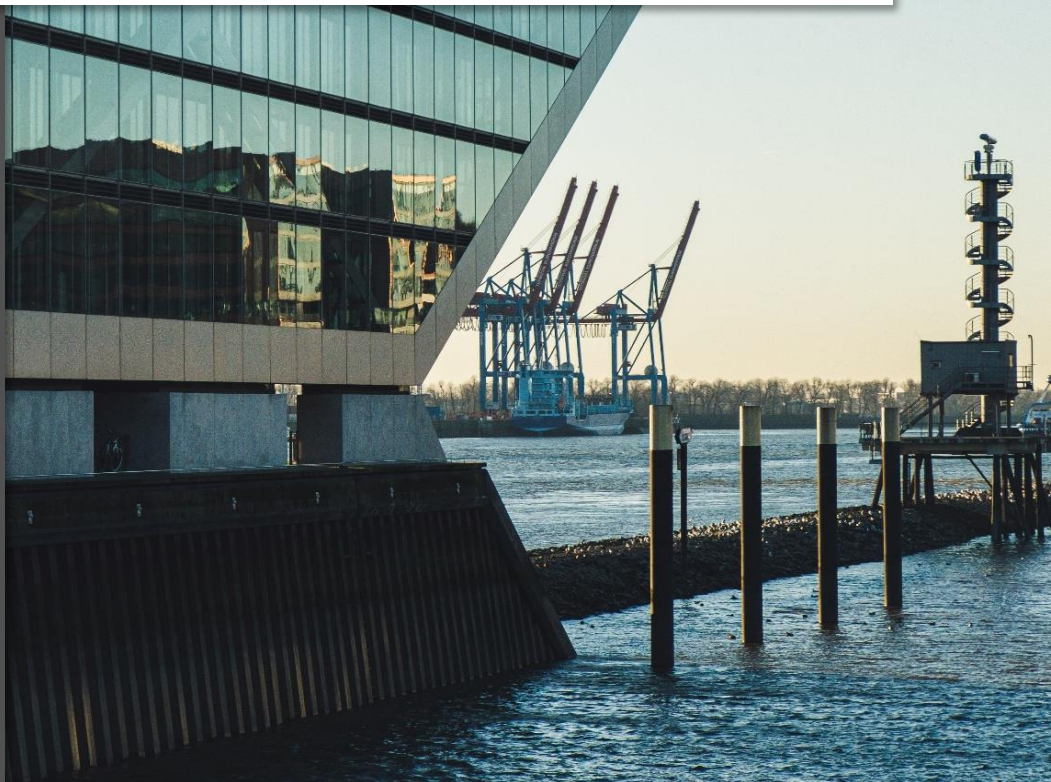


Michael Schöppe, and Kaj Fuehrer

Parametric Selection of Hybrid Parts for Additive Manufacturing



Parametric Selection of Hybrid Parts for Additive Manufacturing

Michael Schöppe¹ and Kaj Fuehrer²

1 – Technische Universität München

2 – enter2net.com AG

Purpose: *The combination of additive and conventional manufacturing techniques allows the combination of the strengths of both approaches. Additive manufacturing can be concentrated on functional and complex geometries while the basic body of a part is produced conventionally leading to cost advantages and thus enables new application fields of additive manufacturing.*

Methodology: *To identify parts suitable for a hybrid production, the application of a software evaluating part properties based on CAD data were examined. Different criteria for the selection of components are presented and tested. The methodology was qualitatively validated by an exemplary application to a library of 3D models of components using the 3D Partfinder software.*

Findings: *By applying the presented criteria for the part selection, the software can automatically perform the necessary part comparison. It can be concluded that the complexity index allows a typologization of parts while respecting economic parameters. In particular products with a high number of variants but only small geometric deviations in volume and surface area show a high potential for hybrid production.*

Originality: *So far, little research on hybrid additive manufacturing has been done. The paper shows the applicability of software solutions and offers typologization criteria as a general search strategy for suitable parts.*

First received: 12. Mar 2021

Revised: 29. Aug 2021

Accepted: 31. Aug 2021

1 Introduction

Additive manufacturing processes were initially used mainly in prototype production (Gibson, Rosen and Stucker, 2015). Today, the implementation of additive technologies into series production is still hindered by a low level of industrialization and a lacking cost competitiveness in many applications (Baumers, et al., 2016; Caviezel, et al., 2017). Despite the frequently mentioned advantages of additive manufacturing, such as production without tools, without corresponding lead times for the creation of tools or the lower dependence of production costs on component complexity compared to conventional manufacturing processes, additive manufacturing is still mainly used to produce components in small quantities (Klahn, Leutenecker and Meboldt, 2014; Lutter-Günther, et al., 2015; Gebhardt, 2016; Thomas, 2016; Klahn, et al., 2018). However, the existing and forecasted market development combined with an increase in the economic efficiency of additive manufacturing processes promise additional use of the technology in the coming years (Strategy&, 2018; Wohlers, 2018; Grand View Research, 2021). When looking for suitable components to be built by one of the various 3D printing technologies, the focus in the metallic area has so far been on highly complex or energy transferring components. Improved performance parameters in existing processes and new technologies such as two-stage metallic binder jetting are leading to significant cost reductions increasing the attractiveness of additive manufacturing (Wildemann, 2019). Components with less complex geometries can also be manufactured cost efficiently in larger quantities using additive manufacturing. As a result, an increasing number of components comes into focus which are used in large quantities in existing products and are to be manufactured additively in the future.

While component selection in additive manufacturing processes is often focused on the identification and evaluation of isolated components or products, hybrid manufacturing concepts would broaden the scope of consideration. To combine conventional and additive manufacturing, there are three basic approaches (Ley, et al., 2018):

1. In Directed Energy Deposition processes (with powder or wire), geometry elements determining the variant or integrating functionality are added to an existing component.

2. Individual geometry elements of a component can be manufactured additively and then joined to a basic body. For components that are only differentiated by individual interfaces or geometry elements, the basic body can be standardized and the number of pieces of the basic body to be produced can be increased.
3. In additive manufacturing processes in which a component is manufactured from the powder bed, as in selective laser beam melting, building platforms made of different base body materials can also be used or base bodies can be attached to the building platform. These then present the starting point for the further building up of layers with the selected material of the 3D printer.

While a direct comparison of different manufacturing alternatives can be made for isolated components, the consideration of hybrid manufacturing requires an additional division and interface definition between the conventionally and additively built component structures and thus changes the approach of identifying suitable components compared to building full parts additively. As a proposal to reduce the effort of the component selection, the possibility of using software to create a preselection and to automate the part selection is qualitatively investigated.

2 State of the Art in Science and Technology

In additive manufacturing, a component is manufactured starting from a 3D digital component model. Additive processes are characterized by the fact that material is built up layer by layer and joined together to form a component. The material, which is built up is usually shapeless material that is provided in powder, paste, liquid or wire form. VDI Guideline 3405 defines additive manufacturing processes as processes in which "the workpiece is built up element by element or layer by layer" (Verein Deutscher Ingenieure, 2014). Here, no component specific tools are required for the additive manufacturing of a component. The layer by layer application results in the possibility to add material only where it is needed. In contrast to subtractive manufacturing processes such as CNC machining, additive manufacturing can thus reduce the amount of material required. A differentiation of additive manufacturing processes with regard to the possibility of manufacturing hybrid parts is offered by the design of the build area in the additive manufacturing machine (Gibson, Rosen and Stucker, 2015; Gebhardt, 2016). For

Parametric Selection of Hybrid Parts for Additive Manufacturing

processes such as selective laser beam melting, selective laser sintering or stereolithography, the build space is filled layer by layer with unfused material, which is then selectively fused into a component. In a fused filament fabrication, direct energy deposition or the MELD™ process, the required material is provided by a conveyor mechanism without the necessity of surrounding material. The working area of the process and the structure of the component is thus geometrically less restricted than in powder bed based processes.

Existing work and practical applications demonstrate the feasibility of manufacturing hybrid parts. For example, the processes grouped under the term Directed Energy Deposition are already being used to repair worn components (Gibson, Rosen and Stucker, 2015; Kumke, 2018; Leuteritz, et al., 2018). This process corresponds to a hybrid construction method in which geometrically determined elements are applied to an existing base body. Components created using selective laser beam melting can also be used as casting molds (Bauer and Nolis, 2014; Leuteritz, et al., 2018). If powder bed based processes are combined with conventional processes, a semi-finished product must be introduced into the powder bed. The prefabricated, semi-finished product must be prepared in such a way that alignment in the installation space of the additive manufacturing system is possible to avoid any collision with the material feed mechanism and to ensure a sufficiently high-quality connection between the semi-finished product and the additively built geometries. For this purpose, the separation direction of the component, the design of the support structures, fixation possibilities of the semi-finished product in the build space, and the possibility of necessary preparations of the semi-finished product for the process must be taken into account (Roj, 2019). The term hybrid part also incorporates parts that are manufactured from a combination of different materials. In this case, structures made of a material that is not the same as the base body are added during additive manufacturing (Scheithauer, et al., 2017; Uhlmann and Kashevko, 2017). The material transition can be discrete or continuous (Yao, et al., 2018). For gradient components, the material transition is built up continuously (vgl. z.B. Zhiyuan Xu, et al., 2019). Here, the gradual material transition serves to reduce residual stresses and the tendency for layer separation between the layers (Bharti, Gupta and Gupta, 2013).

Different approaches exist to evaluate the suitability of a component for additive manufacturing, based on a qualitative or also parameter component analysis. Expert knowledge is often assumed for a heuristic component selection to evaluate the feasibility and usefulness of additive manufacturing (Achillas, et al., 2015; Knofius, van der Heijden and Zijm, 2016; Burkhart and Aurich, 2017; Illgner, Lutter-Günther and Seidel, 2018; Kumke, 2018; Fontana, Klahn and Meboldt, 2019). Many approaches are focused on benefits of additive manufacturing e.g. in terms of improved heat and mass transfer, possibilities for component integration and weight optimization to reason the advantage of the technology (Knofius, van der Heijden and Zijm, 2016; Burkhart and Aurich, 2017; Feldmann and Pumpe, 2017; Fiedler, 2018). While the mentioned criteria have essential relevance for the evaluation of the economic viability of additive manufacturing, the parameterization and evaluation of these criteria by software poses a challenge in the authors' experience. A detailed economic evaluation for additive and conventional manufacturing is only possible if detailed product and usage information is available (Schmidt, 2016).

3 Qualitative Assessment of identification possibilities of economically advantageous hybrid part manufacturing

The presented evaluation aimed at a qualitative assessment of the possibilities to implement a software supported process to partly automate the identification of parts with a high likelihood to be economically beneficial for a hybrid manufacturing process as a combination of conventional and additive manufacturing. The qualitative assessment is based on the following three steps:

1. Qualitative assessment of advantages of hybrid manufacturing to deduce a typology of parts which could be suitable for the manufacturing approach.
2. Identification of parameters which can be used to create filter criteria according to literature and deduction of parameters according to the presented typology.
3. Assessment of filter criteria through the exemplary software implementation in a case study and evaluation of the results.

Parametric Selection of Hybrid Parts for Additive Manufacturing

The proposed steps are described in the following section. A discussion of the results is presented in Section 5.

4 Selection of Hybrid Parts for Additive Manufacturing

Additive manufacturing enables the economic production of complex products and the integration of functionalities into a component that can often only be realized at comparatively higher costs using established manufacturing methods (Klahn, Leutenecker and Meboldt, 2014; Wildemann, 2021). However, the economic advantage of additive manufacturing processes generally diminishes with increasing quantities of a component (Eschner et al. 2017). One way to expand the economic application possibilities of additive manufacturing processes is to combine conventional and additive manufacturing, which is referred to in the following texts as the production of a hybrid part (Eschner, et al., 2017; Silva, et al., 2017). It is assumed that in this manufacturing setup, additive manufacturing is only used to produce functional carriers and complex geometry elements on a base body produced by means of established manufacturing processes.

Because the strength of additive manufacturing lies in the production of complex parts, the basic body is assumed to be a geometrically less complex component than the additively manufactured geometry elements to make use of the advantages of both conventional and additive manufacturing. For hybrid manufacturing, there are the options of additively building up a geometry feature on a conventionally manufactured base body or joining a conventionally manufactured base body to an additively manufactured component via a suitable joining process (Ley, et al., 2018; Oettel, et al., 2019). The basic body could then be manufactured independent of the variant, due to the combination of several component variants, to achieve economic advantages through scale effects.

To create a part by hybrid additive manufacturing showing a profitable business case in comparison to conventional manufacturing, the strengths presented by both manufacturing technologies should be respected. Because hybrid manufacturing

essentially describes a combined manufacturing process, both conventional and additive manufacturing can contribute to the overall profitability of the part.

4.1 Economic Evaluation

The combination of established and additive manufacturing processes enables using the cost wise effective production of components in high volumes by conventional processes while simultaneously applying the extended design possibilities of additive processes. This makes it possible to increase the cost effectiveness of components produced in high quantities using additive processes and thus expanding the range of applications for additive manufacturing. In principle, the economic advantages of additive manufacturing can be transferred to hybrid manufacturing with some limitations (Hague, 2006; Gibson, Rosen and Stucker, 2015; Mavri, 2015; Scott and Harrison, 2015; Lakomic, 2016; Möhrle, 2018):

- reduction of fixed costs and lead times for tools and fixtures for specific components,
- higher manufacturing flexibility due to machine equipment for the additive manufacturing processes which is not specific for manufactured components,
- possibility of decentralized manufacturing of additively manufactured components,
- reduction of manufacturing process steps,
- reduction of the lead time, and
- possibilities for component individualization and economic implementation of complex component designs with advantages in the component utilization phase.

It is assumed by various authors that a high part complexity indicates a high possible advantage of additive manufacturing because manufacturing costs are observed to increase stronger for an increasing part complexity if conventional technologies are used than when additive manufacturing is implemented (Hague, 2006; Conner, et al., 2014; Wildemann, 2019). The focus on part complexity enables linking the part geometry to its suitability for additive manufacturing. In line with this, KUSHNARENKO (2009) and LAKOMIC (2016) present the part complexity as a possible parameter to be used to identify components suitable for additive manufacturing.

Parametric Selection of Hybrid Parts for Additive Manufacturing

However, due to the hybrid manufacturing approach, the advantages of additive manufacturing cannot be considered isolated from the conventional manufacturing process. The economic justification of hybrid manufacturing may result not only from a cost advantage due to additive manufacturing, but also from conventional manufacturing of the basic body, and could thus even partially compensate for possible, additional costs for additive manufacturing. In addition, the size limitation for additively manufactured components due to the installation space of the manufacturing equipment is relativized by the hybrid approach. To produce the basic body, economic advantages may result from the increase in the production quantity in case a technology with scale effects is used. The higher quantity in which a basic body is produced can lead to economies of scale or a change in the manufacturing process with which the respective basic body can be produced at lower, variable costs and possibly with higher quality.

The conversion and combination of several components or assemblies into hybrid parts with a common basic body also results in a modularization, which leads to advantages in the generation of variants, a reduction in error susceptibility and interface complexity (Wildemann, 2016). The variant creation point is shifted, which increases the company's supply flexibility and reduces the planning effort (Waltl and Wildemann, 2014). In addition to the planning effort, the reduction in complexity can also lower the amount of safety stock required and thus reduce a company's working capital (Große-Heitmeyer and Wiendahl, 2004; Wildemann, 2014). A simplified geometry of the basic body can result in advantages regarding tooling, manufacturing process and quality costs. The simplification of the component geometry during casting can for example lead to a reduced use of cores and a reduction in wall thickness differences can lead to a lower probability of shrinkage cavity formation (Klocke, 2015).

The production of hybrid parts could consequently enable improved coordination of cycle times from the perspective of the entire process chain. Additive manufacturing processes have lower material deposition rates compared to established manufacturing processes such as casting. By combining several manufacturing processes, the process time of additive manufacturing can be shortened and thus an increase in productivity can be achieved from an overall process perspective (Eschner, et al., 2017). By combining

different materials for the manufacturing steps according to the requirements due to strength, corrosion, wear requirements and thermal stress between the base body and the additively manufactured geometry elements, cost reductions can be implemented if this means that the basic body can be realized with a favorable material, while only the geometry element is printed with high-quality materials with a higher load capacity.

In the profitability analysis, costs for possible component adaptations in the sense of design for additive manufacturing and design changes to previous manufacturing concepts must also be considered, as significant changes to the cost composition can be associated with the design adaptation. There are high interdependencies between the selected design, the definition of the interface between the basic body and the additively manufactured geometry element, and the resulting total costs for the manufacturing of a component. However, the definition of an interface offers a new possibility for implementing a platform strategy at component level and can thus be a form of modularization with the corresponding advantages (Waltl and Wildemann, 2015).

In accordance with the possible economic advantages presented for hybrid parts, a typologization can be carried out based on the criteria of the geometric conformity of the basic body between different products, the complexity of the differentiating geometric component elements and the marginal scale effects resulting from the increase in the number of units of the basic body (cf. Figure 1). A high degree of conformity of the geometry of the basic body forms the prerequisite for the presented approach to the selection of hybrid parts. If the differentiating geometry elements show a low complexity, normally, a low suitability of additive manufacturing would be assumed. However, in the production of hybrid parts, this decision can be compensated by a high marginal scale effect of increasing the quantity of the basic body. A high marginal scale effect can result in a cost advantages when a component that was previously produced in a low quantity, e.g., in small series, can be merged with a component that is produced in high quantities. From the combination as a carry-over part, cost advantages can be achieved through the transfer of economies of scale. If both components are already manufactured in high quantities, the marginal scale effect decreases, since only a small cost advantage can be achieved from increasing the quantities of one component. If the differentiating geometry elements are highly complex and therefore highly suitable for additive

Parametric Selection of Hybrid Parts for Additive Manufacturing

Match Basic Body

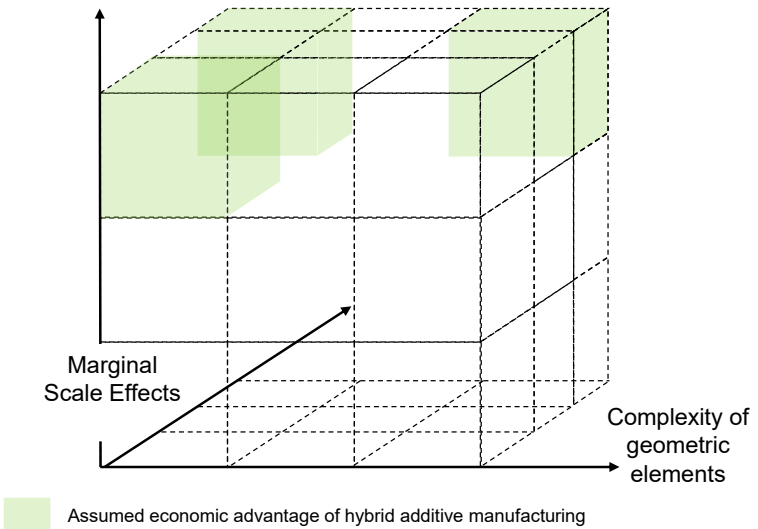


Figure 1: Typologization of economic application fields of hybrid parts

manufacturing, economic advantages can result from additive manufacturing even without taking the marginal scale effect into account.

4.2 Parametric Part Selection

From the preceding deduction of possible economic advantages of a hybrid part, there are two main objectives for component identification:

1. The basic bodies of the original, identified components to be manufactured hybrid should have as high a congruence as possible to be defined as a common part, and
2. the geometry elements that differentiate individual components should have a high suitability for additive manufacturing.

Based on the assumption that the basic body will be produced by a conventional manufacturing method which is advantageous especially when used for high part volumes, the basic body should be usable for many different products to create a high demand. To evaluate the congruence, a different orientation of the 3D model in terms of rotation or translation are not relevant for the use of the basic body as a invariable part. Scaling of the component will preclude its use as a common part, unless it is in such a small range that a common design would be possible considering higher production volumes of the common part.

By using automated and similarity evaluation based on contents of 3D data sets, both, the effort and the possible subjectivity of manual evaluation of data objects can be avoided (Bustos, et al., 2005). In the literature, approaches can be found to reduce the effort of the part comparison and the resulting computation time by extracting essential information regarding the parts resulting in a reduced information complexity still sufficient for a comparison (Roj, 2016). Furthermore, statistical 3D descriptors, extension based methods, volume based methods, descriptions of the surface geometry, image analysis or a feature based vector comparison can be used (Bustos, et al., 2005). In addition to an evaluation of the component geometry, the geometry elements and the hierarchical structure of a data model can also be used for a comparison if the data is available (e.g. Ding, 2014). If the simplification approach is chosen, smaller geometry elements are neglected in the automated part comparison, which can be considered advantageous for the identification of parts with a high similarity in the context of the definition of an identical basic body (Roj, 2016).

Component evaluation and selection can be carried out based on the geometric properties of a component and the characteristic values derived from them such surface area or volume as will be shown in the case study. A parameterization of the geometry evaluation enables a comparison of several components based on the resulting characteristic values. If the parameterization is possible based on the digital models, the entire component selection can be automated across a larger component portfolio. However, when evaluating geometric elements to identify components for hybrid manufacturing, the geometry element must be suitable for additive manufacturing or assembly on a base body, in contrary to conventional approaches for the component

Parametric Selection of Hybrid Parts for Additive Manufacturing

analysis and selection in which a part is fully manufactured by one technology. Accordingly, geometry elements that are produced purely subtractive, such as holes or eroded free forms, are omitted in the part comparison since it is not possible to add them on an existing part.

For the evaluation of the geometric component complexity KUSHNARENKO (2009) presents a parameter which results from a weighted evaluation of the individual geometry features of a CAD model as well as their arrangement. LAKOMIEC (2016) presents a parameter for the evaluation of the component complexity from the quotient of the component surface and volume, which can be derived with values usually available in the 3D modeling software (Lakomic, 2016). Another way to evaluate complexity is to compare it with alternative manufacturing processes. The software Materialise allows component complexity to be assessed by a direct comparison of additive manufacturing with a casting process on a scale from "no undercuts" to "impossible to cast in one piece" (Materialise, 2019). It should be noted here that such a qualitative evaluation may strongly depend on the evaluation competence of the user. Furthermore, the approach neglects other manufacturing processes besides casting, such as CNC machining. RUDOLPH ET AL. (2017) present an automated approach to component evaluation for additive manufacturing. Using an online interface, component data is read, and a topology optimization of the component is performed. The manufacturing cost comparison is performed based on the costs of additive manufacturing of the component which has been optimized regarding its topology and the costs of manufacturing the original component using CNC machining or investment casting.

4.3 Software Based Selection of Hybrid Parts for Additive Manufacturing

From the definition of a hybrid part, it follows that the selection parameters to be derived should enable the detection of components which,

- on the one hand, exhibit a high degree of conformity and,
- on the other hand, differ in detail like geometric elements.

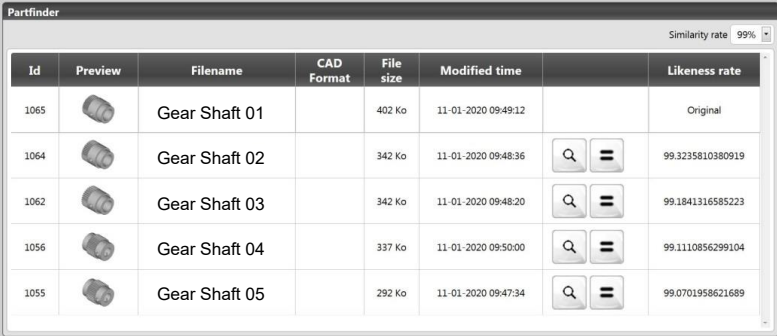
The latter should be complex and have a high suitability for additive manufacturing. In the presented approach, a high complexity of the geometry element to be manufactured additively is used as an indicator for a high economic efficiency of additive manufacturing. In this case study a two-stage approach was used for the component analysis, in which a geometric similarity analysis of all components is first performed in a CAD database, followed by a complexity analysis. Accordingly, the components identified have a high rate of similarity of the basic bodies and complex, differentiating geometric elements. Consequently, it is deduced that such components have a high suitability as hybrid parts. Based on the exemplary case study, the applicability of the procedure is generalized in the following by means of inductive proof. From an exemplary analysis of a CAD database with components from various industries and different areas of application, individual components suitable for hybrid manufacturing are in a first step extracted by filter criteria generally applicable.

The approach of reducing the component information or rewriting the data to substitute values while reducing the information content can be regarded obsolete due to powerful software for component identification. The entire information content of a CAD file can be used for part identification. Such a solution is offered by the 3D Partfinder of the company CoreTechnologie, which completely reads the data contained in a CAD file and enables intelligent, evaluations based on filters by storing all parameters in a database (enter2net, 2021). In addition to parametric data, the software also considers features, PMI (Product Management Information), and values calculated from geometric data, such as area, volume, or wall thickness. Advantageous in this context is the trend to integrate information that was previously noted in 2D drawing derivations, such as surface roughness or data regarding fittings, into the parametric data model thus making this information available for automated analysis. Furthermore, the geometric values can be supplemented by economic values from the ERP systems (Enterprise Resource Planning systems) to consider further decision criteria. In addition to cost data, parameters from the supply chain, such as production lot sizes and replenishment times, also can be considered.

Parametric Selection of Hybrid Parts for Additive Manufacturing

4.3.1 Software supported analysis of geometric data to identify components whose basic bodies have a high degree of conformance

The comparison criteria proposed are the similarity of the volume of the investigated components and the projected area of the component based on normalized coordinate systems. Both criteria are weighted equally in the evaluation. The relative index calculated from this then provides a statement on components with the same or similar basic bodies in terms of percentages. Figure 2 and Figure 3 show the results of such an automated evaluation, which was carried out with the help of the 3D Partfinder. A degree of agreement of at least 99% was selected here, with the application of which many components with matches can already be identified.



The screenshot shows the 3D Partfinder software interface. At the top right, it indicates a 'Similarity rate' of 99%. The main area contains a table with the following columns: Id, Preview, Filename, CAD Format, File size, Modified time, and Likeness rate. The table lists five gear shaft components, with the first one being the 'Original' and the others having high similarity rates (99.32%, 99.18%, 99.11%, and 99.07%). Each row includes a small 3D preview of the gear shaft and search icons (magnifying glass and equals sign).






Id	Preview	Filename	CAD Format	File size	Modified time	Likeness rate
1065		Gear Shaft 01		402 Ko	11-01-2020 09:49:12	Original
1064		Gear Shaft 02		342 Ko	11-01-2020 09:48:36	99.3235810380919
1062		Gear Shaft 03		342 Ko	11-01-2020 09:48:20	99.1841316585223
1056		Gear Shaft 04		337 Ko	11-01-2020 09:50:00	99.1110856299104
1055		Gear Shaft 05		292 Ko	11-01-2020 09:47:34	99.0701958621689

Figure 2: Results of the similarity search (excerpt 1)

Figure 3 shows an excerpt of the analysis showing parts made of bended sheet metal which are in the experience of the authors not producible with a good business case in additive manufacturing because the sheet metal and the manufacturing processes are very cost effective. It quickly becomes apparent that hybrid manufacturing does not promise advantages for all identified components. A differentiation of the identified components with a similarity rate of at least 99% is required regarding the suitability for hybrid manufacturing based on the complexity of the geometry elements.

4.3.2 Software based identification of geometry elements that have a high suitability for additive manufacturing.

To select suitable components, the detected components from the previous analysis were filtered according to geometric complexity indicators. The parametric evaluation of the component complexity is regarded as an indicator for determining whether a geometry element is suitable for additive manufacturing. In combination with the initial analysis, the user is supported in deriving a statement as to whether hybrid manufacturing is advantageous for the part. In the 3D Partfinder, a parametric evaluation of complexity metrics can be mapped for this purpose, as illustrated in Figure 4. The following key figures are suggested by the authors for a complexity evaluation:

- Value of the first quartile of wall thickness data values ordered by size: The lower the value, the more thin-walled areas the component has. This is an indicator of parts with many thin-walled elements. This is beneficial for a variety of 3D printing processes.
- Minimum wall thickness: This serves to exclude components with wall thicknesses that cannot be produced by the respective 3D printing processes available.
- The standard deviation in the wall thickness distribution of a component: The higher the standard deviation, the more different the wall thicknesses are in the component.

Partfinder							Similarity rate: 99%
Id	Preview	Filename	CAD Format	File size	Modified time		Likeness rate
5		Massive_Zone_Hollow.stp	Step	1 Mo	05-10-2018 07:18:14		Original
8		Massive_Zone_Hollow.stp	Step	1 Mo	05-10-2018 07:18:14		100
16		Metal_support.stp	Step	1 Mo	05-10-2018 07:18:14		100
30		PartBody1.stl	STL	5 Mo	14-03-2016 15:24:38		99.3337761174846
31		schwenklagerv5_param_new.CATPart	Catia V5	3 Mo	13-11-2006 09:56:32		99.3229383607324
26		PartBody(2).stl	STL	4 Mo	14-03-2016 15:24:38		99.0698600160891
29		schwenklagerv5_param.CATPart	Catia V5	3 Mo	13-11-2006 10:20:22		99.028901003537

Figure 3: Results of the similarity search (excerpt 2)

Parametric Selection of Hybrid Parts for Additive Manufacturing

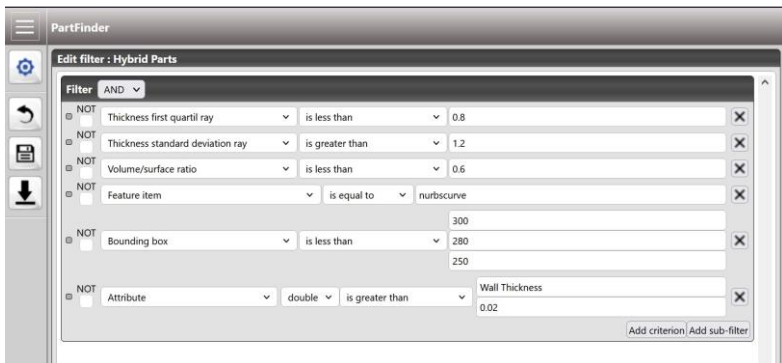


Figure 4: Definition of complexity filter criteria

- The ratio of volume to surface area of the component: A low value is an indicator for filigree or large surface components with low mass (lightweight construction). It should be noted that thin-walled components with a corresponding surface area also have a low value. These are often components with predominantly constant wall thickness, such as sheets, washers, or screws. In combination with a high standard deviation in the wall thickness distribution, such components can easily be excluded.
- Freeform surfaces: The identification of geometrically complex surfaces can be identified by means of design features such as nurbscurves or nurbssurfaces.

The filtering in the example is practically supplemented by the criterion of the bounding box to take into account the maximum installation space of the printer. In this way, components that would not fit into the installation space of the selected systems can be excluded in the search.

Figure 5 exemplary shows the result of the similarity analysis based on geometric complexity indices. Various components were found which, based on a shaft, have different variants of gears regarding their geometry. As a function of a reference component, components were selected from the previous analysis with a similarity rate of at least 99%.

Preview	ID	Filename	CAD Format	Volume	Bounding Box	File size	Surface/Volume	Modified time	Similar parts
	1063	Gear Attache- ment 01		700.98 mm ³	Length: 13.06 mm Width: 11.60 mm Height: 11.46 mm	381 Ko	35.36	11-01-2020 10:48:12	4
	1047	Gear Shaft ABC		771.18 mm ³	Length: 12.95 mm Width: 11.59 mm Height: 11.52 mm	245 Ko	27.18	11-01-2020 10:49:46	3
	1054	Gear Shaft 123		743.49 mm ³	Length: 13.41 mm Width: 11.66 mm Height: 11.29 mm	272 Ko	32.18	11-01-2020 10:47:56	3
	1057	Gear Shaft AZ		707.75 mm ³	Length: 13.34 mm Width: 10.94 mm Height: 10.7 mm	406 Ko	32.91	11-01-2020 10:47:22	1
	1023	Gear Ring		582.76 mm ³	Length: 14.27 mm Width: 13.62 mm Height: 12.85 mm	259 Ko	35.64	11-01-2020 10:33:38	1
	1052	Gear Shaft XYZ		740.67 mm ³	Length: 13.42 mm Width: 12 mm Height: 11.73 mm	295 Ko	32.72	11-01-2020 10:51:02	3

Figure 5: Result of the combined search with the prioritized components

5 Evaluation and Discussion

By qualitatively assessing possible advantages of hybrid manufacturing by combining conventional and additive manufacturing technologies, a typology of parts which might show advantages for hybrid manufacturing was deduced. This typology assumes that a basic body of a part is created by conventional manufacturing methods showing advantages through scale effects and thus the production of a high volume of identical parts. Advantages for additive manufacturing are assumed for the production of complex geometric elements which can be added on the basic body either by directly manufacturing these elements on the body or by separate additive manufacturing and a subsequent assembly of both parts.

Based on the identified advantages of the technologies, parameters were deduced to be used in an automated software based approach to identify parts fulfilling the criteria constituted in the typology. These parameters were subsequently successfully translated in filtering criteria to be used in the software 3DPartFinder in a two-stage approach combining filtering strategies to identify parts with a high congruence and complex differentiating geometric elements. The filter criteria were then used on a sample to create a case study.

Parametric Selection of Hybrid Parts for Additive Manufacturing

Combining both filtering strategies, several groups of components were found, each having an almost identical basic body differentiated by complex geometry elements in the form of gears that differ in positioning and interlocking. It is striking that the identified components are compact in design. The criterion of the ratio of volume to surface area of the component is of limited value for identifying components for hybrid manufacturing in this example. Nevertheless, generic values can be derived from the analysis results that can be used for future evaluations. However, these must always be validated and adapted according to the component spectrum to be analyzed.

The use of the software enables users to reduce the effort of the portfolio analysis by automating the part selection process. However, it will still be necessary to subsequently analyze the identified parts regarding suitability for hybrid manufacturing and its business case.

6 Summary and Conclusion

A method was presented with which component selection for additive manufacturing can be carried out through a software application. An exemplary case study was used to demonstrate the feasibility of the approach. The identification of possible hybrid parts is based on criteria for the selection of suitable components. It should be noted that the identified components usually have to be modified in terms of design for the optimal implementation of a hybrid design. The 3D Partfinder enables the analysis of components with a high degree of similarity and thus a high potential for a possible overlap and unification of the component defined as the basic body. However, it is important to note that the interface between the basic body and the geometry element to be manufactured additively must be defined by the user, who has to break down the originally analyzed component into diverse assemblies.

The developed typology for evaluating the economic suitability of hybrid parts adds to the scientific discussion by systemizing and pointing out possible levers to economically justify hybrid additive manufacturing. The typology thus offers a new field of possible application areas for additive manufacturing. Additionally, it could be shown that selection criteria for additive manufacturing and in this case especially for hybrid

additive manufacturing can be translated for software use and thus for automatically analyzing a part portfolio. The successful application of the software according to the defined goal was demonstrated by a case study.

Limitations of the presented research result from the case study presented being a generic example using CAD data from a pool of standardized components. The applicability of the presented approach and the presented software should be used for further validation in industry using the respective own database of the company. The concrete economic evaluation shows a high dependency on the circumstances in the company and the quantity structure. In addition to testing the approach on a practical example, possibilities should be sought for implementing an automated interface definition between the conventionally manufactured basic body and the additively manufactured geometry element. This would reduce the necessary know-how of the user and the component selection could be further accelerated.

Parametric Selection of Hybrid Parts for Additive Manufacturing

References

- Achillas, C., Aidonis, D., Iakovou, E., Thymianidis, M. and Tzetzis, D., 2015. A methodological framework for the inclusion of modern additive manufacturing into the production portfolio of a focused factory. *Journal of Manufacturing Systems*, 37, pp. 328–339. <http://dx.doi.org/10.1016/j.jmsy.2014.07.014>.
- Bauer, A. and Nolis, P., 2014. Verfahrenskombination von SLM und Gießen ermöglicht wirtschaftliche Herstellung großvolumiger Bauteile. [e-book]. <https://www.ilt.fraunhofer.de/ilt/PM_GenCast_zur_EuroMold_2014>.
- Baumers, M., Dickens, P., Tuck, C. and Hague, R., 2016. The cost of additive manufacturing: machine productivity, economies of scale and technology-push. *Technological Forecasting and Social Change*, 102, pp. 193–201. <http://dx.doi.org/10.1016/j.techfore.2015.02.015>.
- Bharti, I., Gupta, N. and Gupta, K. M., 2013. Novel applications of functionally graded nano, optoelectronic and thermoelectric materials. *International Journal of Materials, Mechanics and Manufacturing*, pp. 221–224. <http://dx.doi.org/10.7763/IJMMM.2013.V1.47>.
- Burkhart, M. and Aurich, J. C., 2017. Bauteilidentifikation in der additiven Fertigung: Kriterien zur Identifikation geeigneter Bauteile für das Selective Laser Melting-Verfahren. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 112(1-2), pp. 37–40.
- Bustos, B., Keim, D. A., Saupe, D., Schreck, T. and Vranic, D. v., 2005. Feature-based similarity search in 3D object databases. *ACM Computing Surveys*, (37), pp. 345–387.
- Caviezel, C., Grünwald, R., Ehrenberg-Silies, S., Kind, S., Jetzke, T. and Bovenschulte, M., 2017. Additive Fertigungsverfahren (3D-Druck): Innovationsanalyse. Berlin. <<https://www.tab-beim-bundestag.de/de/pdf/publikationen/berichte/TAB-Arbeitsbericht-ab175.pdf>> [Accessed 22 February 2019].
- Conner, B. P., Manogharan, G. P., Martof, A. N., Rodomsky, L. M., Rodomsky, C. M., Jordan, D. C. and Limperos, J. W., 2014. Making sense of 3D printing: Creating a map of additive manufacturing products and services. *Additive Manufacturing*, 1-4, pp. 64–76. <http://dx.doi.org/10.1016/j.addma.2014.08.005>.

- Ding, B., 2014. 3D CAD model representation and retrieval based on hierarchical graph. *Journal of Software*, 9(10). <http://dx.doi.org/10.4304/jsw.9.10.2499-2506>.
- enter2net, 2021. 3D Partfinder. [online] Available at: https://www.enter2net.com/3d_partfinder_en/ [Accessed 15 July 2021].
- Eschner, N., Kopf, R., Lieneke, T., Künneke, T., Berger, D., Häfner, B., Lanza, G. and Zimmer, D., 2017. Kombination etablierter und additiver Fertigung. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, (7-8), pp. 469–472. <http://dx.doi.org/10.3139/104.111751>.
- Feldmann, C. and Pumpe, A., 2017. A holistic decision framework for 3D printing investments in global supply chains. *Transportation Research Procedia*, 25, pp. 677–694. <http://dx.doi.org/10.1016/j.trpro.2017.05.451>.
- Fiedler, A., 2018. Ein Verfahren zur Teileauswahl für den 3D-Druck. Merseburg. https://www.hs-merseburg.de/fileadmin/Hochschule_Merseburg/Hochschule/Fachbereiche/Wirtschaftswissenschaften_und_Informationswissenschaften/3D%40KMU/3D_at_KMU_Arbeitsbericht_14_Teileauswahl.pdf [Accessed 12 May 2019].
- Fontana, F., Klahn, C. and Meboldt, M., 2019. Value-driven clustering of industrial additive manufacturing applications. *Journal of Manufacturing Technology Management*, 30(2), pp. 366–390. <http://dx.doi.org/10.1108/JMTM-06-2018-0167>.
- Gebhardt, A., 2016. Additive Fertigungsverfahren: Additive manufacturing und 3D-Drucken für Prototyping - Tooling - Produktion. 5th ed. München: Hanser.
- Gibson, I., Rosen, D. and Stucker, B., 2015. Additive manufacturing technologies. New York: Springer.
- Grand View Research, 2021. 3D printing market size worth \$62.79 billion by 2028: CAGR: 21%. [online] Available at: <https://www.grandviewresearch.com/press-release/global-3d-printing-market> [Accessed 17 July 2021].
- Große-Heitmeyer, V. and Wiendahl, H.-P., 2004. Einführung. In: H.-P. Wiendahl, D. Gerst, and L. Keunecke, eds. 2004. Variantenbeherrschung in der Montage. Berlin, Heidelberg: Springer, pp. 3–17.

Parametric Selection of Hybrid Parts for Additive Manufacturing

- Hague, R., 2006. Unlocking the design potential of rapid manufacturing. In: N. Hopkinson, R. Hague, and P. Dickens, eds. 2006. Rapid manufacturing. An industrial revolution for the digital age. Chichester: John Wiley, pp. 5–18.
- Illgner, M., Lutter-Günther, M. and Seidel, C., 2018. Potenziale additiver Verfahren systematisch bewerten und in Produkte umsetzen. *wt Werkstattstechnik online*, 108(6), pp. 426–428.
- Klahn, C., Leutenecker, B. and Meboldt, M., 2014. Design for additive manufacturing: supporting the substitution of components in series products. *Procedia CIRP*, 21, pp. 138–143. <http://dx.doi.org/10.1016/j.procir.2014.03.145>.
- Klahn, C., Meboldt, M., Fontana, F., Leutenecker-Twelsiek, B. and Jansen, J., 2018. *Entwicklung und Konstruktion für die Additive Fertigung: Grundlagen und Methoden für den Einsatz in industriellen Endkundenprodukten*. Würzburg: Vogel Business Media.
- Klocke, F., 2015. *Fertigungsverfahren 5: Gießen, Pulvermetallurgie, Additive Manufacturing*. 4th ed. Berlin, Heidelberg: Springer.
- Knofius, N., van der Heijden, M. C. and Zijm, W., 2016. Selecting parts for additive manufacturing in service logistics. *Journal of Manufacturing Technology Management*, 27(7), pp. 915–931. <http://dx.doi.org/10.1108/JMTM-02-2016-0025>.
- Kumke, M., 2018. *Methodisches Konstruieren von additiv gefertigten Bauteilen*. Wiesbaden: Springer.
- Kushnarenko, O. M., 2009. *Entscheidungsmethodik zur Anwendung generativer Verfahren für die Herstellung metallischer Endprodukte*. Dissertation. Aachen: Shaker.
- Lakomicz, M., 2016. *Wirtschaftliche und technische Bewertung additiv hergestellter Triebwerkskomponenten für die Serienfertigung*. Dissertation. Aachen: Shaker.
- Leuteritz, G., Demminger, C., Maier, H.-J. and Lachmayer, R., 2018. Hybride Additive Fertigung: Ansätze zur Kombination von additiven und gießtechnischen Fertigungsverfahren für die Serienfertigung. In: R. Lachmayer, R. B. Lippert, and

- S. Kaierle, eds. 2018. *Additive Serienfertigung*. Berlin, Heidelberg: Springer, pp. 115–126.
- Ley, M., Buschhorn, N., Stephan, N., Teutsch, R., Deschner, C. and Bleckmann, M., 2018. Hybrid-optimierte Fertigung von tragenden Bauteilen durch Kombination konventioneller und additiver Fertigungsverfahren. In: K. Berns, K. Dressler, P. Fleischmann, D. Görges, R. Kalmar, B. Sauer, N. Stephan, R. Teutsch, and M. Thul, eds. 2018. *Commercial Vehicle Technology 2018*. Wiesbaden: Springer, pp. 215–232.
- Lutter-Günther, M., Seidel, C., Kamps, T. and Reinhart, G., 2015. Implementation of additive manufacturing business models. *Applied Mechanics and Materials*, 794, pp. 547–554. <http://dx.doi.org/10.4028/www.scientific.net/AMM.794.547>.
- Materialise, 2019. 3D Print Barometer. [online] Available at: <http://3dprintbarometer.com/> [Accessed 3 January 2020].
- Mavri, M., 2015. Redesigning a production chain based on 3D printing technology. *Knowledge and Process Management*, 22(3), pp. 141–147. <http://dx.doi.org/10.1002/kpm.1466>.
- Möhrle, M., 2018. *Gestaltung von Fabrikstrukturen für die additive Fertigung*. Berlin, Heidelberg: Springer.
- Oettel, M., Fluegel, S., Polenz, S., Kleine, A., Gebauer, M. and Müller, B., 2019. Additiv-Guss ein neuartiger Hybridansatz für automobiler Anwendungen: Additive-casting a novel hybrid approach for automotive application. In: M. Kynast, M. Eichmann, and G. Witt, eds. 2019. *Rapid.Tech + FabCon 3.D*. München: Hanser, pp. 34–48.
- Roj, R., 2016. Eine Methode für eine automatisierte Informationsextraktion aus großen CAD-Datenbeständen zur Bauteilsuche und Klassifikation. Dissertation. Bergische Universität Wuppertal.
- Roj, R., 2019. KI-basierte Herstellung von Hybridbauteilen aus konventionellen und LBM-gefertigten Segmenten. Remscheid.
- Rudolph, J.-P., Solbach, A. and Emmelmann, C., 2017. Automatisierte Bauteilsichtung und -selektion für die Luftfahrtindustrie: Automated Part Screening for

Parametric Selection of Hybrid Parts for Additive Manufacturing

- Aerospace Industry. In: M. Kynast, G. Witt, and M. Eichmann. Rapid.Tech. München: Hanser, pp. 481–494.
- Scheithauer, U., Schwarzer, E., Günther, P., Ahlhelm, M., Gradmann, R., Pohl, H.-J., Moritz, T. and Michaelis, A., 2017. Herstellung von funktionellen, hybriden keramik-basierten Komponenten durch Kombination additiver und konventioneller Fertigungsverfahren: Additive manufacturing of ceramic-based multi-functional components. In: M. Kynast, G. Witt, and M. Eichmann. Rapid.Tech. München: Hanser, pp. 497–511.
- Schmidt, T., 2016. Potentialbewertung generativer Fertigungsverfahren für Leichtbauteile. Berlin: Springer.
- Scott, A. and Harrison, T. P., 2015. Additive Manufacturing in an End-to-End Supply Chain Setting. 3D Printing and Additive Manufacturing, 2(2), pp. 65–77. <http://dx.doi.org/10.1089/3dp.2015.0005>.
- Silva, M., Felismina, R., Mateus, A., Parreira, P. and Malça, C., 2017. Application of a hybrid additive manufacturing methodology to produce a metal/polymer customized dental implant. Procedia Manufacturing, 12, pp. 150–155. <http://dx.doi.org/10.1016/j.promfg.2017.08.019>.
- Strategy&, 2018. Marktvolumen für gedruckte Produkte steigt bis 2030 auf 22,6 Milliarden Euro). <<https://www.strategyand.pwc.com/de/de/presse/2018/3d-druck.html>> [Accessed 17 July 2021].
- Thomas, D., 2016. Costs, benefits, and adoption of additive manufacturing: A supply chain perspective. The International Journal of Advanced Manufacturing Technology, 85(5-8), pp. 1857–1876. <http://dx.doi.org/10.1007/s00170-015-7973-6>.
- Uhlmann, E. and Kashevko, V., 2017. Untersuchungen zur Herstellung hybrider Werkstoffverbände mittels Laserstrahlschmelzen am Beispiel der Kupferlegierung CuCr1Zr (2.1293) und Stahl (1.2344): Investigations on the fabrication of hybrid material combination copper ally CuCr1Zr (2.1293) and tool steel (1.2344) using selective laser melting. In: M. Kynast, G. Witt, and M. Eichmann. Rapid.Tech. München: Hanser, pp. 363–376.
- Verein Deutscher Ingenieure, 2014. VDI-Richtlinie 3405. Additive manufacturing processes. Berlin: Beuth.

- Waltl, H. and Wildemann, H., 2014. Der Modulare Produktionsbaukasten: Teil 1. PRODUCTIVITY Management, 19(4).
- Waltl, H. and Wildemann, H., 2015. Modularisierung der Produktion in der Automobilindustrie. 2nd ed. München: TCW-Verlag.
- Wildemann, H., 2014. Modularisierung: Die DNA des Erfolgs. PRODUCTIVITY Management, 19(3), pp. 57–59.
- Wildemann, H., 2016. Modularisierung 4.0: Leitfaden zur modularen Gestaltung von Organisation, Produkten, Produktion und Services. 4th ed. München: TCW-Verlag.
- Wildemann, H., 2019. 3D-Metalldruck: Wertschöpfungskette - Teileauswahl - Industrialisierung - Wirtschaftlichkeit - Einführungsstrategien. München: TCW-Verlag.
- Wildemann, H., 2021. Implementation of Additive Manufacturing Processes / 3D Printing: Part selection, profitability calculation, investment, factory and personnel planning. 3rd ed. München: TCW-Verlag.
- Wohlers, T. T., 2018. Wohlers Report: 3d printing and additive manufacturing state of the industry. Fort Collins: Wohlers Associates.
- Yao, X., Moon, S. K., Bi, G. and Wei, J., 2018. A multi-material part design framework in additive manufacturing. The International Journal of Advanced Manufacturing Technology, 99(9-12), pp. 2111–2119. <http://dx.doi.org/10.1007/s00170-018-2025-7>.
- Zhiyuan Xu, A., Bo Chen, B., Caiwang Tan, C. and Jicai Feng, D., 2019. Inconel625/316L functionally graded material using spectral diagnostics during laser additive manufacturing process. Journal of Laser Applications, 31(2), p. 22001–22001.