AM 4
INDUSTRY

Project report – AM 4 Industry

Quality optimisation and cost analyses to prepare implementation of additive manufacturing processes

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1 Motivation of the research project

The primary objective of the AM 4 Industry project was to develop a model that demonstrates the benefits of integrating additive manufacturing into a company's production technologies. To this end, both the resulting costs and the benefit generated by production with additive manufacturing were identified.

The cost–benefit model is designed to provide a model that is practicable for the industry and makes it possible to compare various production methods for specific parts. This is intended to enable companies to make informed decisions as to whether they want to include additive manufacturing into their production. Today, these decisions are often based on incomplete information, partial costs, and improper judgement.

Use of additive manufacturing to manufacture parts often changes more than one aspect of the supply chain. For this reason, it is difficult to get a clear overview of possible benefits and costs. For a comparison that takes all aspects into account, a holistic approach is required. To this end, all the influencing factors must be considered. This includes, in particular, a sound consideration of the entire product life cycle: Product Design / Engineering, Production / Quality, Service / After Sales. The advantages of production with additive manufacturing are, for example, integration of functions into individual components, or new possibilities in spare parts production. On the other hand, however, there are high implementation costs for the technology, and in some cases longer production times.

Since it is not possible to evaluate the benefits of additive manufacturing with a classical cost comparison alone, a new generic model had to be developed that compares the costs incurred over the entire life cycle against the technological advantages. This knowledge allows companies to gain a competitive advantage, because, obviating the need for time-consuming trial-and-error tests, the model can accelerate the decision-making process and increase the success rate of decisions.

In addition, economically more efficient use of the technology is made possible by identifying new advantages of additive manufacturing in the application of the developed model, and finally making them usable. The applicability of the model already at an early stage, even without accurate data, enables users to focus their efforts on the promising use cases and thus utilise resources more efficiently.

2 Identification of requirements and analysis of existing models

To create an assessment system for additive manufacturing, the system requirements were first identified through a survey and expert interviews. In addition, existing models were analysed.

2.1 Identification of the requirements for an assessment system for additive manufacturing

In a **survey** on the evaluation of the potential benefits of additive manufacturing, with a total of 107 companies participating, mainly small and medium-sized enterprises (SMEs) from the industrial sectors of plant and equipment construction, the automotive industry, and electrical engineering/electronics answered the questions. Most of them reported employing between 50–250 people. ¾ of the respondents see their place in the value chain as (component) producers.

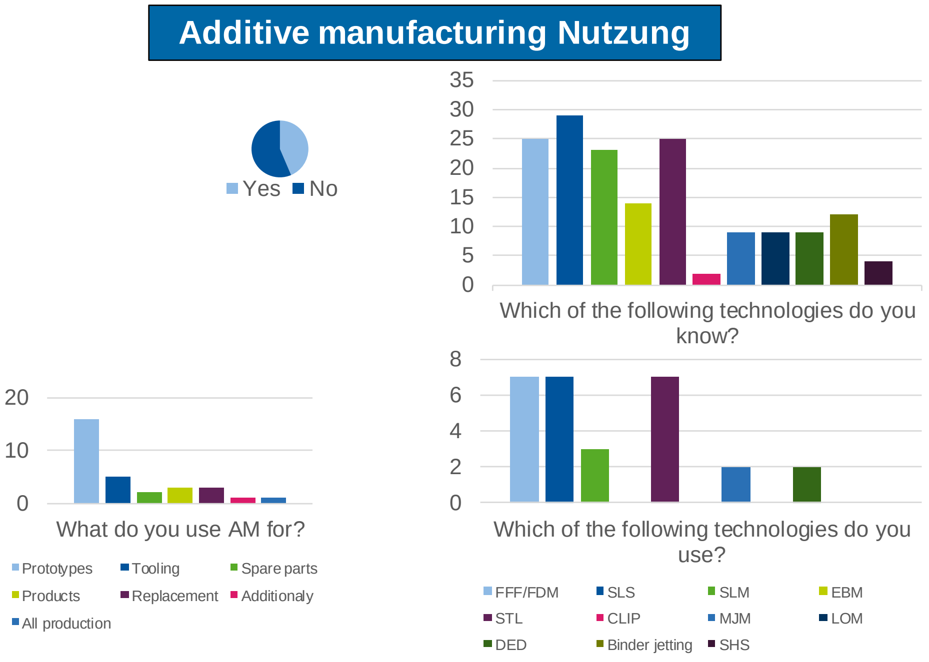


Fig. 2.1: Survey results on the use of additive manufacturing

Somewhat fewer than ½ of the respondents already use additive manufacturing. The additive manufacturing processes are primarily used for production of prototypes. Establishment of direct manufacturing of end products is thus not widespread yet. Companies that do not use additive manufacturing processes yet are concerned with uncertainties with regard to the assessment of the costs and potential of the production technology, which is not widely used yet.

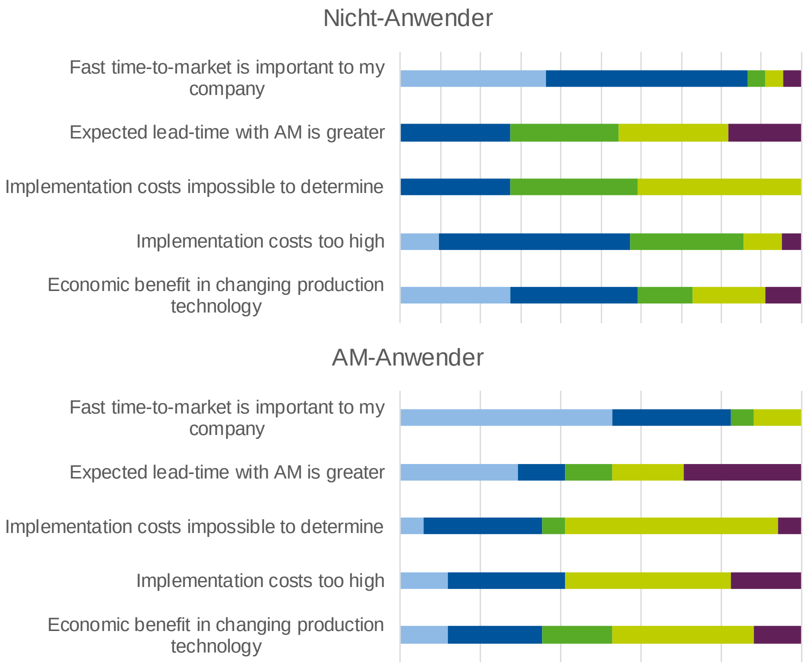


Fig. 2.2: Survey results on the economic aspects of AM

The respondents showed a general interest in application of the technology. Apart from technical advantages, the main reasons for using additive manufacturing are the reduction of throughput times and of the time-to-market. There is particularly great interest in the integration of new functions or additional components into current designs. Implementation costs are a barrier for many. Even those companies that already have experience with additive manufacturing technology see little economic benefit from the change in production technology. The survey results confirm the theory that companies are not fully aware of the advantages of additive manufacturing and lack a holistic view of costs.

In addition to the need for creating a clear cost structure and uncovering economic advantages, further requirements were identified with the project partners in **expert interviews**. On the one hand, the costs of an additively manufactured component must be determined with regard to the entire life cycle in order to be able to assess the economic advantage of additive manufacturing. Furthermore, cost comparison of several technological alternatives must be possible in order to assess the economic efficiency of the systems. In particular, it must be taken into account that additive manufacturing unlocks new potentials that cannot be realised with conventional processes. Thus e.g. higher geometric freedom of design allows a plurality of product components to be combined into one single component, saving assembly costs. A suitable valuation model must be developed especially for such application cases in which there is no direct comparability of diverse technology variants.

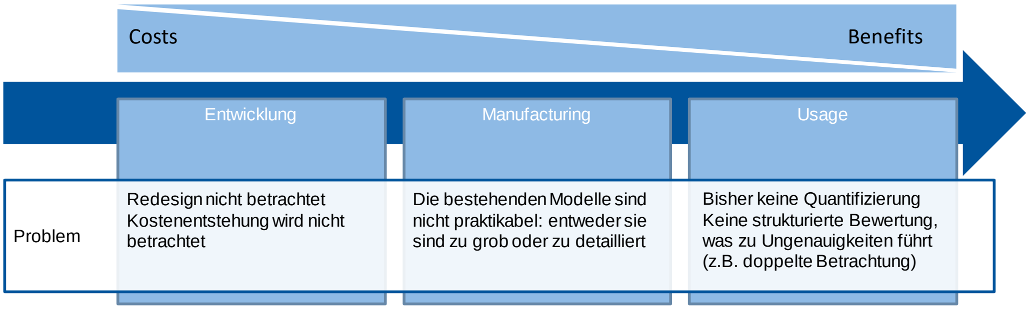
The requirements were summarised on the basis of the survey results and the expert interviews. The cost–benefit model is to be created primarily for technical staff, engineers or managers of manufacturing companies with or without prior knowledge of additive manufacturing. It should be comprehensive, consistent in itself, relevant, and dependable. It is to be used primarily in the product development phase and serve as a valid basis for decision-making. Another important requirement for the cost model is to keep the analysis effort as low as possible and to make it user-friendly.

2.2 Overview of existing models

For implementation of the requirements, various approaches to model development were compared with the help of a comprehensive literature search, and existing cost models for additive manufacturing from the literature were identified and analysed.

2.2.1 Basics of the life cycle cost analysis

Life cycle costing (LCC) was chosen as the method of economic analysis. LCC is a model of strategic cost management. With the help of LCC, savings potentials can be calculated along the entire product life cycle. Costs and benefits arising along the product life cycle must be taken into account. The insights: Core problems were identified.

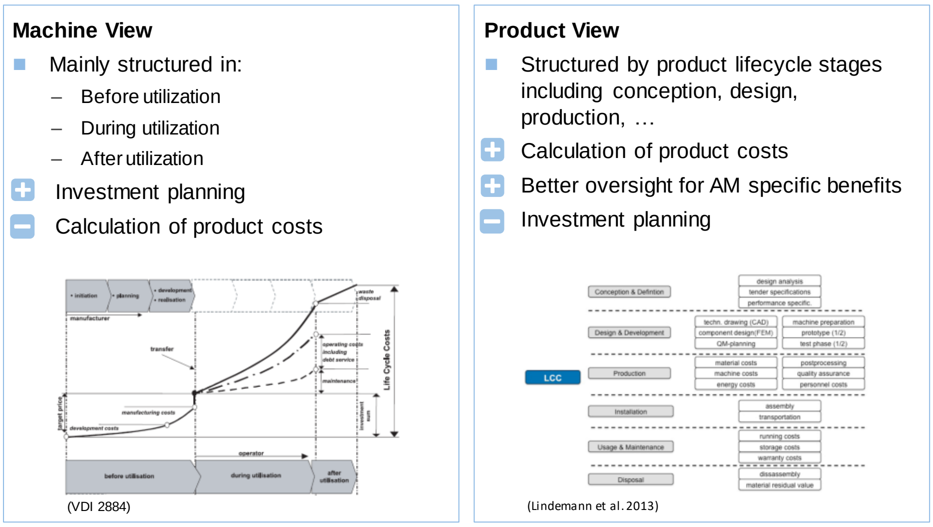


	Entwicklung	Manufacturing	Usage
Problem	Redesign nicht betrachtet Kostenentstehung wird nicht betrachtet	Die bestehenden Modelle sind nicht praktikabel: entweder sie sind zu grob oder zu detailliert	Bisher keine Quantifizierung Keine strukturierte Bewertung, was zu Ungenauigkeiten führt (z.B. doppelte Betrachtung)

Fig. 2.3: Identification of core problems by means of LCC

DIN 60300-3-3 offers an application guideline for the analysis of life cycle costs, which was used here as a basis for the development of the cost model (Deutsches Institut für Normung 2014). Six main phases of the product life cycle are defined: *Concept & definition*, *design & development*, *production*, *installation*, *operation & maintenance* and *disposal*.

A cost analysis can as a matter of principle be carried out from the product perspective or from the machine perspective. In a first step, therefore, the two perspectives were compared in relation to the problem at hand.



Machine View

- ■ Mainly structured in:
  - Before utilization
  - During utilization
  - After utilization
- ⊞ Investment planning
- ⊟ Calculation of product costs

(VDI 2884)

Product View

- ■ Structured by product lifecycle stages including conception, design, production, …
- ⊞ Calculation of product costs
- ⊞ Better oversight for AM specific benefits
- ⊟ Investment planning

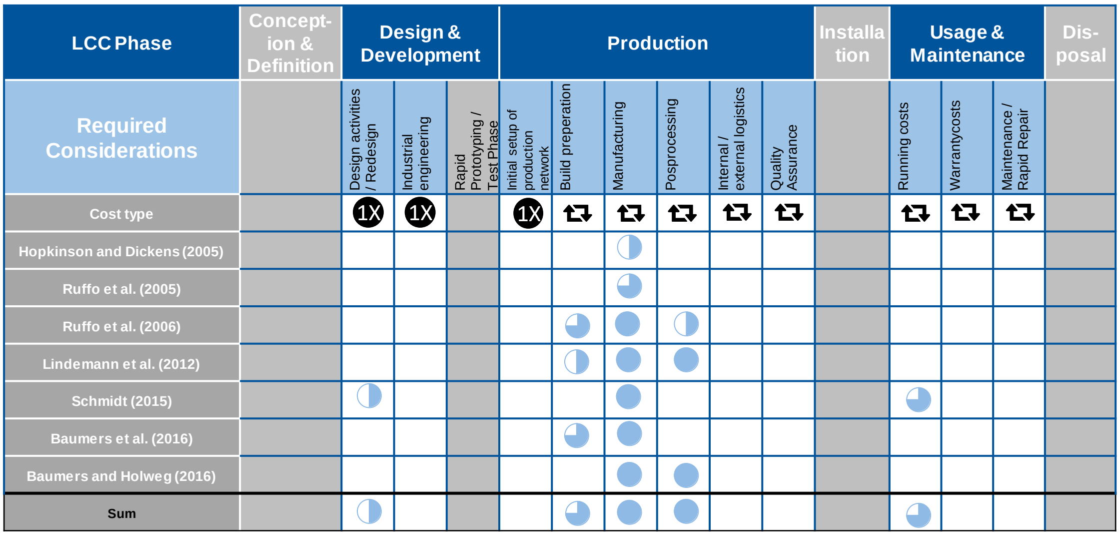
(Lindemann et al. 2013)

Fig. 2.4: LCC – Product perspective vs. machine perspective (Verein Deutscher Ingenieure 2005; Lindemann et al. 2013)

Over the further course, in the context of this project the product-related view was taken as the starting point for life cycle cost considerations. This is the only way to demonstrate in particular advantages in the use of the product. The phases to be considered as a matter of principle include conception and definition of the component, design and development, the actual production as well as installation, use and maintenance, and finally recycling. This provides the framework for further considerations and can serve in particular to classify benefits.

2.2.2 Existing cost models for additive manufacturing

The following provides an overview of existing cost considerations for additive manufacturing. These models were classified into the various product life cycle phases in accordance with DIN 60300-3-3. The pie charts indicate the qualitative levels of detail of the studies. Thus, research gaps for the full cost consideration of additive manufacturing technology could be uncovered.



LCC Phase	Concept-ion & Definition	Design & Development			Production						Installa tion	Usage & Maintenance			Dis-posal
Required Considerations		Design activities / Redesign	Industrial engineering	Rapid Prototyping / Test Phase	Initial setup of production network	Build preperation	Manufacturing	Posprocessing	Internal / external logistics	Quality Assurance		Running costs	Warrantycosts	Maintenance / Rapid Repair	
Cost type		1X	1X		1X	🔁	🔁	🔁	🔁	🔁		🔁	🔁	🔁	
Hopkinson and Dickens (2005)							◑								
Ruffo et al. (2005)							◕								
Ruffo et al. (2006)						◕	●	◑							
Lindemann et al. (2012)						◑	●	●							
Schmidt (2015)		◑					●					◕			
Baumers et al. (2016)						◕	●								
Baumers and Holweg (2016)							●	●							
Sum		◑				◕	●	●				◕			

Fig. 2.5: Overview of existing cost considerations

The most relevant cost models for additive manufacturing are those of Hopkinson u. Dickens (2005), Ruffo et al. (2006), Lindemann et al. (2012) and Lindemann et al. (2013). Further cost considerations, which are not explained in more detail below, are those of Ruffo et al. (2005), Schmidt (2015), Baumers et al. (2015) and M. Baumers (2016).

Previous cost models focused primarily on the production costs of individual additive manufacturing technologies. As a rule, only individual aspects of the life cycle are examined. The production in particular has already been intensively examined.

The cost model according to Hopkinson u. Dickens (2005) is one of the first economic considerations as to whether rapid prototyping technology can be used for direct production. This analysis compares the cost structure of additive manufacturing with the injection moulding process. Additive manufacturing processes include stereolithography, fused deposition modelling, and laser sintering. Based on the costs per component, broken down into machine costs, wage costs and material costs, it was analysed in different batch sizes whether additive manufacturing processes can be the more suitable approach for component production. Both tool-free production and the possibility of manufacturing complex geometries are regarded as advantages over injection moulding. Regarding the cost model according to Hopkinson and Dickens (2005), it is noted that no consideration is given to the material, and that the determination of the injection moulding costs, which serve as a comparison to the additive processes, is unclear. (vgl. Hopkinson u. Dickens 2005, S. 31–39)

The following are considered:

- Direct machine costs
- Indirect machine costs
- Machine operating costs
- Material costs
- Tooling costs
- Production details

RUFFO ET AL. (2006) evaluate and extend the cost model of HOPKINSON U. DICKENS (2005). Here, laser sintering is compared with injection moulding. In this cost analysis, some of the above criticisms have been addressed and overcome. The costs of a generative process were divided into direct and indirect costs, with direct costs consisting mainly of material costs and indirect costs including labour, machinery and overhead costs. One change is that in this model wage costs are considered as indirect costs, but post-processing is not included in the analysis. Furthermore, in contrast to the model of Hopkinson and Dickens (2005), the assumption is not that of a constant cost function but of a cost function similar to a sawtooth pattern. This sawtooth pattern results in a considerably larger share of costs, especially for small batch sizes (vgl. COSTABILE ET AL. 2017, S. 269–270).

The following aspects, among others, are also taken into account:

- Realistic machine utilisation
- Realistic material recycling rate
- Packing density

LINDEMANN ET AL. (2012) consider the entire production process of additive manufacturing instead of merely calculating machine costs. Here, four relevant processes are defined for cost estimation: Manufacturing preparation, manufacturing process, component cleaning, post-processing and improving component properties. Post-processing is therefore also regarded as a cost-relevant process, which includes quality control, surface post-processing and the removal of the auxiliary structure from the construction process. (vgl. COSTABILE ET AL. 2017, S. 272)

They employ time-driven activity-based cost calculation to model the production process.

The following aspects, among others, are also considered:

- Construction preparation costs
- Post-processing costs
- Cost impact of time

LINDEMANN ET AL. (2013) go beyond this and define the need for a life cycle cost model that considers the entire life cycle from conception and definition up to disposal. In the long term, additive manufacturing is regarded as a genuine production alternative to conventional manufacturing, which is why the costs are determined on the basis of a life cycle cost analysis. In this approach, the cost causation is seen on both the production and the consumer side. The production costs are calculated according to the cost models of Hopkinson u. Dickens (2005) and Ruffo et al. (2006) already explained. In Fig. 2.6 the relevant phases for this life cycle model are shown:

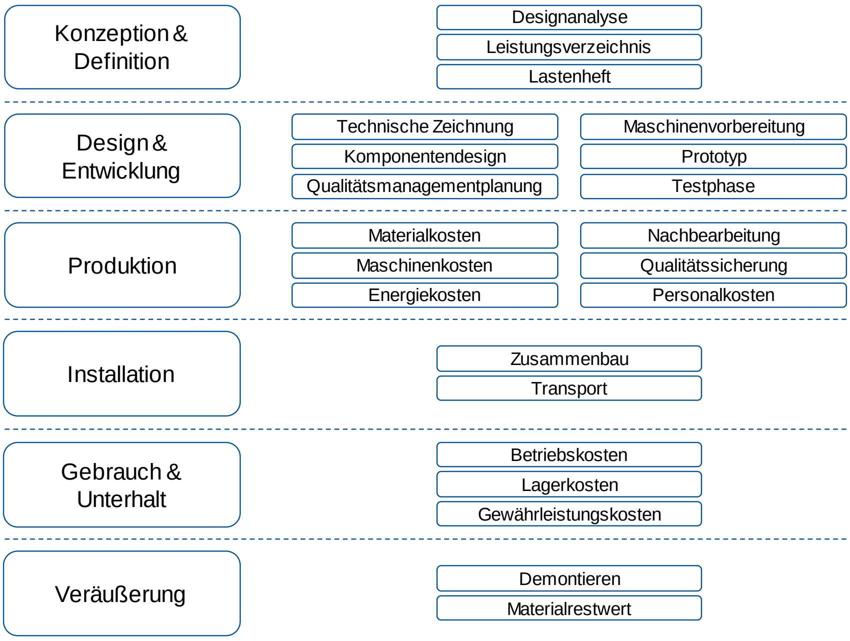


Fig. 2.6: Relevant phases of the life cycle model

The main cost drivers are the design phase, use and maintenance, as well as production. Thus, these are also the phases in which cost optimisation has the greatest impact on overall cost efficiency.

In Fig. 2.7, the cost models of Ruffo et al. (2006) and Hopkinson u. Dickens (2001) depending on the production volume for a sample part are compared. As a comparator, the curve for the production by injection moulding is given.

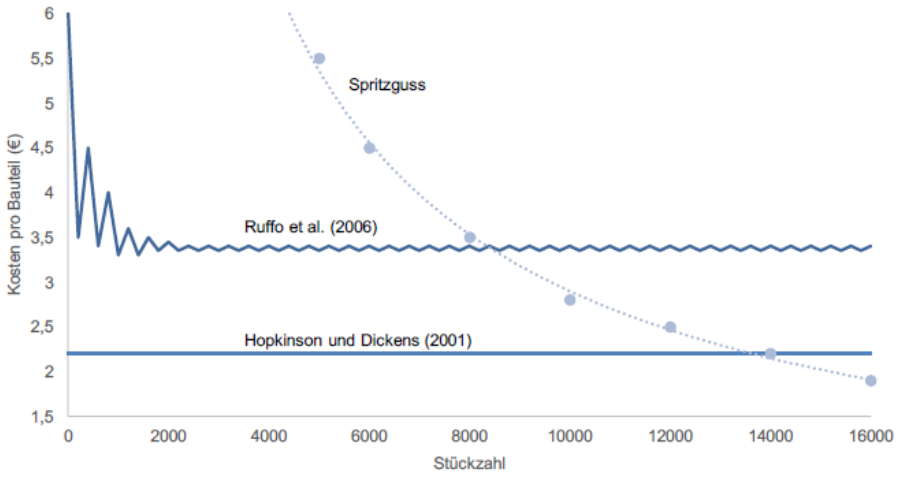


Fig. 2.7: Comparison of the cost models of Ruffo et al. as well as Hopkinson and Dickens (i. A. a.RUFFO ET AL. 2006, S. 1424)

The cost model of HOPKINSON U. DICKENS (2001) assumes a constant cost function across the production volume. This assumption is justified by the fact that the indirect costs are evenly distributed over all components. In contrast to this, in the injection moulding process, for example, the initially high tool costs are amortised by the fact that large numbers of components are produced. (HOPKINSON U. DICKENS 2001, S. 198). RUFFO ET AL. (2006) argue, however, that a constant cost function cannot be assumed for low production volumes, since high investment costs have to be amortised in additive manufacturing as well, which mainly consist of the acquisition costs of the machine. Furthermore, in this cost model, the costs incurred for high production volumes are virtually constant and higher than for HOPKINSON U. DICKENS (2005). These higher costs are achieved by taking into account a realistic machine utilisation rate of 60% and a material recycling rate of only 50%. The most significant difference of this cost model is the “sawtooth pattern” of the cost function, which is caused by inefficient utilisation of the installation space for certain lot sizes (RUFFO ET AL. 2006, S. 1420–1422). In a further study, RUFFO ET AL. investigate the cost effect of a “parallel production” in which various components are produced simultaneously in one machine. Within this study, a cost model was developed for calculating the cost reduction with effective installation space filling (see RUFFO and HAGUE 2007, p. 1590).

In contrast to the above cost models of HOPKINSON and DICKENS as well as RUFFO ET AL., which consider only the quantification of the manufacturing costs, LINDEMANN ET AL. want to develop a complete model with which an estimation of the life cycle costs of a product is possible. For this purpose, first a model for the production process was developed using Time-Driven Activity-Based Costing (TDABC), which allows the costs of the production processes to be allocated to the components according to the cause.

Furthermore, in addition to the manufacturing costs, the pre- and post-processes of production can also be used, and analysis of the effect of various influencing factors such as construction rate, material costs or investment costs on the allocation of process cost rates is made possible. (see LINDEMANN et al. 2012, p. 188)

The cost model by LINDEMANN ET AL. explained above is, however, only an alternative model for computation of the production costs of a generative manufacturing, in which at first no inclusion of further life cycle phases is possible. There are already numerous approaches to calculating the manufacturing costs of generative manufacturing, but comprehensive cost considerations are currently still incomplete. For a more detailed analysis of the cost-effectiveness of generative manufacturing, cost models must be developed that permit assessment of the monetary influence of the manufacturing process on the product life cycle or the entire supply chain, respectively.

Overall, it can be seen that the perspective has expanded over time. LINDEMANN ET AL. (2013) have developed the most comprehensive cost model to date in terms of life cycle cost considerations. The following figure gives a qualitative overview of the development of the cost models:

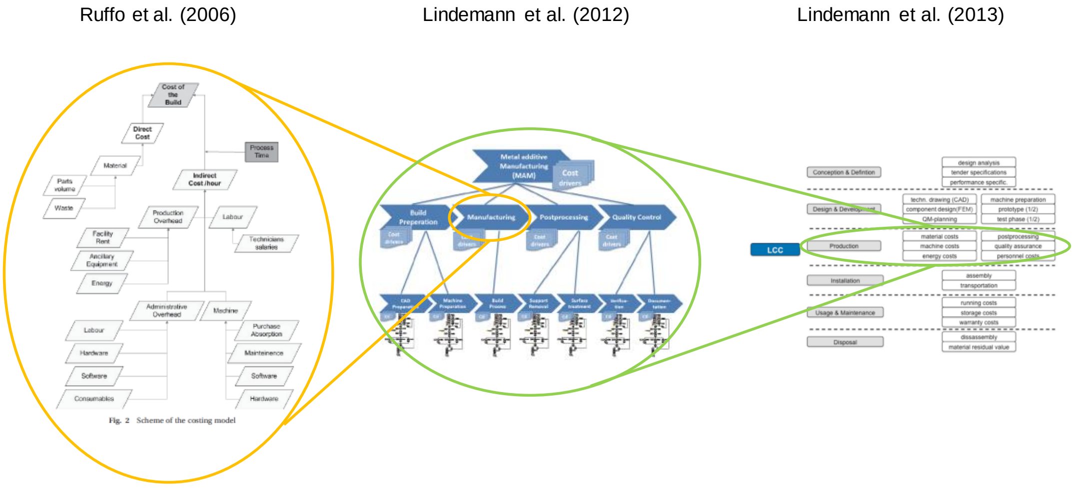
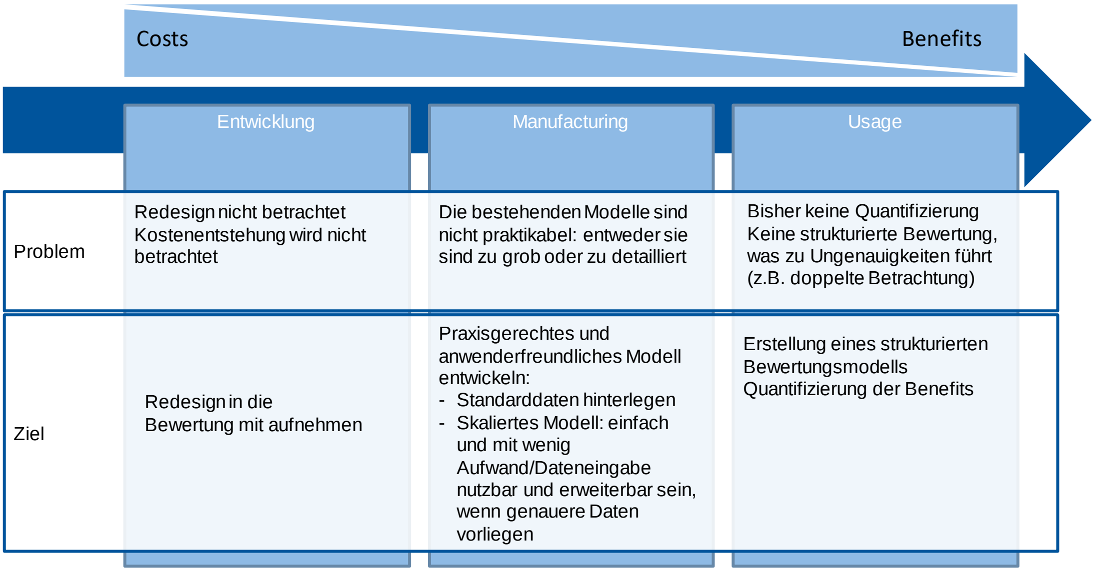


Fig. 2.8: Overview of the relevant AM cost models (RUFFO ET AL. 2006; LINDEMANN ET AL. 2012; 2013)

The objectives were identified by comparing the identified problems against the requirements identified for the valuation model.



	Entwicklung	Manufacturing	Usage
Problem	Redesign nicht betrachtet Kostenentstehung wird nicht betrachtet	Die bestehenden Modelle sind nicht praktikabel: entweder sie sind zu grob oder zu detailliert	Bisher keine Quantifizierung Keine strukturierte Bewertung, was zu Ungenauigkeiten führt (z.B. doppelte Betrachtung)
Ziel	Redesign in die Bewertung mit aufnehmen	Praxisgerechtes und anwenderfreundliches Modell entwickeln: - Standarddaten hinterlegen - Skaliertes Modell: einfach und mit wenig Aufwand/Dateneingabe nutzbar und erweiterbar sein, wenn genauere Daten vorliegen	Erstellung eines strukturierten Bewertungsmodells Quantifizierung der Benefits

Fig. 2.9: Target identification through juxtaposition of problems and requirements

The need for a valuation model that goes beyond a mere cost analysis was highlighted. Potentials of additive manufacturing should be quantified in the form of a benefit model. First, the advantages of additive manufacturing were collected with the help of a literature search.

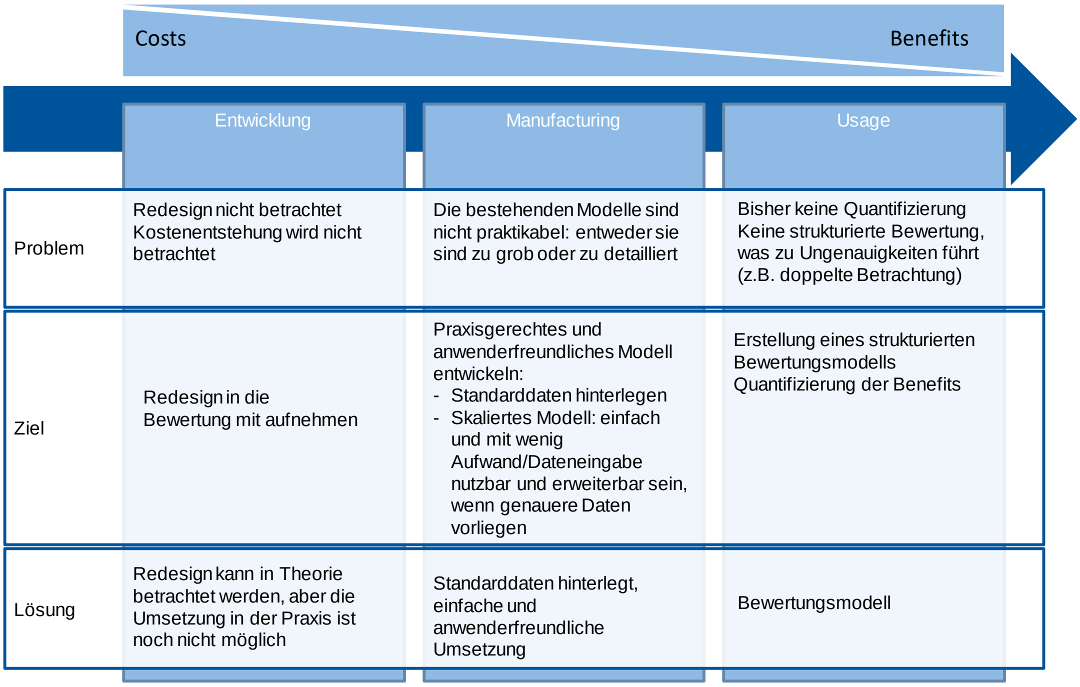
3 Development of the assessment system for additive manufacturing

Based on the identified requirements, a workable assessment system for additive manufacturing was developed, which consists of a cost and a benefit model.

3.1 A workable cost model for additive manufacturing

For the **cost model**, relevant parameters and their interconnections were identified in a comprehensive literature search. The calculations and correlations were carried out and determined from a product perspective in order to enable product pricing on the one hand and product-specific cost advantages on the other to be considered during the product life cycle.

Based on DIN 60300-3-3, the identified costs were broken down into the product life cycle phases of *concept & definition*, *design & development*, *production*, *installation*, *operation & maintenance*, and *disposal*. By aggregating different approaches from the literature, these cost categories were detailed as far as possible. Thus, a first basic structure for the programming of the cost model was created. In the present case, costs incurred in the *production* and *operation & maintenance* phases were considered in particular.



	Entwicklung	Manufacturing	Usage
Problem	Redesign nicht betrachtet Kostenentstehung wird nicht betrachtet	Die bestehenden Modelle sind nicht praktikabel: entweder sie sind zu grob oder zu detailliert	Bisher keine Quantifizierung Keine strukturierte Bewertung, was zu Ungenauigkeiten führt (z.B. doppelte Betrachtung)
Ziel	Redesign in die Bewertung mit aufnehmen	Praxisgerechtes und anwenderfreundliches Modell entwickeln: - Standarddaten hinterlegen - Skaliertes Modell: einfach und mit wenig Aufwand/Dateneingabe nutzbar und erweiterbar sein, wenn genauere Daten vorliegen	Erstellung eines strukturierten Bewertungsmodells Quantifizierung der Benefits
Lösung	Redesign kann in Theorie betrachtet werden, aber die Umsetzung in der Praxis ist noch nicht möglich	Standarddaten hinterlegt, einfache und anwenderfreundliche Umsetzung	Bewertungsmodell

Fig. 3.1: Solution to overcome the identified problems

3.1.1 Explanation of the calculation basis of the cost model

Fig. 3.2 shows the data structure developed, on which the cost model is based. Operating data such as wage costs for technicians and engineers, working hours, energy costs and the machine utilisation rate are included into the machine data for additive manufacturing. In addition, there are data concerning technology, investment costs and indirect material costs, among other things. These aggregated machine data from additive manufacturing are combined with part data and values regarding the raw material. Parts data includes, among other things, the part volume and the part ID. The raw material data include the material ID, costs per kilogram, and the powder recycling rate, among other things. Job combines parts, material and machine data and supplements them with further data such as lot size or layer thickness. Manufacturing Process (SLM) records the job data and adds process data to them. Process data here are, for example, the machine preparation time, the construction time broken down into individual factors, and the machine post-processing time. Data for post-processing, which are divided into obligatory and optional processes, are also supplemented. Finally, benefits are listed. These include improved product utilisation costs, production costs and strategic costs, as well as shortening of the lead time.

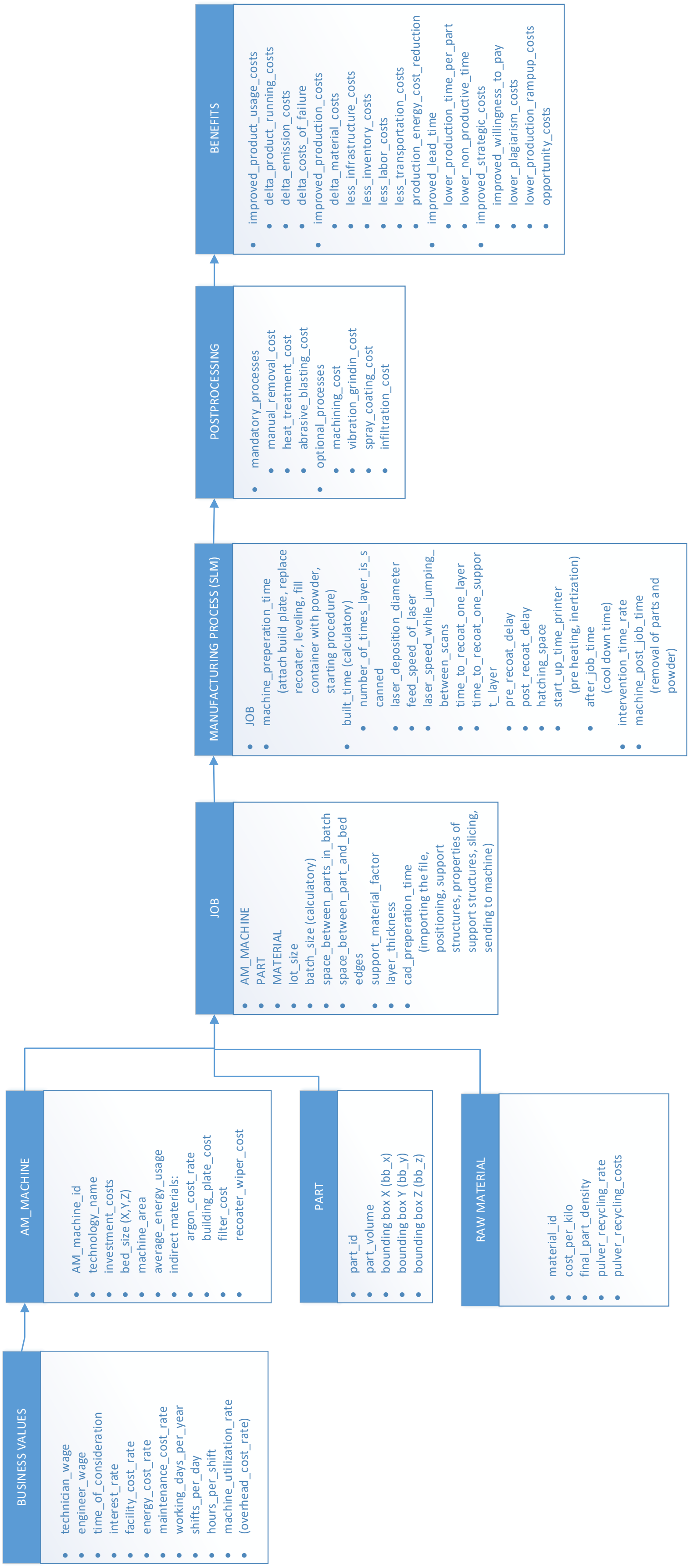


Fig. 3.2: Data structure

This data structure provided the basis for the cost model. For integration of specific cost functions into the model, four relevant approaches were used as central calculation bases:

- Cost structure for SLM (Selective Laser Melting) production according to Schmidt (vgl. Schmidt 2015, 145 ff.)
- Direct material costs according to Gibson et al. (vgl. Gibson et al. 2010, S. 388)
- Construction time estimation according to Gibson et al. (vgl. Gibson et al. 2010, 389 ff.)
- Hourly machine rate according to VDI 3258 Sheet 1 (Verein Deutscher Ingenieure 1962)

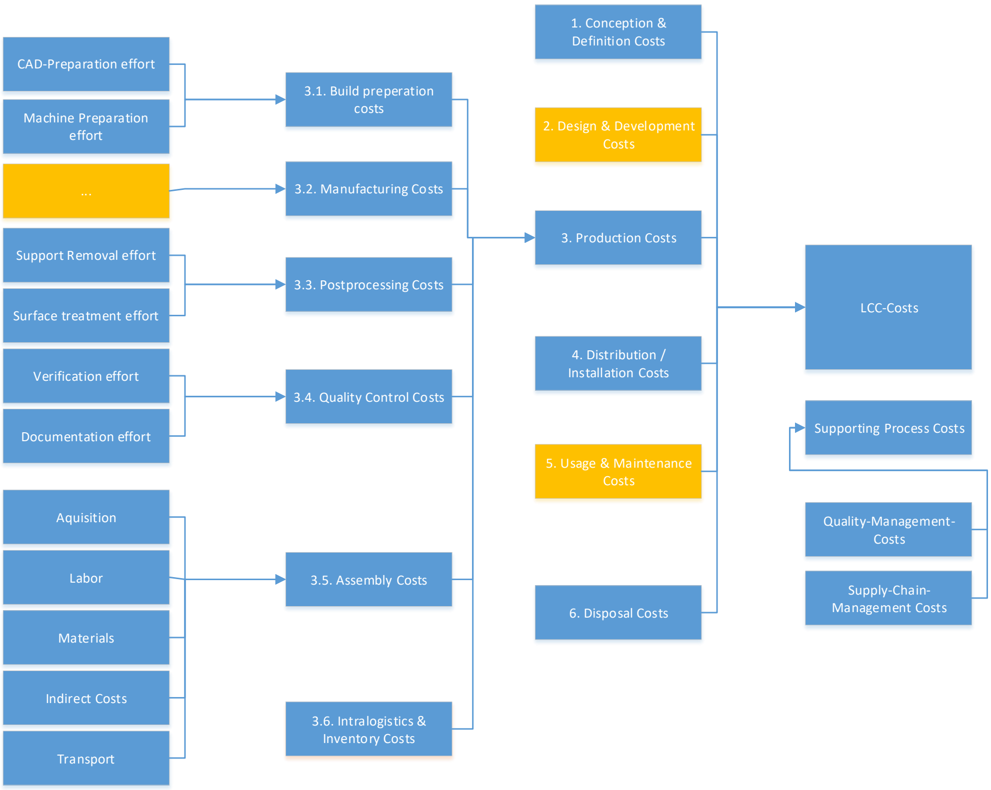


Fig. 3.3: Main overview of the cost model

For the calculation, the LCCs were first considered. The costs were broken down and presented according to the identified main phases of the product life cycle. The initial focus is on production costs, which comprise preparation costs, manufacturing costs, quality control costs and assembly costs as well as intralogistics and storage costs, and can be broken down further.

The starting point was the calculation of costs for Design & Development, see Fig. 3.4.

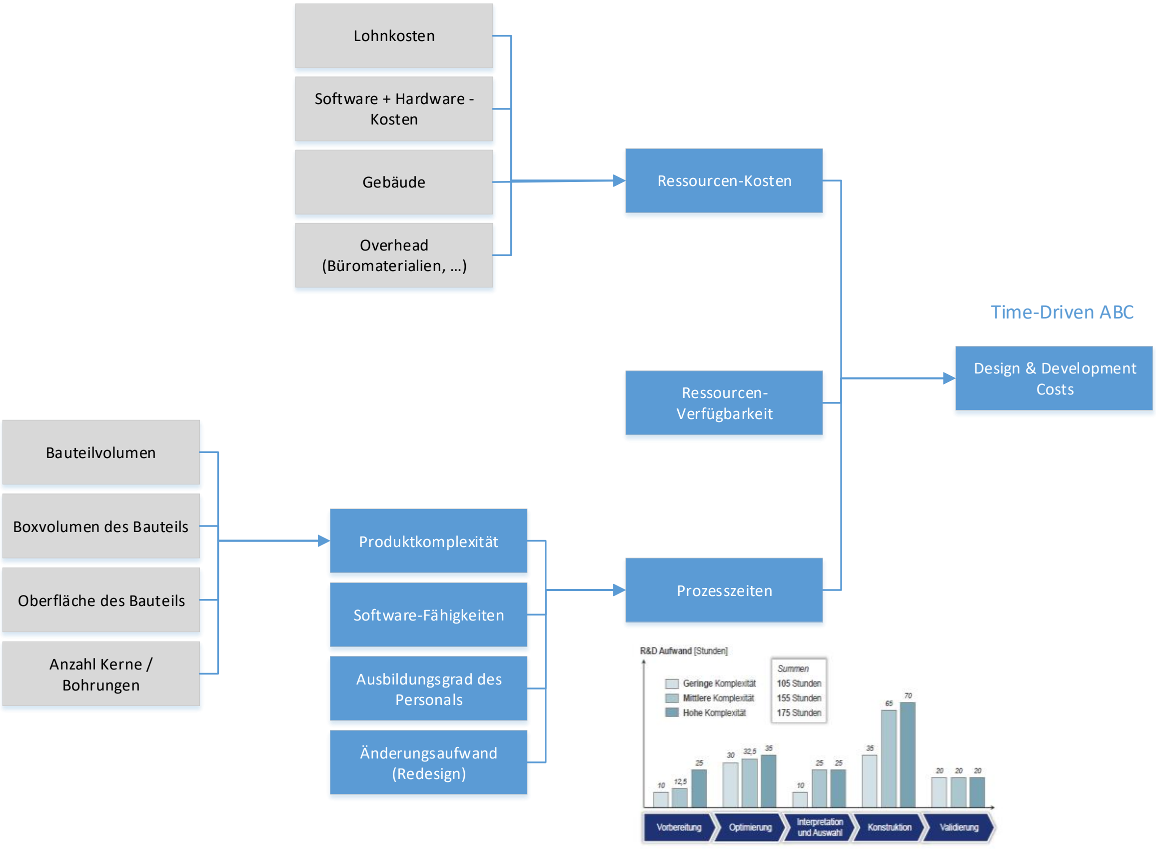


Abbildung 4.33: Durchschnittliche Entwicklungszeiten [eigene Darstellung]

Fig. 3.4: Design & Development

The costs are determined by three components: Costs of resources costs, availability of resources, and process times. The manufacturing costs are the focus of the calculations, see Fig. 3.5.

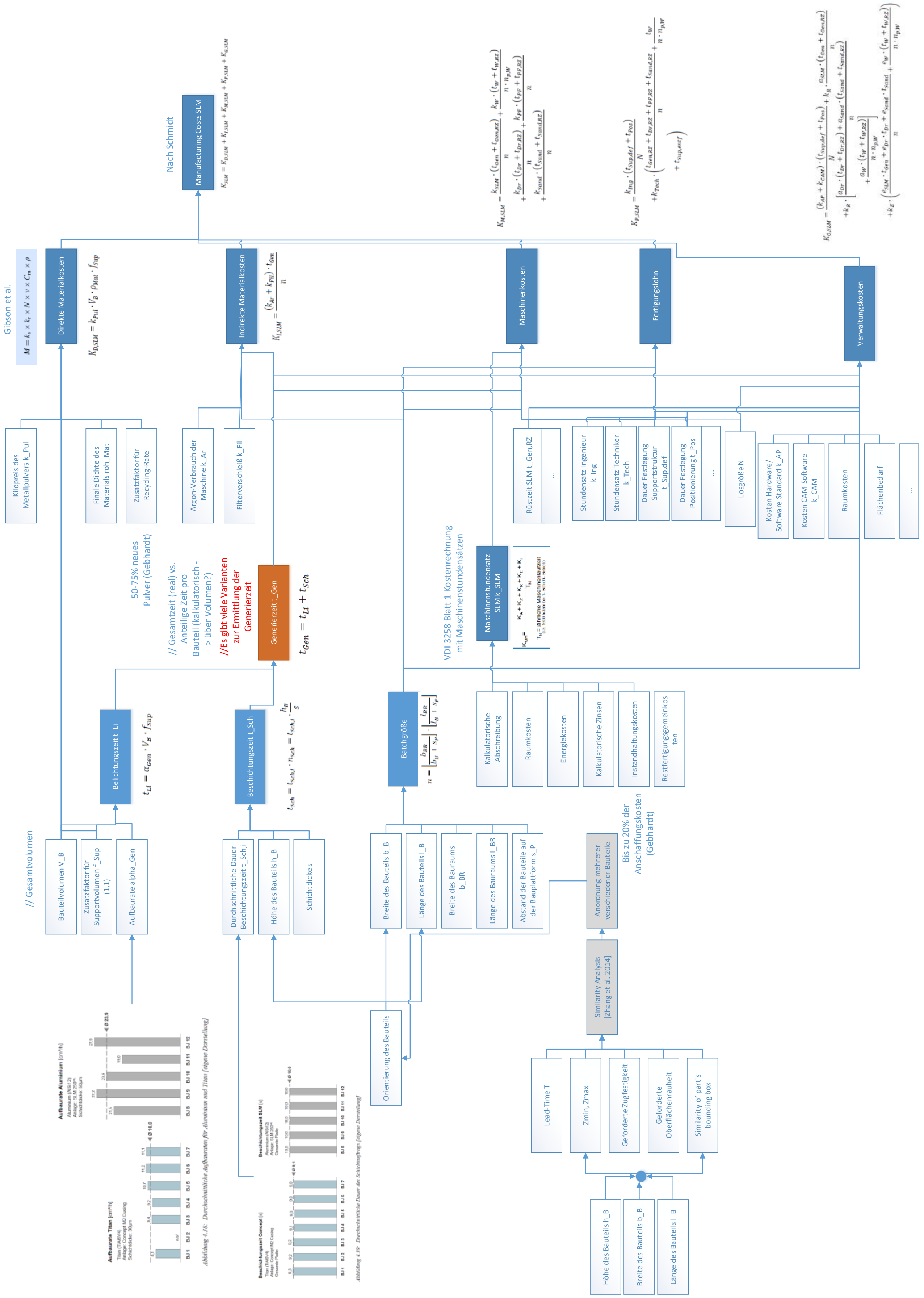


Fig. 3.5: SLM manufacturing

For the production costs of the SLM method, which was used as a reference method in the context of the project, the cost functions were determined and correlated, see Fig. 3.5. The calculation is based on the approach of SCHMIDT (SCHMIDT 2015, S. 145 ff.).

Subsequently, the costs for use and maintenance were calculated. According to VDI 2884, these consist of factors such as auxiliary and operating materials, maintenance costs / spare parts costs, and performance and quality data (VEREIN DEUTSCHER INGENIEURE 2005).

Finally, disposal costs are also included, which are determined according to VDI 2884 by the decommissioning and recovery of the material (VEREIN DEUTSCHER INGENIEURE 2005).

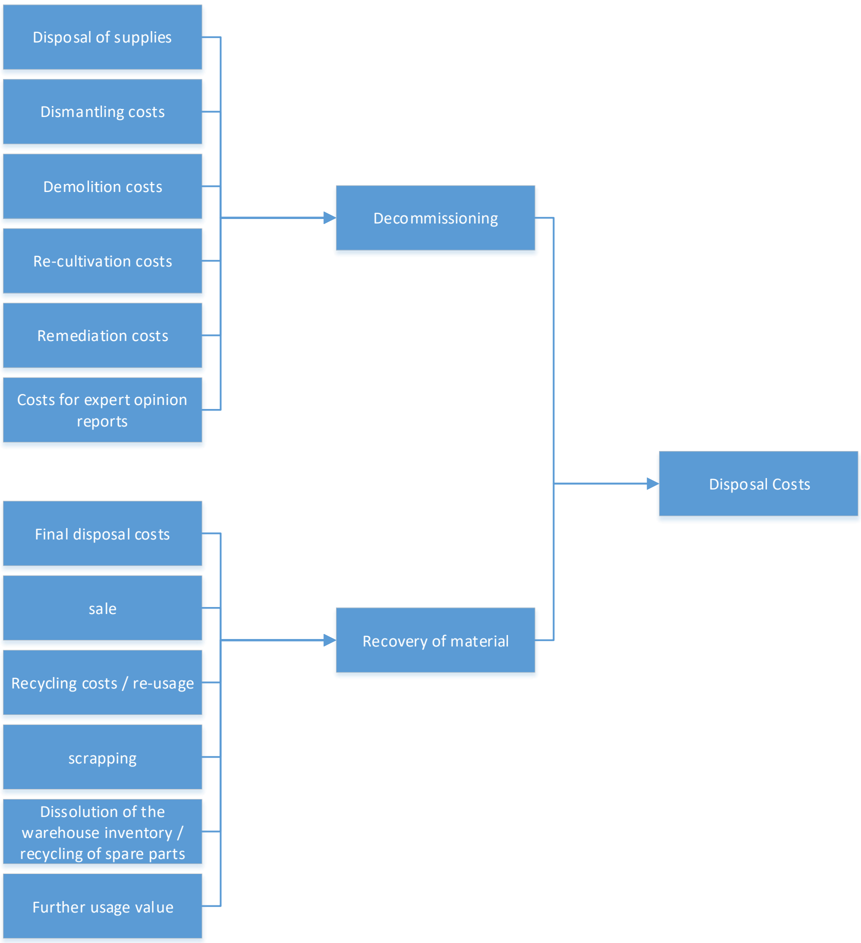
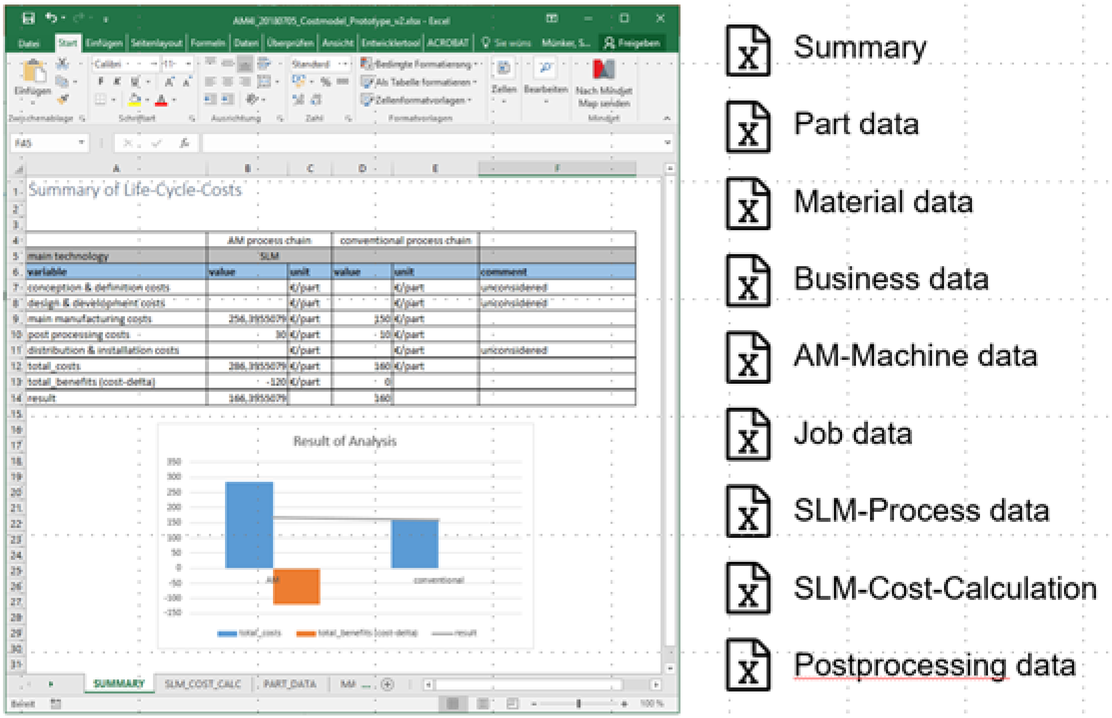


Fig. 3.6: Disposal costs

3.1.2 Aggregation of the calculation bases into a cost model

By aggregating the various calculation methods and the available data, the cost model was created with MS Excel. This served as a cost model prototype. The file comprises nine sheets. Eight of the sheets realise the separate calculation or input possibility of the individual costs. A further sheet is used to summarise the costs, as shown in the following figure. Here the life cycle costs of additive manufacturing can be compared with conventional technologies.


Summary of Life-Cycle-Costs

	AM process chain		conventional process chain		
main technology	SLM				
variable	value	unit	value	unit	comment
conception & definition costs		€/part		€/part	unconsidered
design & development costs		€/part		€/part	unconsidered
main manufacturing costs	256,3955079	€/part	150	€/part	
post processing costs	30	€/part	10	€/part	
distribution & installation costs		€/part		€/part	unconsidered
total_costs	286,3955079	€/part	160	€/part	
total_benefits (cost-delta)	-120	€/part	0		
result	166,3955079		160		

Fig. 3.7: Cost model in Excel

Requirements for the model included minimum analysis effort and user-friendly handling. The user should be able to project his/her specific problem case into the cost model. For the first and easy use of the model, different realistic values should be stored in the model as a data base. For this purpose, best-practice values and values from the literature were used and provided in the cost model prototype.

3.2 A workable benefit model for additive manufacturing

The **benefit model** is intended to uncover potentials and to reveal these and their interdependencies. In order to structure the advantages and potentials identified by means of a literature search, these were first differentiated into unique features and resulting added values. For this purpose, the unique features of additive manufacturing were identified, which give rise to all known added values. This structuring provides the basis for quantifying these added values so that they can be reflected in the overall assessment.

The vertical differentiation was based on means–end chains, so a division into five categories was made:

- Unique property
- Methods / applications of unique properties
- Purposes of methods / applications
- Generic purposes
- Quantified value added / advantage

The results were initially documented with MS Visio, see Fig. 3.8.

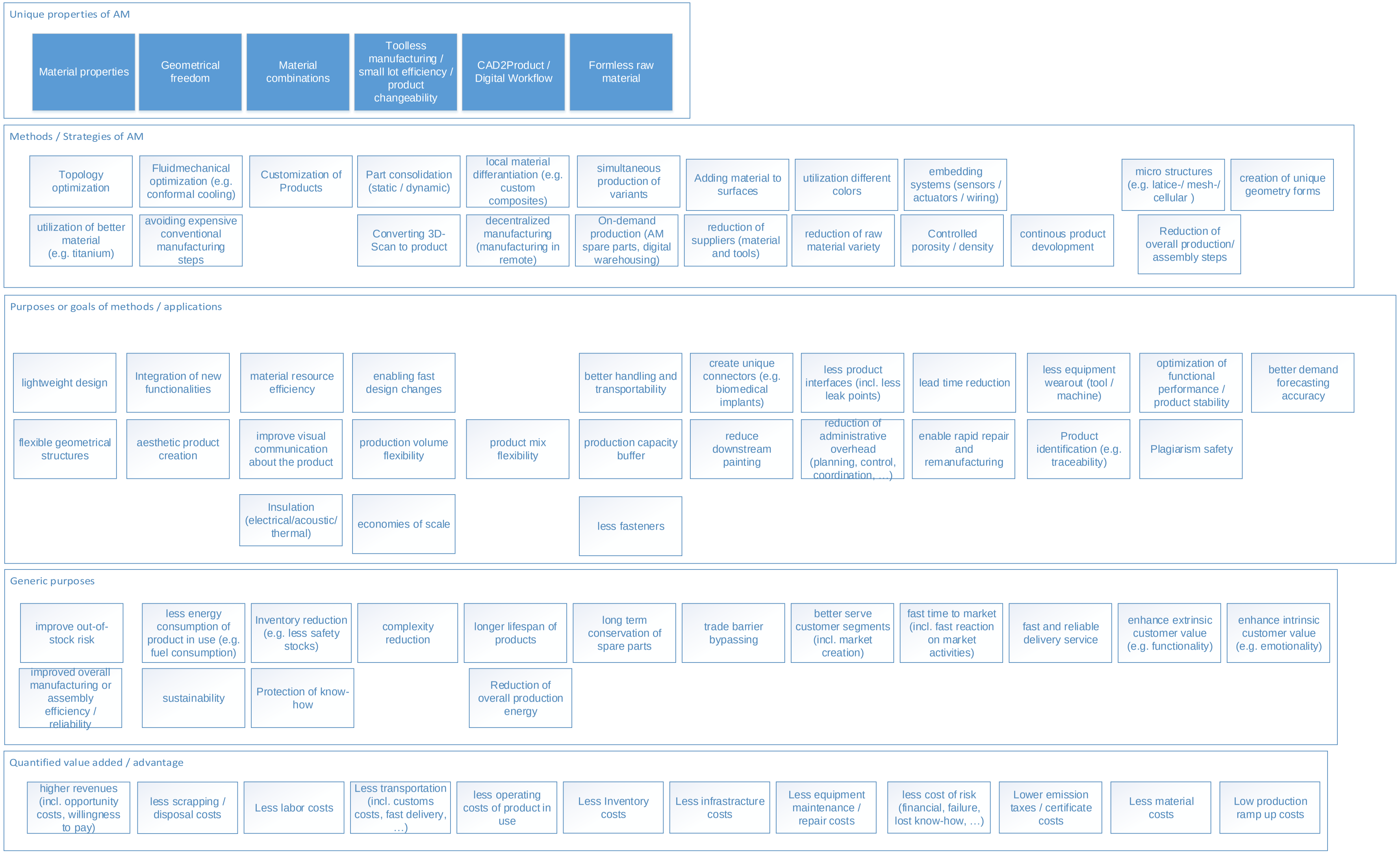
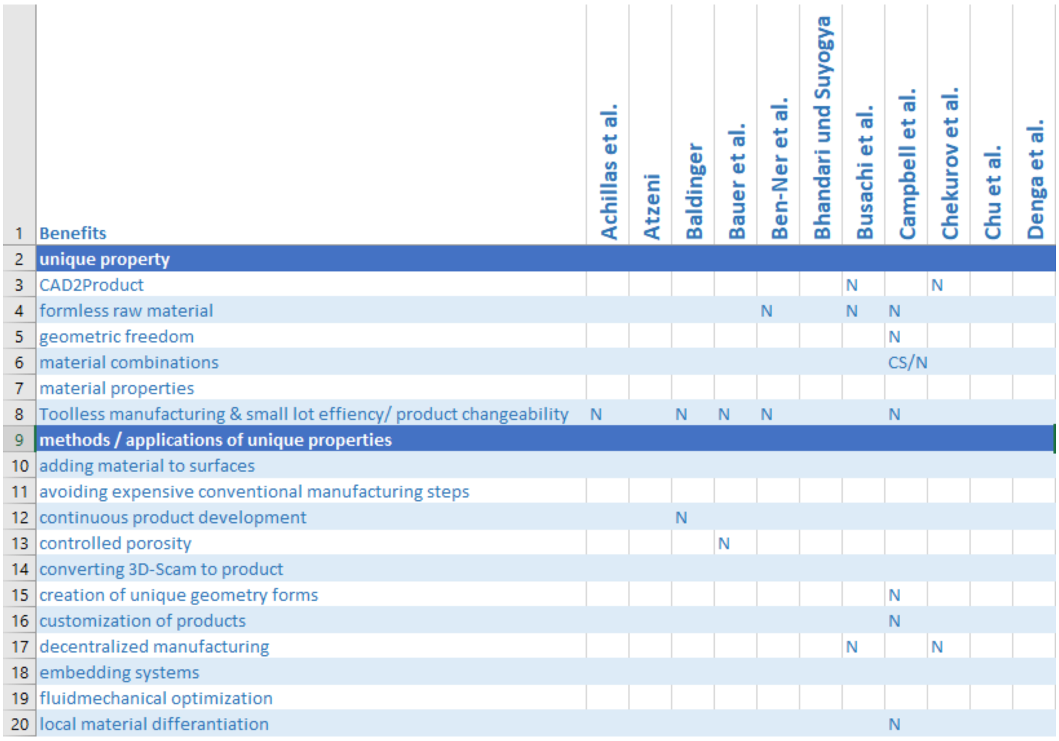


Fig. 3.8: Results of the benefit model

In addition, a literature matrix was created in which the individual benefits and their dependencies are recorded. Both the potentials themselves and the dependencies between them were classified according to the extent to which they were mentioned in the literature. Differentiation yields the classes Mentioned Potential, Case Study, Empirical Study, Simulation and Author's Hypothesis. All the benefits identified are listed in the rows of the literature matrix. The columns list the individual references. Fig. 3.9 shows a section of the matrix.



1	Benefits	Achillas et al.	Atzeni	Baldinger	Bauer et al.	Ben-Ner et al.	Bhandari und Suyogya	Busachi et al.	Campbell et al.	Chekurov et al.	Chu et al.	Denga et al.
2	**unique property**											
3	CAD2Product							N		N		
4	formless raw material					N		N	N			
5	geometric freedom								N			
6	material combinations								CS/N			
7	material properties											
8	Toolless manufacturing & small lot effiency/ product changeability	N		N	N	N			N			
9	**methods / applications of unique properties**											
10	adding material to surfaces											
11	avoiding expensive conventional manufacturing steps											
12	continuous product development			N								
13	controlled porosity				N							
14	converting 3D-Scam to product											
15	creation of unique geometry forms								N			
16	customization of products								N			
17	decentralized manufacturing							N		N		
18	embedding systems											
19	fluidmechanical optimization											
20	local material differantiation								N			

Fig. 3.9: Section of the literature matrix regarding the benefits

On the basis of the data obtained, the benefit model was supplemented by the vertical and horizontal interdependencies of the individual benefits and implemented in a Cytoscape project. The result is a graph model that maps the benefits vertically grouped into five categories in the form of nodes, and the dependencies in the form of links between them, both within a category and across categories.

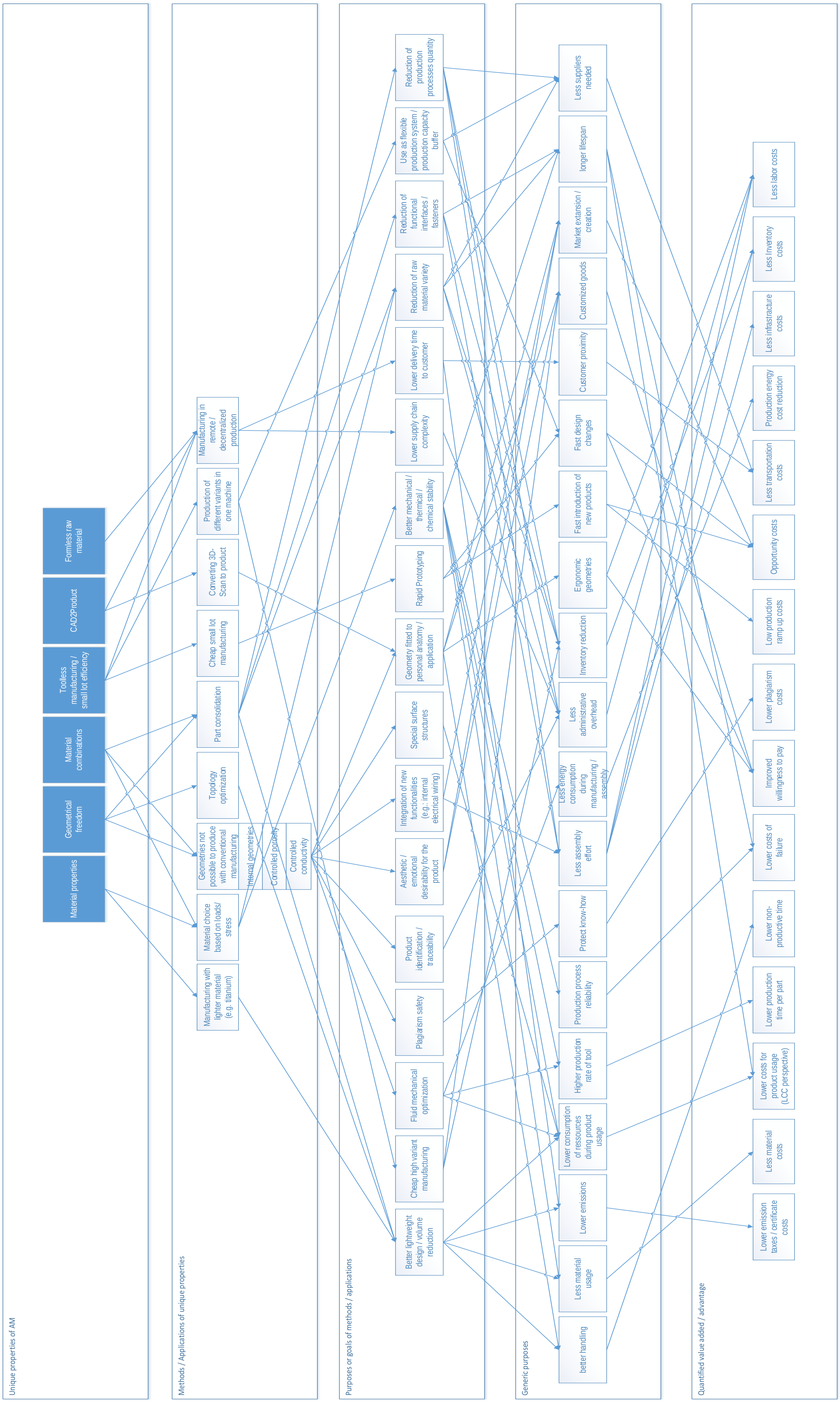


Fig. 3.10: Graph model

The graph model is designed to be interactive. Each node is followed by a definition of the benefit, including the corresponding source. Each link is based on literature references. A click on a node or a connection, respectively, displays the corresponding information. From this overview, the user can take a closer look at the relationships of individual benefits by displaying only the neighbours of a node. Thanks to this structuring, all potentials are uncovered by the user himself/herself. This not only simplifies a subsequent benefit analysis, but also provides inspiration for numerous product and process improvements. This enables companies to understand existing success stories and derive measures for their own production.

3.2.1 Essential advantages of additive manufacturing

The components of the benefit model are the essential advantages of additive manufacturing, broken down into the unique features of additive manufacturing, the methods, the purposes, the goals and the values.

3.2.1.1 Unique features of additive manufacturing

The unique features of additive manufacturing are the material properties, the geometric freedom, the possible material combinations, the tool-free manufacturing, the CAD-to-product process, and the formless raw material. The individual unique selling points are described in Table 1.

Table 1: Unique features of additive manufacturing

Material properties:	The main difference of AM to conventional materials regarding the material properties is, that AM technologies define the object's geometry and its material properties at the same time (THOMPSON ET AL. 2016, S. 738). Therefore, AM technology is capable of utilize a high variety of materials with different properties. While CNC for example works good for brittle materials like steels and other metal alloys, AM is not purposed to specific materials. Another difference to conventional material properties is, that final AM parts may have voids or anisotropy dependent on part orientation, process parameters or the product design (GIBSON ET AL. 2010, S. 10).
Material combinations:	AM can be used to combine different sets of materials. For example in metal 3D-printing the technology can be used to create custom metallurgies (THOMPSON ET AL. 2016, S. 743). In technologies based on filament, laying it is possible to use different materials by feeding material via different nozzles. The local differentiation of materials with unique properties is an AM advantage, which cannot be attained with conventional technologies in one manufacturing step.

Geometrical freedom:	Through the layer-by-layer characteristics of AM it is possible to produce highly complex geometries (BAUMERS ET AL. 2012, S. 933). So product design can be nearly free from any geometrical restrictions (BAUER ET AL. 2016, S. 17). Compared to conventional manufacturing technologies the product designer has a high degree of freedom. He can easily create geometric forms like undercuts or internal features without a lot of effort for process planning (GIBSON ET AL. 2010, S. 11).
Toolless manufacturing & small lot efficiency	Traditional manufacturing technologies like casting, joining or machining are making use of forms, tools or fixtures. Using these manufacturing aids, it is recommended to produce in higher lot sizes for cost efficiency. Because AM doesn't need any tools for building a product the production of small lot sizes is getting more feasible (REEVES ET AL. 2011).
CAD2Product	For most conventional technologies the CAD product model has to be manipulated manually to prepare the production process (e.g. by using CAM-Software). For AM the product model can be used directly to manufacture the part. (BREUNINGER ET AL. 2013, S. 2)
Formless raw material	Raw material of AM is available in form of pulver, liquid or filament. The aggregation state of the raw material is in either way formless.

3.2.1.2 Methods of additive manufacturing

The methods of additive manufacturing are described in Table 2.

Table 2: Methods of the Benefit Model

Methods	
Local material differentiation	Local differentiation of mechanical, thermal or chemical properties can be achieved through the combination of different materials or the setting of specific local properties with one material. The differentiation is possible on macro and micro scales. An example for micro scale material differentiation is the creation of custom alloys with powder-bed fusion technologies (THOMPSON ET AL. 2016, S. 743)
Utilization of different colors	The creation of local color differentiation can be achieved by adding color to the raw material, by using different color feedstock or by inducing different colors in a single feedstock via in-process activation of pigments (KERMER ET AL. 1998; POPAT U. EDWARDS 2000).
Adding material to surfaces	Some AM technologies (e.g. direct energy deposition or material extrusion technologies) are suitable to add material on 3D surfaces. This can be used for example to repair damaged, worn-out or corroded parts (DUTTA U. FROES 2015, S. 456).

Utilization of better material	In case a weak material has been used before, AM can facilitate the utilization of a strong material like titanium. The usage of titanium with AM is more cost efficient than with conventional technologies, because only the needed amount of material gets consumed and difficult machining processes are avoided (Bauer et al. 2016, S. 21).
Reduction of material variety	Producing with AM the same material can be used to produce different parts of one assembly or different products in general. This can lead to an overall reduction of raw material variety in a company (Ben-Ner u. Siemsen 2017, S. 9).
Fluidmechanical optimization	Parts like pipes, valves or restrictors can be optimized for their fluidmechanical properties. For example the exchange of thermal energy, gas distribution or critical strength can be optimized by using freeform geometries (Gausemeier et al. 2014, S. 12)
Micro structures	AM also allows the designer to influence the micro- and meso-structures of a part. Typical application is the creation of lattices or mesh structures. (Thompson et al. 2016, S. 744)
Controlled porosity	Size, type, orientation and boundary conditions of periodic cells on a micro-scale influence the porosity of an AM produced part (Thompson et al. 2016, S. 744).
Creation of unique geometry forms	Artists, artisans and industrial designers often adopt AM to create unique, intriguing and appealing geometries (Thompson et al. 2016, S. 741).
Part consolidation	The consolidation of parts is understood as the redesign of an assembly with fewer, but therefore often more complex parts (Knofius et al. 2018, S. 1).
Customization of products	AM products can easily be customized to personal needs. Customization can have a functional purpose (e.g. in the medical sector) or can add personal value to single customers by creating unique products. (Doubrovski et al. 2011, S. 3)
Topology optimization	Topology optimization usually uses finite element methods to generate an optimal material distribution to reduce weight for given mechanical properties. Because AM can easily produce highly complex geometries an optimized topology can be produced without many manufacturing restrictions. (Brackett et al. 2011, S. 348)
Reduction of overall production/assembly steps	Because a variety of products or multiple parts of an assembly can be produced in a single AM machine, the number of steps in a production chain typically gets reduced (Heutger 2016, S. 4).
Simultaneous production of variants	With AM it is possible to produce a variety of products in a single 3D printer (Heutger 2016, S. 4)

Embedding systems	Through the layer-by-layer characteristic of AM technologies it is possible to integrate sensors/actors, electronic wiring or connectors during the production process (Gausemeier et al. 2014, S. 12).
Converting 3D-Scan to product	AM does not need product specific machine settings neither product specific tools. Therefore, it is possible to “directly” use 3D data for manufacturing obtained by 3D scanners. (Gebhardt 2012, S. 104)
Avoiding expensive conventional manufacturing steps	Using AM some expensive conventional manufacturing can be avoided. For example the CNC milling of titanium alloy aerospace parts is considered as slow, expensive and produces a lot of metal scrap. By producing these parts additively this disadvantages will be reduced. (Wohlers Associates Inc. 2017, S. 193)
Reduction of suppliers	The total number of suppliers decreases when producing with AM. For example it is possible to order big bags of granulate/filament from a limited number of suppliers instead of sourcing a large variety of materials and parts from different suppliers. (Feldmann u. Pumpe 2017, S. 686)
On-demand production / digital warehouse	With AM it is possible to let the production happen on demand and at the point of consumption. This is possible because products and tools do not need to be stored physically but can be stored in digital warehouses. (Mohr u. Khan 2015, S. 22)
Decentralized manufacturing	In order to reduce transportation time and increase the service level there is a tendency to decentralize production sites. Decentralized manufacturing gets facilitated by many characteristics of AM. (Heutger 2016, S. 4)
Continuous product development	Additively produced products can be developed iteratively without any further investments in tools, machines or other physical components. Therefore it is possible to cost efficiently improve products continuously. (Baldinger 2015)

3.2.1.3 Purposes of additive manufacturing

The purposes of additive manufacturing are described in Table 3.

Table 3: Purposes of additive manufacturing

Purposes	
Material resource efficiency	Theoretically, only the material quantity needed to form the geometry layer-by-layer is used. Because AM is consuming less material than subtractive manufacturing methods it has a higher material resource efficiency. (Feldmann u. Pumpe 2017, S. 687)

Less product interfaces	Through consolidating multiple parts of an assembly, the number of interfaces between these parts get reduced. Product interfaces are often considered as major weak points of a product. (GRUND 2015, S. 234)
Flexible geometrical structures	Flexible structures like inflatable (deployable) parts can be realized by enclosed lattices (MAHESHWARAA NAMASIVAYAM U. CONNER SEEPERSAD 2011).
Product identification	Specific identification measures like imprinted serial numbers or QR-Codes can be printed in order to identify similar-looking products or protect manufacturers and customers against counterfeit (FELDMANN U. PUMPE 2017, S. 692).
Less fasteners	If components get consolidated or a product is designed to fulfill multiple functions by complex geometries, a lot of simpler components like fasteners are getting obsolete (CAMPBELL U. BERNABEI 2017, S. 73).
Lightweight design	Lightweight design is considered as the reduction of a components weight without decreasing the functional specification of the product (WOHLERS ASSOCIATES INC. 2017, S. 186).
Optimization of functional performance	With AM products can be designed for functional optimization without compromising restrictions given by the manufacturing process (CAMPBELL U. BERNABEI 2017, S. 77).
Plagiarism safety	The integration of embedded systems (e.g. RFID-Chips, barcodes or surface structures) can be used for plagiarism safety purposes (SCHMIDT 2015, S. 131).
Create insulations	Multifunctional structures can be created to build acoustic or thermal insulation (GAUSEMEIER ET AL. 2014, S. 10).
Create unique connectors	By printing embedded interfaces for assemblies it is possible to create unique connectors which differ a lot from standardized fasteners, e.g. biomedical implants (GAUSEMEIER ET AL. 2014, S. 10)
Integration of new functionalities	By using multifunctional structured components it is possible to enhance and upgrade the functionality of a part (GAUSEMEIER ET AL. 2014, S. 10).
Better demand forecasting accuracy	With a replenishment of raw material by only a few raw material suppliers, the planning activities decrease and the forecasting accuracy of material demand increases (FELDMANN U. PUMPE 2017, S. 685).
Aesthetic product creation	Through the high geometrical freedom the product designers can explore aesthetic forms to improve emotional values (CAMPBELL ET AL. 2013, S. 7).
Better handling and transportability	Better handling and transportability can be achieved for raw material, assemblies or finished products (BEN-NER U. SIEMSEN 2017, S. 10).

Enabling fast design changes	In case of a design change there is no production of new tools needed. Therefore the design changes of a product can be realized a lot faster (Hopkinson u. Dickens 2005, S. 32).
Production capacity buffer	Even if an additive manufacturing machine is purchased for other purposes, it can be utilized to react as a capacity buffer for other production systems. So AM can help in case of unexpected surges in demand. (Khajavi et al. 2014, S. 58)
Lead time reduction	Lead time can be reduced (e.g. compared to injection moulding), because no tools need to be produced previously. This can lead to a faster time to market. (Wohlers Associates Inc. 2017, S. 181)
Less equipment wearout	Conventional technologies to produce parts with strong materials like titanium suffer a high equipment wear out. Because AM doesn’t use subtractive procedures, the equipment wear out gets reduced. (Grund 2015, S. 234)
Reduction of downstream painting	Some AM technologies can print parts directly in different colors. This possibly eliminates downstream painting operations. (Thompson et al. 2016, S. 741)
Product volume flexibility	Different products can be produced without changing the machine setup. Thus the production rates can be modified quickly to match changing demands. (Wohlers Associates Inc. 2017, S. 182)
Product mix flexibility	Because no tooling is needed, the product mix can be changed on short notice. Thus AM usage can result an a high product volume flexibility. (Wohlers Associates Inc. 2017, S. 182)
Reduction of administrative overhead	Administrative overhead like documentation, inspection, production planning, etc. can be reduced by consolidating parts (Wohlers Associates Inc. 2017, S. 182)
Economies of scale	AM allows scaling the production capacity more closely to the market demands (Ben-Ner u. Siemsen 2017, S. 9)
Enable rapid repair and remanufacturing	Customer gain profit from shorter downtimes if missing spare parts can be remanufactured any time (Bauer et al. 2016, S. 18)

3.2.1.4 Goals of additive manufacturing

The goals of additive manufacturing are described in Table 4.

Table 4: Goals of additive manufacturing

Goals	
Less energy consumption of product in use	Energy consumption of the product, where the AM produced part gets deployed, can get reduced if product improvements got achieved (e.g. by lightweight design). (Yang et al. 2017, S. 838)

Protection of know-how	By imprinting hidden characteristics AM can be used to protect manufacturers and customers against counterfeit (Feldmann u. Pumpe 2017, S. 692)
Longer lifespan of products	Longer lifespans can achieved by consolidating parts, because less functional interfaces result in less failure possibilities (Deutsches Institut für Normung 2017, S. 234)
Sustainability	Usage of AM can result in many sustainability benefits. For example through a higher raw material efficiency, reduction of energy or production closer to the customer. (Sreenivasan et al. 2010, S. 82)
Long term conservation of spare parts	Any part can be replicated at any time, if the digital model is available. Therefore a long term conservation of spare parts is possible without the need of physical space. (Wohlers Associates Inc. 2017, S. 182)
Enhance intrinsic customer value	Intrinsic customer values refer to emotional customer relationships. The intrinsic value can be increased by offering customized products. (Spallek u. Krause 2017, S. 74)
Enhance extrinsic customer value	Extrinsic customer values refer to customized functionalities, which enhances the usability for individual customers (Spallek u. Krause 2017, S. 74).
Reduction of energy during production	Production energy can be reduced e.g. by avoiding energy intensive manufacturing steps like casting, or CNC machining (Sreenivasan et al. 2010, S. 82)
Fast time/reaction to market	Mainly because there is no need for tooling and designs can be adjusted quickly, fast reaction on market activities can be achieved with AM (Schmidt 2015, S. 33)
Improved overall manufacturing / assembly performance	Assembly performance can be improved by reducing the amount of parts to be assembled (Atzeni u. Salmi 2012). Also the connectors can be designed freely and can be shaped ergonomically
Better serve customer segments	AM enables companies to serve small customer segments cost efficiently, because individual parts can be produced with no enhancement of production effort (Feldmann u. Pumpe 2017, S. 677)
Fast and reliable delivery service	In case of long transport distances a distributed production system based on AM can reduced delivery times and thus improve the delivery service level (Heutger 2016, S. 4)
Reduction out-of-stock risk	Out-of-stock risk describes the risk, which a customer cannot be served with the product. It can be reduced by storing parts digitally. (Sirichakwal u. Conner 2016, 57ff.)

Inventory reduction	Many aspects, especially the digital workflow of AM and the absence of tools, lead to an reduction of inventory and needed shop floor area (Wohlers Associates Inc. 2017, S. 182)
Trade barrier bypassing	High customs and trade barriers can be avoided by sending products digitally and producing them decentral (Feldmann u. Pumpe 2017, S. 686)

3.2.1.5 Values of additive manufacturing

The values of the additive manufacturing are described in Table 5.

Table 5: Values of additive manufacturing

Values	
Less operating costs for product in use	The usage of beneficial additive manufactured parts saves costs – either for the customer or the company
Higher revenues	The company gets higher revenues while utilizing additive manufacturing. Major reasons are for example better delivery reliability, lower lead time, higher flexibility and a high variety of the product portfolio (Feldmann u. Pumpe 2017, S. 692).
Less labor costs	Create reduction of labor costs can be achieved, for example if parts get consolidated and assembly gets eliminated (M. Zanardini et al. 2015, S. 5).
Less material costs	Material costs can be saved when less material gets used or material gets recycled in a high rate
Lower emission costs	Emissions like CO2 emission can be priced and so the cost savings for emission reduction can be evaluated
Less manufacturing / assembly costs	By reducing the number of production steps, the overall manufacturing/assembly costs can be reduced (Campbell et al. 2013, S. 9)
Less transportation costs	Transportation costs can be reduced by lightweight design or by sending the products digitally and printing them locally (Feldmann u. Pumpe 2017, S. 690).
Less inventory costs	Inventory costs can be saved by producing on demand and because no tool storages are needed (Giffi et al. 2014, S. 4)
Less infrastructure costs	Less production steps lead to less material handling equipment and other infrastructural components, which saves investment and running costs
Less equipment maintenance/repair costs	Maintenance and repair costs can be saved. E.g. if no tools are needed, there are no tools which need to be maintained etc. (Wohlers Associates Inc. 2017, S. 181)

Less scrapping/disposal costs	Scrapping and disposal costs get reduced, e.g. while printing on demand, because there is no storage of products being phased-out (Feldmann u. Pumpe 2017, S. 686)
Less cost of risks	“Total cost of risk is the sum of all aspects of an organization's operations that relate to risk, including retained (uninsured) losses and related loss adjustment expenses, risk control costs, transfer costs, and administrative costs.” https://www.irmi.com/term/insurance-definitions/cost-of-risk
Lower production ramp up costs	Production ramp up (introducing a new product) gets reduced in time and costs, e.g. because no tools are needed (Holmström et al. 2010, S. 692).

3.2.2 Application of the Benefit Model

In Fig. 3.11 the vertical differentiation of the benefit model is shown, segmented into five categories. Here, the unique features of additive manufacturing are the material properties, the geometric freedom, the possible material combinations, the tool-free manufacturing, the CAD-to-product process, and the formless raw material. On the basis of these specific properties or already known advantages, the model enables the user to work in a structured manner on the identification and combination of advantages in order to determine economic use cases in the totality of potential use cases within the framework of the cost–benefit assessment. The procedure for this is described below.

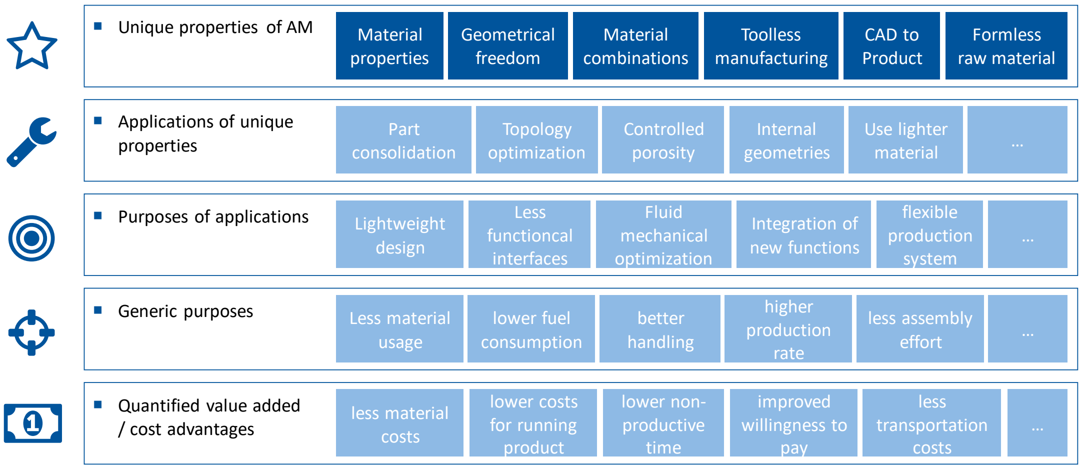


Fig. 3.11: Vertical differentiation of the Benefit Model

Fig. 3.12 shows how the causes and possible direct consequences arise within the benefit model. Starting with the consideration of a specific benefit, such as the optimisation of fluid mechanics, there result possible direct consequences on the levels of generic purposes and cost advantages, such as higher production rate and consequently shorter piece processing time. Furthermore, the root causes of the considered node are displayed on the superordinate levels, which in this case correspond to the internal geometries in the category of application of the unique features, as well as the geometric freedoms, as the causal unique feature.

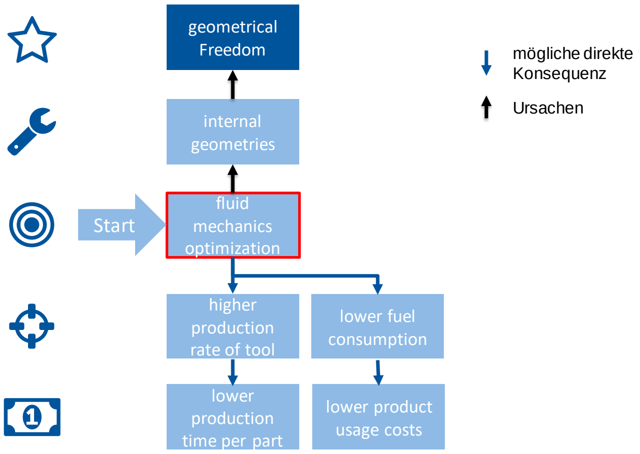


Fig. 3.12: Benefit Model – root causes and direct consequences

The structuring of the benefit model also allows to display the neighbours of any other node, as shown in Fig. 3.13. In addition to the possible direct consequences of an optimisation of the fluid mechanics, the nodes connected to the superordinate internal geometry are also shown here. This allows additional analysis of the possible consequences that may arise when the node superordinate to the fluid mechanics is changed. For a redesign of this would not only have an effect on the (starting) node under consideration, but could also lead to further positive effects. Optimisation of the internal geometries could, in addition to the consequences for the fluid mechanics, also improve safety against copying without much additional effort, which in turn has an advantageous effect on the protection of the know-how and thus leads to lower plagiarism costs.

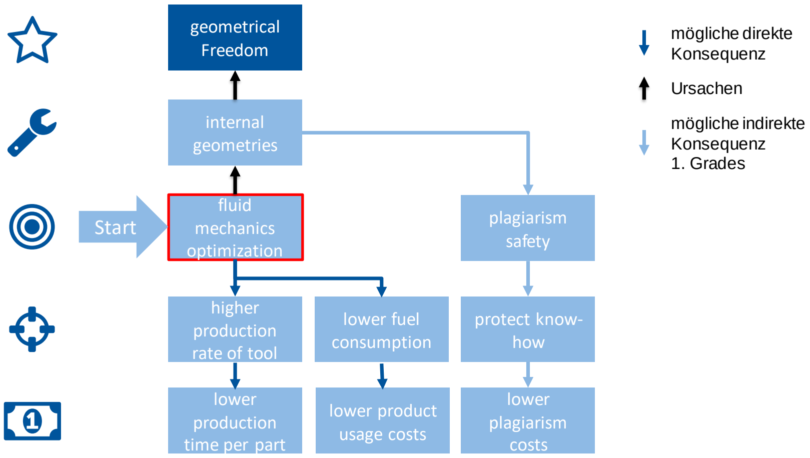


Fig. 3.13: Benefit Model – I° causes and possible indirect consequences

In a manner similar to the procedure described in the previous paragraph, the possible consequences of the redesign of the next higher-level node are mapped in Fig. 3.14. By changing the geometric freedoms, positive effects could be achieved in the areas of topology optimisation and part consolidation in addition to the resulting optimisation of internal geometries and thus of fluid mechanics. These in turn have an impact on the subordinate levels of application purposes, generic purposes and cost benefits.

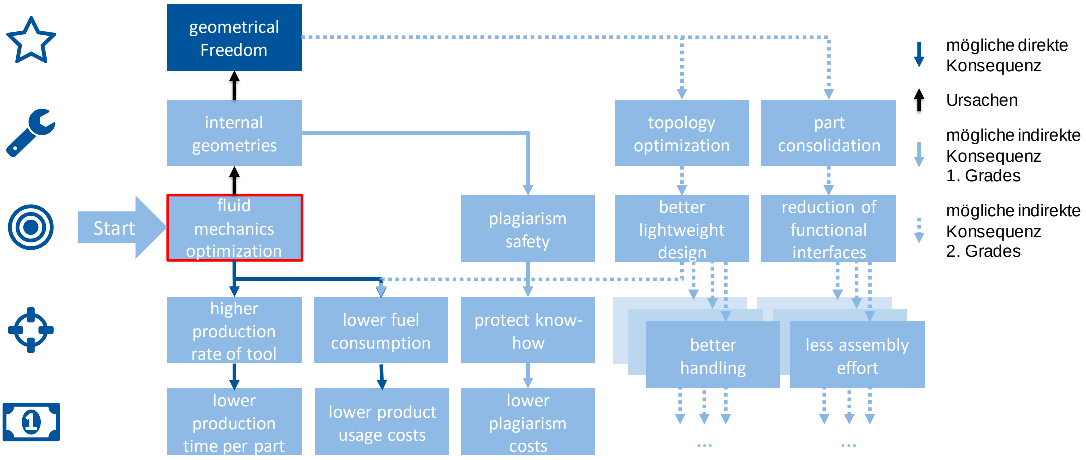


Fig. 3.14: Benefit Model – II° causes and possible indirect consequences

Thus, a major success of the benefit model is that it provides an overview of the characteristics of additive manufacturing and the relationships between them. This allows the effects of the optimisation of a feature on the associated features to be estimated, thus revealing great potential for product and process improvements.

3.3 A web-based integrated cost-benefit tool

The result is a cost model prototype that allows straightforward generic application and cost calculation with only a few parameters. On this basis, the cost model was transformed into a dashboard in the Python programming language. The following figure gives an overview of the structuring of the Cost–Benefit Model.

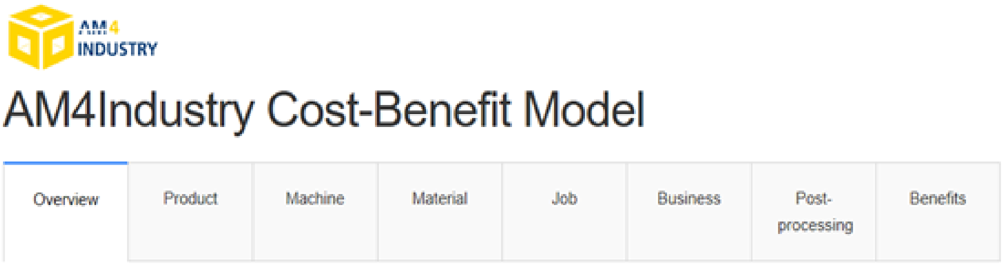
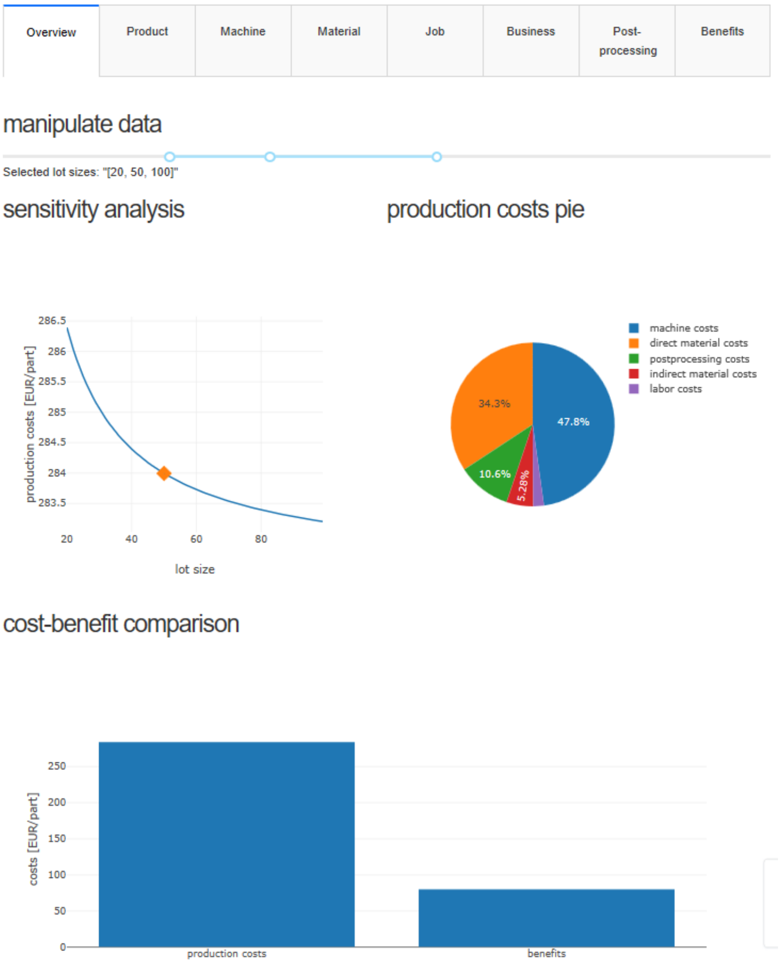


Fig. 3.15: Cost–Benefit Model

The user can navigate between various tabs on this dashboard. An overview page and one page each for entering product, machine, material, job, business and post-processing data are available. A last page comprises the benefits that are relevant for the part of the benefit model.

On the **Overview** page, the data calculated on the basis of the entered parameters are clearly summarised. Here, too, the costs are broken down into cost categories.

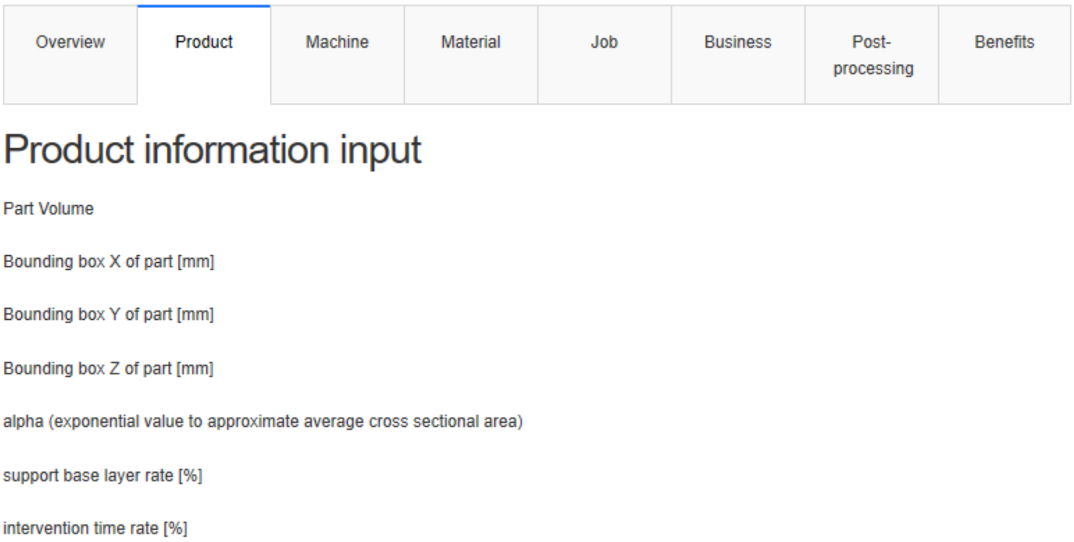


Selected lot sizes: "[20, 50, 100]"

Fig. 3.16: Cost–Benefit Model – Overview

A controller can be used to set the range of the batch size under consideration. The sensitivity analysis shows the production costs depending on the lot size. The pie chart shows the relative composition of the production costs in percent. These are divided into machine costs, direct and indirect material costs, post-processing costs, and labour costs. All calculations are based on the structures and calculation bases already explained. The juxtaposition of costs and possible savings by using the identified advantages in analogy to the previously explained procedure enables the user to assess the inputs. The individual input pages of the model are explained below.

Product-specific information is entered under **Product**.



Product information input

Part Volume

Bounding box X of part [mm]

Bounding box Y of part [mm]

Bounding box Z of part [mm]

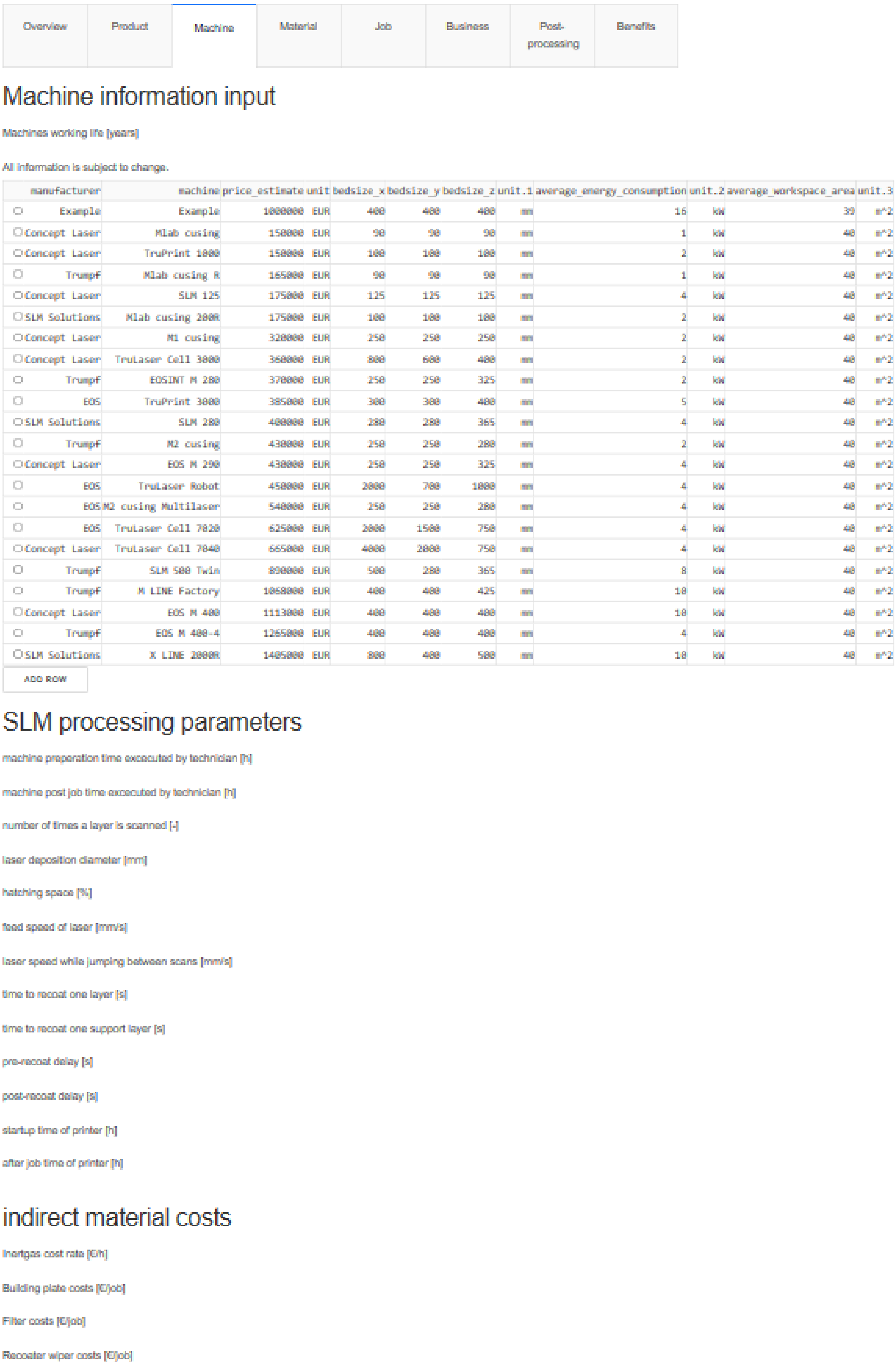
alpha (exponential value to approximate average cross sectional area)

support base layer rate [%]

intervention time rate [%]

Fig. 3.17: Cost–Benefit Model – Product

Under **Machine**, machine-related information, SLM processing parameters and indirect material costs can be entered. The exemplary data identified from the literature are already stored with regard to the machine information for the low-cost initial application. These can be adapted by the user, or new rows can be added.



Machine information input

Machines working life [years]

All information is subject to change.

	manufacturer	machine	price_estimate	unit	bedsize_x	bedsize_y	bedsize_z	unit.1	average_energy_consumption	unit.2	average_workspace_area	unit.3
○	Example	Example	1000000	EUR	400	400	400	mm	16	kW	39	m^2
○	Concept Laser	Mlab cusing	150000	EUR	90	90	90	mm	1	kW	40	m^2
○	Concept Laser	TruPrint 1000	150000	EUR	100	100	100	mm	2	kW	40	m^2
○	Trumpf	Mlab cusing R	165000	EUR	90	90	90	mm	1	kW	40	m^2
○	Concept Laser	SLM 125	175000	EUR	125	125	125	mm	4	kW	40	m^2
○	SLM Solutions	Mlab cusing 200R	175000	EUR	100	100	100	mm	2	kW	40	m^2
○	Concept Laser	M1 cusing	320000	EUR	250	250	250	mm	2	kW	40	m^2
○	Concept Laser	TruLaser Cell 3000	360000	EUR	800	600	400	mm	2	kW	40	m^2
○	Trumpf	EOSINT M 280	370000	EUR	250	250	325	mm	2	kW	40	m^2
○	EOS	TruPrint 3000	385000	EUR	300	300	400	mm	5	kW	40	m^2
○	SLM Solutions	SLM 280	400000	EUR	280	280	365	mm	4	kW	40	m^2
○	Trumpf	M2 cusing	430000	EUR	250	250	280	mm	2	kW	40	m^2
○	Concept Laser	EOS M 290	430000	EUR	250	250	325	mm	4	kW	40	m^2
○	EOS	TruLaser Robot	450000	EUR	2000	700	1000	mm	4	kW	40	m^2
○	EOS	M2 cusing Multilaser	540000	EUR	250	250	280	mm	4	kW	40	m^2
○	EOS	TruLaser Cell 7020	625000	EUR	2000	1500	750	mm	4	kW	40	m^2
○	Concept Laser	TruLaser Cell 7040	665000	EUR	4000	2000	750	mm	4	kW	40	m^2
○	Trumpf	SLM 500 Twin	890000	EUR	500	280	365	mm	8	kW	40	m^2
○	Trumpf	M LINE Factory	1060000	EUR	400	400	425	mm	10	kW	40	m^2
○	Concept Laser	EOS M 400	1113000	EUR	400	400	400	mm	10	kW	40	m^2
○	Trumpf	EOS M 400-4	1265000	EUR	400	400	400	mm	4	kW	40	m^2
○	SLM Solutions	X LINE 2000R	1405000	EUR	800	400	500	mm	10	kW	40	m^2

SLM processing parameters

machine preperation time excecuted by technician [h]

machine post job time excecuted by technician [h]

number of times a layer is scanned [-]

laser deposition diameter [mm]

hatching space [%]

feed speed of laser [mm/s]

laser speed while jumping between scans [mm/s]

time to recoat one layer [s]

time to recoat one support layer [s]

pre-recoat delay [s]

post-recoat delay [s]

startup time of printer [h]

after job time of printer [h]

indirect material costs

Inertgas cost rate [€/h]

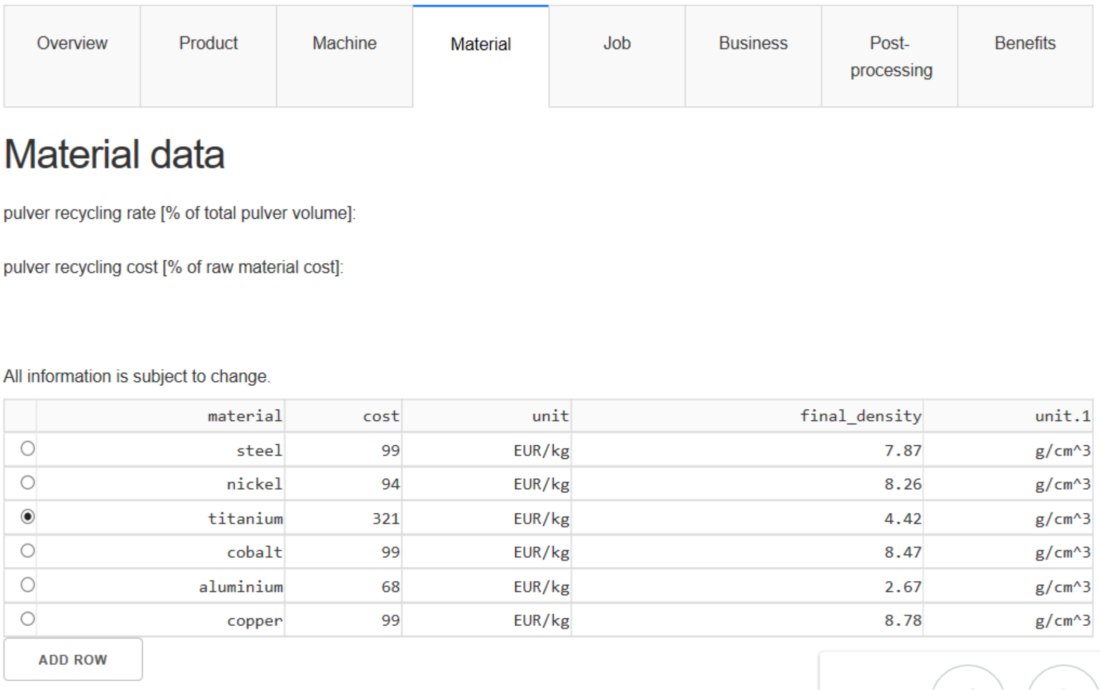
Building plate costs [€/job]

Filter costs [€/job]

Recoater wiper costs [€/job]

Fig. 3.18: Cost–Benefit Model – Machine

Under **Material**, information on the materials used is listed. Here, too, sample data are already stored. The user can edit them, or add a new material in a new row. The user selects the respective material for the calculation.



Material data

pulver recycling rate [% of total pulver volume]:

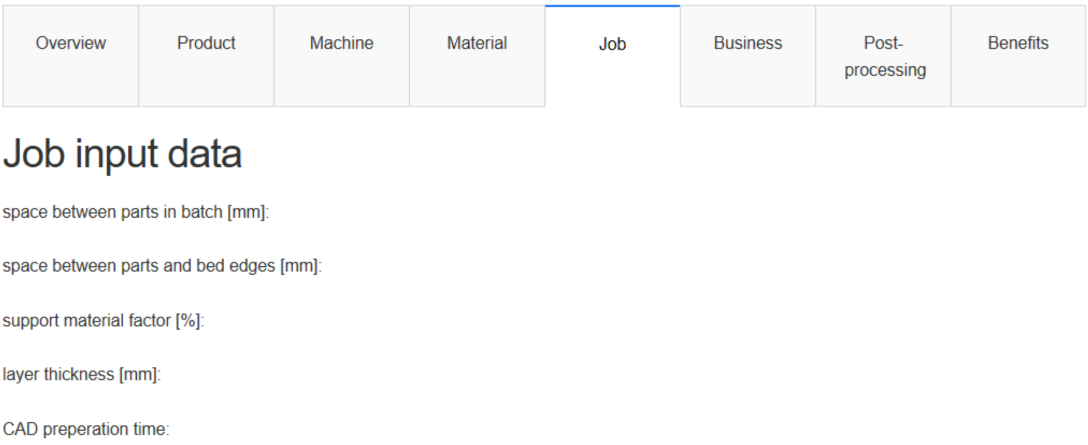
pulver recycling cost [% of raw material cost]:

All information is subject to change.

	material	cost	unit	final_density	unit.1
○	steel	99	EUR/kg	7.87	g/cm^3
○	nickel	94	EUR/kg	8.26	g/cm^3
●	titanium	321	EUR/kg	4.42	g/cm^3
○	cobalt	99	EUR/kg	8.47	g/cm^3
○	aluminium	68	EUR/kg	2.67	g/cm^3
○	copper	99	EUR/kg	8.78	g/cm^3

Fig. 3.19: Cost–Benefit Model – Material

Under **Job**, the order-specific information is added.



Job input data

space between parts in batch [mm]:

space between parts and bed edges [mm]:

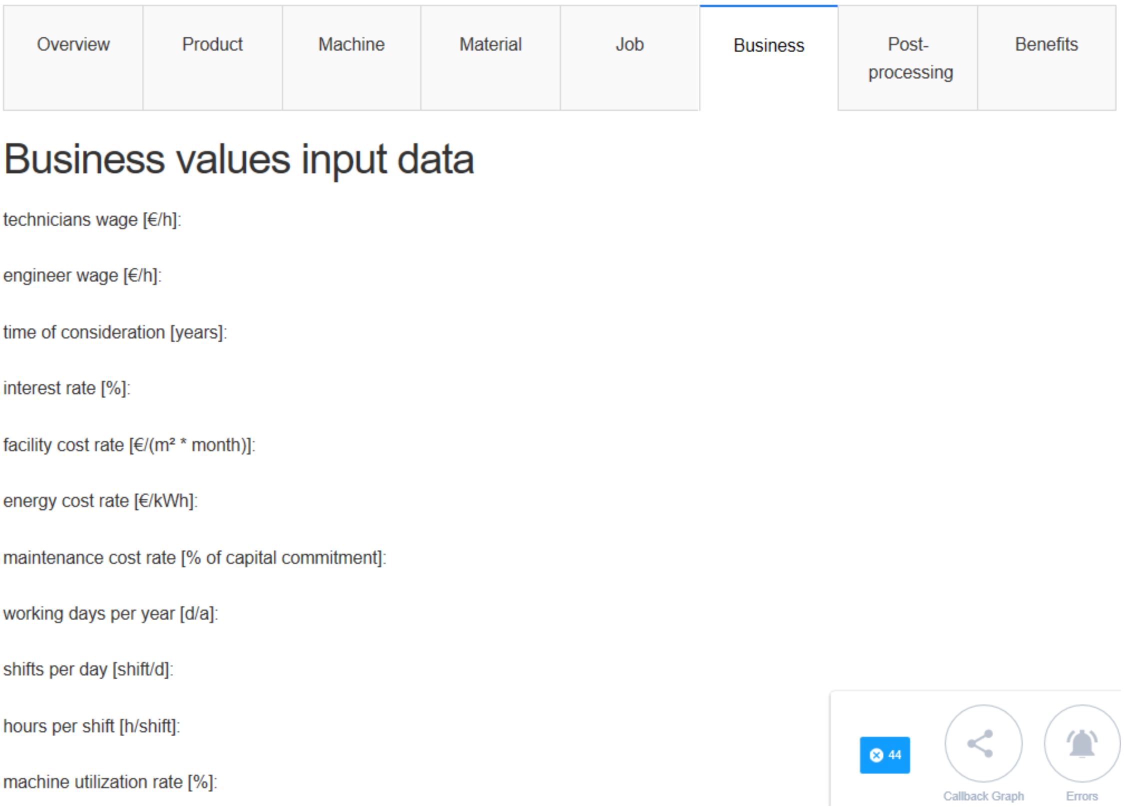
support material factor [%]:

layer thickness [mm]:

CAD preperation time:

Fig. 3.20: Cost–Benefit Model – Job

Under **Business**, the enterprise-specific information is entered.



Business values input data

technicians wage [€/h]:

engineer wage [€/h]:

time of consideration [years]:

interest rate [%]:

facility cost rate [€/(m² * month)]:

energy cost rate [€/kWh]:

maintenance cost rate [% of capital commitment]:

working days per year [d/a]:

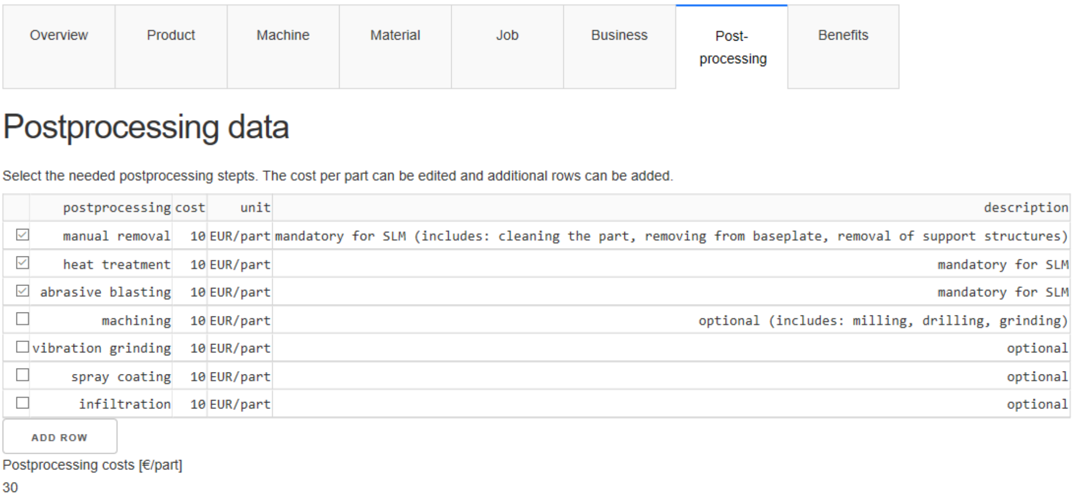
shifts per day [shift/d]:

hours per shift [h/shift]:

machine utilization rate [%]:

Fig. 3.21: Cost–Benefit Model – Business values input data

Post-processing data lists the costs for possible post-processing steps. The exemplary data can also be edited here, or new data can be added. The Description field allows adding comments to each procedure. Here, for example, it can specified whether the post-processing procedure is optional or mandatory. For the calculation, the user selects the post-processing steps to be carried out. Post-processing costs relate to one part at a time.



Postprocessing data

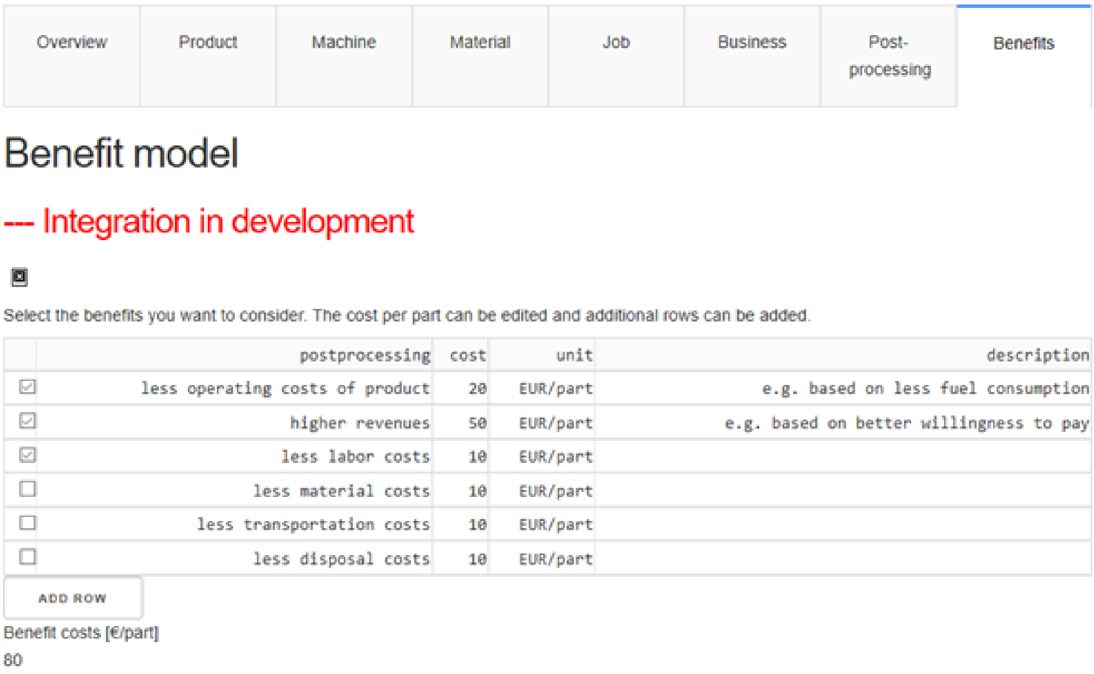
Select the needed postprocessing stepts. The cost per part can be edited and additional rows can be added.

	postprocessing	cost	unit	description
☑	manual removal	10	EUR/part	mandatory for SLM (includes: cleaning the part, removing from baseplate, removal of support structures)
☑	heat treatment	10	EUR/part	mandatory for SLM
☑	abrasive blasting	10	EUR/part	mandatory for SLM
☐	machining	10	EUR/part	optional (includes: milling, drilling, grinding)
☐	vibration grinding	10	EUR/part	optional
☐	spray coating	10	EUR/part	optional
☐	infiltration	10	EUR/part	optional

Postprocessing costs [€/part]
30

Fig. 3.22: Cost–Benefit Model – Post-processing data

After selecting the models in Cytoscape, the user finds the relevant user dimensions in the web-based evaluation and can quantify them individually to enable comparability (Fig. 3.23).



Benefit model

--- Integration in development

Select the benefits you want to consider. The cost per part can be edited and additional rows can be added.

	postprocessing	cost	unit	description
☑	less operating costs of product	20	EUR/part	e.g. based on less fuel consumption
☑	higher revenues	50	EUR/part	e.g. based on better willingness to pay
☑	less labor costs	10	EUR/part	
☐	less material costs	10	EUR/part	
☐	less transportation costs	10	EUR/part	
☐	less disposal costs	10	EUR/part	

Benefit costs [€/part]
80

Fig. 3.23: Benefit model

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