chains. This enables the necessary description of processes for evaluation. Furthermore, the potential of existing technology chain planning approaches to select feasible manufacturing process chains has been identified. But also, the lack of an interface to the 3D CAD model has been identified. For this purpose, the information of a 3D CAD model was analyzed and additional information was identified. Based on this, a CAD-Wrapper was implemented to identify the geometrical elements, which makes it possible to add quality information and material requirements that are not directly included in the model. Furthermore, a proper database consisting of material, process, and machine information and the combination of processes and machines with skills are required. The implemented procedure of generating feasible manufacturing process chains demonstrates the ability to use the PPRS approach in this context. The combination of the CAD-Wrapper, the PPRS approach, and the database structure enables the automatic determination of economic and ecological evaluation models of 3D CAD models. Through adding process time models to the process database, and energy consumption and consumable consumptions to the machines, the LCI and cost analysis of the material and manufacturing process chain combinations is possible.

Through the connection of the CAD Assistant to OpenLCA 2.1 and the combination with the ecoinvent database, the results of the LCI can be directly transferred to the impact analysis. As a result, the ecological evaluation can be integrated in the decision process in the CAD system. The case studies show the possibility of selecting design, material, and manufacturing process chain combinations based on the 3D CAD model combined with the database structure. So, this paper can answer RQ2 with yes as well. Additionally, the necessary expert knowledge regarding economic and ecological evaluation can be significantly reduced through the digital toolchain and the database structure. This reduces the interfaces between the experts, which leads to a reduced development time and improved decision-making. Through this, it is also possible to analyze the impact of improvements in processes and machines regarding economic and ecological sustainability.

The results of the case study confirm that the economic efficiency and ecological assessment of additive manufacturing depend heavily on how the design freedom is utilized. For parts that are not optimized in their design, conventional manufacturing shows better economic and ecological results. However, in the second case study, the best manufacturing process chain from a cost perspective for the third variant is the chain including additive manufacturing. Compared to the conventional manufacturing process chains for variants one and two, this manufacturing process chain is still more expensive than the other conventional manufacturing process chains.

Besides the potential of the CAD assistant, it needs to be considered that the results of the evaluation strongly depend on the available database. General ecoinvent datasets are used to model the materials. If it is possible to integrate the original values of the specific materials, the quality of the results can be improved. Furthermore, currently, the process is just described with one production rate per time period, which is independent of the processed material. Therefore, the material has a very high impact on the evaluation, because if two materials have the same manufacturing process chain, the differences occur due to the different costs and ecological impacts of the material. A current limitation of the CAD assistant is the use of material-independent production rates. The machine data are based on the datasheets of the manufacturers and the literature. Using more specific data generated on the shop floor can improve the quality of the evaluation.

6. Outlook

Further developments of the CAD assistant can be the integration of material-specific correction factors to improve the quality of process time calculations. Through this, the calculations will be made more sensitive to different manufacturing processes. Furthermore, the databases can be connected to Manufacturing Execution Systems to enable automatic updates of time models. This can lead to a continuous improvement of data quality, which has been identified as a major factor in the accuracy of the calculations.

The results of the case study show that the topology-optimized parts show additional potential regarding reduced weight. Currently, the CAD assistant cannot evaluate this potential because it is focused on the raw material and production phase. Furthermore, additional models are required to evaluate the impact on the usage phase of the products.

A possible solution for this can be the integration of the different variants in a physical simulation to evaluate their impact on the usage phase. The CAD assistant can provide the resulting weight of the parts for further analysis. The results of the physical simulation will be the input to the LCI and cost modeling of the usage phase.

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