

AN ALGORITHM-BASED METHOD FOR PROCESS-SPECIFIC THREE-DIMENSIONAL NESTING FOR ADDITIVE MANUFACTURING PROCESSES

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Abstract

To achieve optimal and high-quality results through additive manufacturing, the process- and technology-specific orientation and positioning of components within the virtual space, the so-called nesting, is essential. Primarily the nesting step is examined in this paper. From a scientific perspective it is a matter of examining this process and furthermore to analyze the optimal insertion of supporting structures, since the critical machine-specific parameters have been insufficiently studied. Within this paper a new multi-criteria optimization based on a conceptual algorithm is proposed. The most important point is the consideration of a technical and not only geometric nesting process. The objective is the demonstration of restrictions and boundary conditions and a first developing for a new approach for the nesting process. As an example, the influence of the orientation of the spring rate is presented with a sample component here. Furthermore, there will be a prototype implementation and a short validation. Finally, a brief conclusion and an outlook is given.

Introduction

Additive manufacturing processes imply considerable advantages compared to conventional processes. The technological development enables manufacturing of simple prototypes, small batches, and individual products. Due to the renunciation of formative tools and material-intensive subtractive machining methods, costs can be lowered, while more particularly the additive manufacturing process chain can be shortened significantly, accelerating the process. Real models and prototypes can be manufactured straight on the base of digital 3D CAD models. Thus, rapid manufacturing or the use of rapid prototyping, which takes advantage of the direct linkage to the CAD-interface, benefit the product development process.

The additive manufacturing process chain characterizes the essential steps of the product development. The essential steps of the process chain are the preparation of the building process, the manufacturing of the physical model itself, followed by the post-processing and finally the use of the product. According to [Gib10], the process chain can be categorized into eight different steps, as can be seen in Figure 1. The first process step comprises the creation of the 3D CAD model, which contains all necessary geometric data regarding the constructing guidelines. The creation of the CAD model is followed by the conversion into a STL (Standard Tessellation Language) data format by triangulation. This step is a de facto industry standard. Given the STL data format, within the next step the parameters size, position and orientation of components are defined, the so-called nesting. Additionally, if needed, support structures are determined and generated, and a sliced model is passed on to the manufacturing machine. For the manufacturing, further steps as the choice of material are necessary. After the manufacturing, the last three steps

of the additive manufacturing process chain consist of the withdrawal of the product, the possible post-processing, and the utilization of the product.

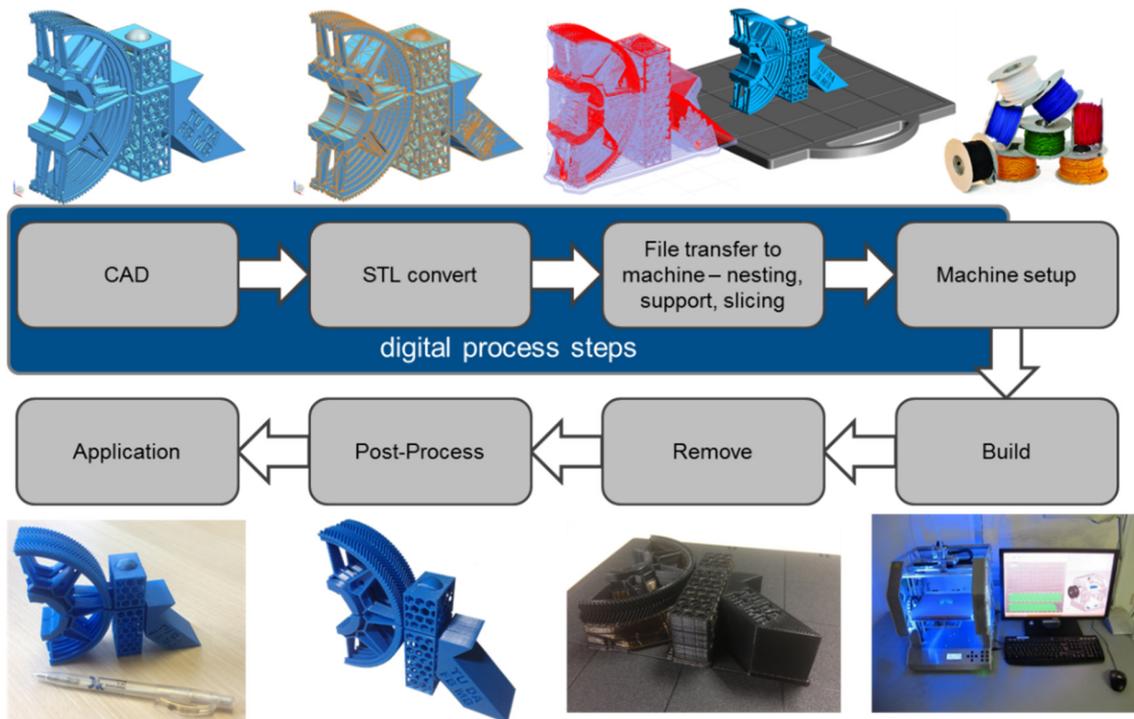


Figure 1: Process chain additive manufacturing. Adapted from [Gib10]

Motivation

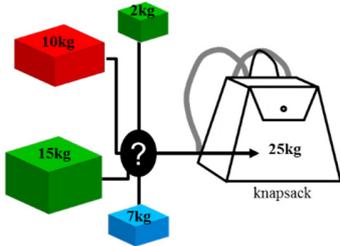
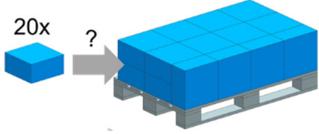
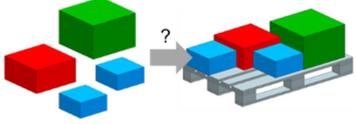
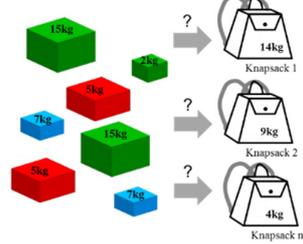
Prerequisite for an economically feasible utilization of any additive manufacturing process is a best possible preparation of the process. The process- and technology-specific orientation and positioning of components within the virtual space is essential in order to achieve optimal and high-quality results through additive manufacturing. From a scientific perspective this process still has potential to be analyzed and examined to achieve optimal solutions by using a conceptual algorithm. With an optimal nesting, which consists of the positioning and orientation of components, negative effects as the staircase effect, curling, surface roughness or component accuracy can be enhanced significantly.

State of the Art

As current research shows, the nesting process and the filling of the manufacturing work space can be categorized into different bin packing problems. The classification by Dyckhoff [Dyc90] is used for the identification of the arrangement and categorizes the dimension, the distribution, the room assortment, and the range of goods. All problems are NP-complete (non-deterministic polynomial-time-complete) and can be approximated with genetic algorithms. As Table 1 gives an overview, the main bin packing problems are the knapsack problem, the container loading problem, the pallet loading problem, and the general cutting stock problem. All algorithms

attempt an optimal filling of the virtual space based on the geometric data, packing density and the orientation of the components.

Table 1: Overview of the main bin packing problems

Packing problem	Description	Figure
Knapsack problem	The knapsack problem can be illustrated visually with the optimum filling of a knapsack. The knapsack has a limited volume and every object which is to be packed has a specific volume and value, e.g. the weight. The aim of optimization should be to load the knapsack with the maximum weight but without exceeding the volume of the knapsack with the sum of the object volumes. [Wäs07]	
pallet loading problem	If rectangular block objects of the same size are given and to be placed on a rectangular base while achieving the maximum number of objects accommodated without exceeding the maximum, one speaks of pallet loading problem. [Sch08b]	
container loading problem	The container loading problem can be illustrated visually by packing a container with rectangular block objects. Compared to the pallet loading problem, the objects have different dimensions. [Sch08b]	
cutting stock problem	The cutting stock problem can be presented pictorially. There is a defined number of objects with defined volumes available to be distributed to as few knapsacks as possible. The knapsacks have a maximum capacity. [Sch08b]	

First research specifically for additive manufacturing was done by Corcoran [Cor92]. With a 3D Next Fit Algorithm and a 3D First Fit Algorithm cuboids are placed into a virtual space. An advanced algorithm was applied by Ikonen [Iko97] to place nonconvex, three-dimensional figures with cavities in a virtual space. It was optimized for selective laser sintering. The component cavities are used for positioning but component penetration has to be eliminated manually and the

influence of orientation on the component quality is disregarded. Hence, Lutters, Dam and Faneker used the “brazil nut”-effect to simulate three-dimensional nesting of complex figures [Lut12]. Based on the criteria “Preferred Nesting Orientation” and “Preferred Quality Orientation” it is possible to exclude component penetration, but optimal utilization of the virtual space cannot be reached and cavities are not used. For stereolithography an efficient nesting was developed by Canellidis [Can13]. The component positioning is done two-dimensionally due to the negative effect of stacking in the stereolithography process. The component orientation is assumed to be ideal and therefore, not changed during the packing. To determine the packing, different deterministic approaches as the Left-Bottom/Down-Bottom and the No-Fit Polygon are considered.

However, in all algorithms solely geometric parameters are considered which are not machinery-specific yet utilization-oriented. Hence, an analysis in its entirety with all manufacturing and component restrictions is necessary, see also Figure 2. The current geometric STL data format is irreversibly faceted as a result of the staircase effect, surface roughness and other effects when transforming and approximating the CAD data. To achieve optimal nesting which is not only based on geometric data, but also considers further process parameters, a new data format and nesting process has to be developed. Ideally, a consistent, general data format which processes geometric and orientation data as the STL format [Arn14], additionally considers and gathers information concerning the material properties, endurance strength of the material based on the chosen orientation in the nesting process and post-processing. A consistent information and data management enables an optimal nesting process, but also optimal component quality, support and economic viability. In the first step, the STL format will be further used and build on the nesting investigated. With a multi-criterial optimization of the process, an algorithm processing all the different information and boundary conditions has to be developed.

Boundary Conditions and Restrictions

The nesting process has a significant influence on the additive manufacturing process as well as on the final product. Therefore, it has to be well considered when establishing a consistent information and data management with information additionally concerning the material and the manufacturing process. Boundary conditions and restrictions concerning the geometry are explained in the following, but in order to accumulate restrictions in its entirety, boundary conditions concerning the manufacturing process have to be considered furthermore. The aim is to achieve a technological- and process-specific nesting process rather than just the common geometrical nesting.

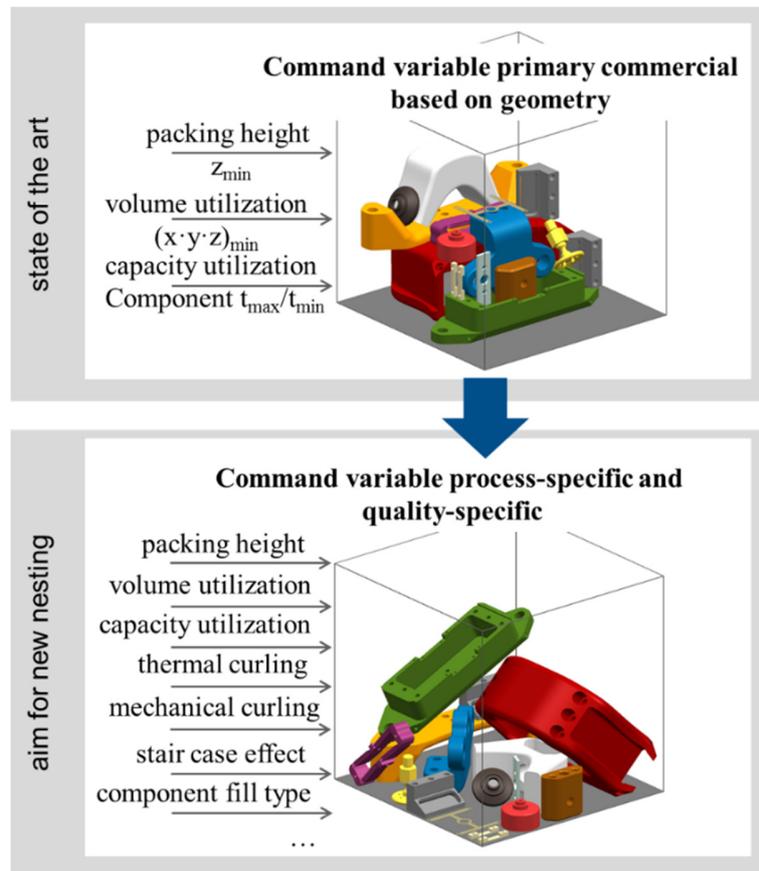


Figure 2: geometrical nesting vs. process-specific nesting

All additively manufactured components use a construction based on successive layers of material. After the slicing process of the STL data, the component is manufactured. The resulting difference in the contour of the single layers is the so-called staircase effect. The effect depends on the density, the surface angle of the mounting direction and influences the surface finish as well as the fidelity of transformation. The thinner the layers and the higher the number of layers, the higher the quality of the surface and the smaller the staircase effect [Bre13]. These positive factors are in contrast to the process time and therefore, the cost of the process. Another factor influencing the cost is the use of support structures. Some processes need additional support structures to fix the manufactured component in place. Support structures require elaborate post-processing as the depletion of the additional support material and surface finishing [Gur14]. According to [Mar11], it is additionally important to control the temperature gradient during the manufacturing process in order to avoid curling and negative effects on the mechanical properties. Temperature gradients may lead to a reduction of the surface quality and therefore, are to be avoided. Nevertheless, an advantage of the additive manufacturing process are the scarcely restrictions concerning the manufacturable geometries of the components [Ver14]. Indentation and cavities are producible, which enhance the ability of an optimal packing of the virtual space.

The influence of the nesting on the final product can be categorized into the resulting strength of the material, the surface quality, the curling and the wall thickness [Weg12]. An anisotropy in the mechanical behavior and a lowered ultimate tensile strength of the component always result depending on the orientation and positioning of the component. Kirchner [Kir10]

tested different tensile samples in terms of ultimate tensile strength and ultimate strain with results pending $\pm 25\%$ around the average. Best results in terms of tensile strength could be accomplished with a horizontal manufactured component, which achieves twice the ultimate tensile strength compared to vertical manufactured samples according to Schäfer [Sch08a]. Research still needs to be done to integrate the strength into a genetic algorithm in order to regard the mechanical behavior already during the nesting process. As mentioned earlier, the surface finish also depends on the positioning and orientation of the manufactured component. Depending on the depletion of support material and the staircase effect, the roughness average and roughness depth differs significantly with $200\mu\text{m}$ according to [Sch08a]. Aftertreatment can improve the surface finish, but is always linked to a deviation of the geometry.

Figure 3 gives an overview of the interactions between nesting-dependent component and process characteristics. For this paper, these rudimentary descriptions should suffice. Since the physics of each process are so complex and different only worked with assumptions is below. For a detailed description of the physical quantities and effects, reference is made to the relevant literature.

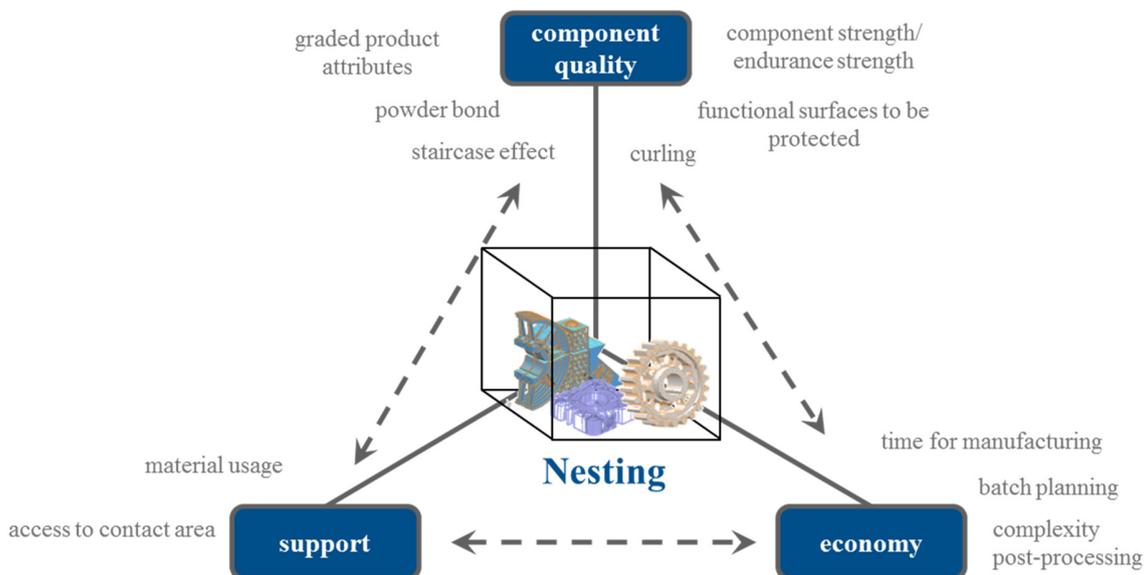


Figure 3: Interactions between a nesting-dependent component and process characteristics. Adapted from [Dan10]

Based on the shown packing problems and the boundary conditions and restrictions, a process-specific three-dimensional nesting for additive manufacturing processes is derived in the following conceptual design.

Concept

As it can be seen in Figure 2, the nesting is to be conducted with regard to technological- and process-specific characteristics. With respect to the preceded research, the state of the art, and the requirements for the manufacturing, the following requirements for the concept of the process-specific three-dimensional nesting have to be fulfilled. Simultaneously, an objective function has to be defined.

The optimization is divided into two individual optimizations with its own genetic algorithm, as can be seen in Figure 4. In the orientation optimization a limited number of optimal

x-y-orientations is determined for the components (STL files). Each of these x-y-orientations is then rotated in x-steps around the z-axis. In every step, a voxel is generated. In this voxel, the part geometry, the orientation and the distance between components to be observed is displayed. In a second optimization step, the optimization of the component positioning, the voxel is to be placed inside the virtual space then tried by each component.

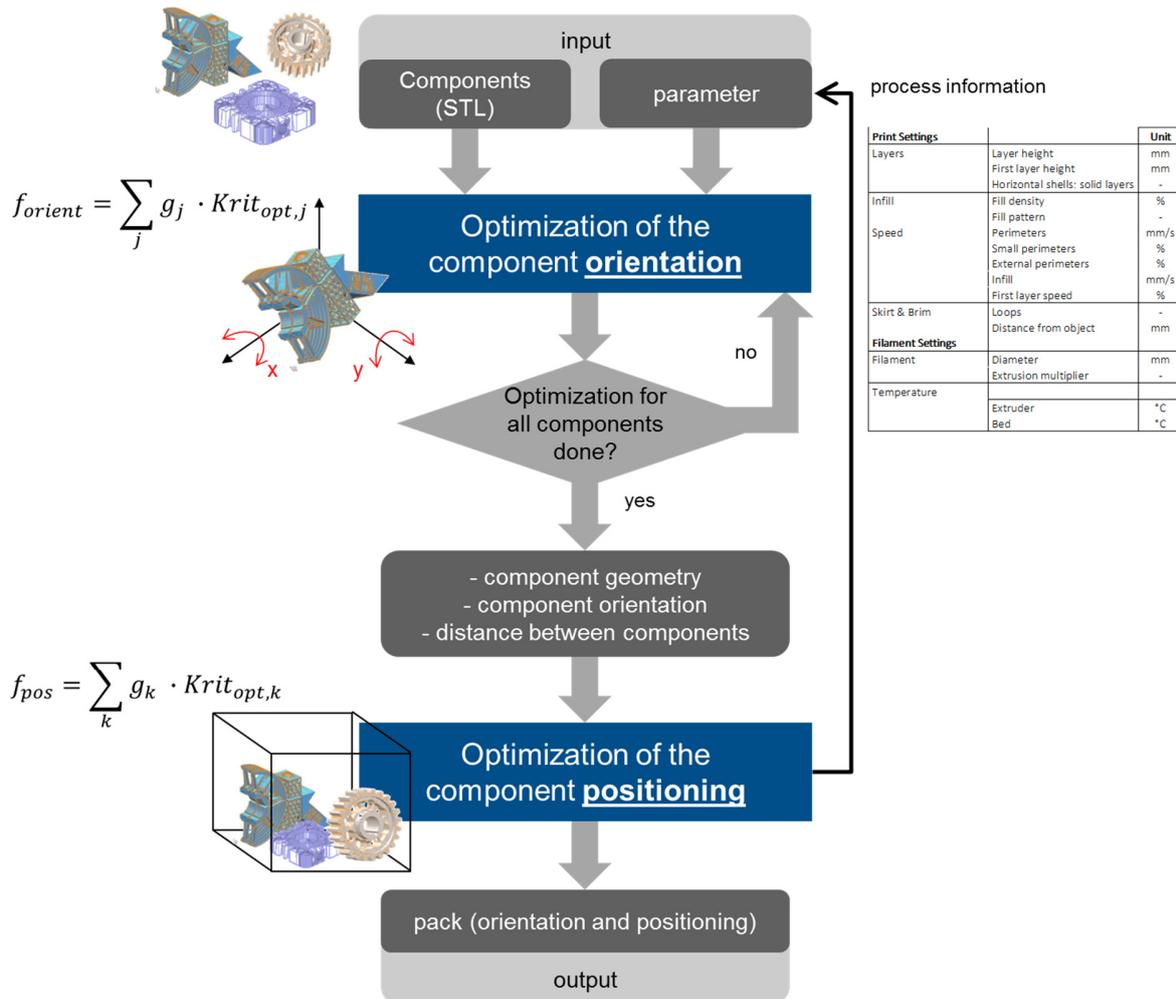


Figure 4: algorithm of optimization

Optimization of the component orientation

The orientation of the component in the virtual space in relation to the orientation of the manufacturing is essential for the processing of the component and has a significant influence on the achievable manufacturing quality and the characteristics of the manufactured component. In general, it is necessary to consider the geometric target variables as the optimal packing height, the volume utilization, as well as the capacity utilization. Additionally, for the process-specific nesting, the curling effect should not be neglected and has to be implemented into the packing-algorithm. The effect is solely referring to shape deviation and can be categorized in four ways in terms of the additive manufacturing process, which implements a machinery-specific consideration: thermal curling, mechanical curling, the staircase effect, and component and endurance strength.

Based on this knowledge, the curling effects are used as optimization criterions for the objective function f_{orient} of the orientation, see equation (1). The objective function is defined as a linear combination of the weighting factor g_i with the respective optimization criteria $Krit_{opt,i}$:

$$f_{orient} = \sum_j g_j \cdot Krit_{opt,j} = g_{sce} \cdot Krit_{opt,sce} + g_{tc} \cdot Krit_{opt,tc} + g_{mc} \cdot Krit_{opt,mc} + g_{cs} \cdot Krit_{opt,cs} \quad (1)$$

The optimization criteria $Krit_{opt,sce}$ considers the staircase effect, while the criteria $Krit_{opt,tc}$ considers the thermal curling. $Krit_{opt,mc}$ accounts for the mechanical curling. The criteria $Krit_{opt,cs}$ considers the component and endurance strength. The weighting factors g_j depend on the type of additive manufacturing process and are edited manually.

The specific value of the staircase effect is represented by the sum of the resulting area of the error triangles. These triangles can be computed by the stretched area between two corners representing the reference point in the voxel grid and the inner corner. For better comparison, the sum of the triangles is presented in relation to the overall volume of the component's voxel grid. Even though the computed area of the error triangles can differ slightly from the actual error, this computation seemed to achieve reasonable estimations in first evaluations. The smaller the result of criteria $Krit_{opt,sce}$ more better optimization exists. This also applies to the following criteria.

In processes that produce material bond thermally or by means of photopolymerization, may lead to thermal curling due to the heat input. The optimization criteria $Krit_{opt,tc}$ for the thermal curling resulting from temperature gradients is not fully understood yet and therefore, is based on empirical values according to [Dan10]. Since the heat input with the exposed surface contour of a layer is related to the area can use to detect the effect, see [Dan10].

The curling effect, called mechanical curling, as a result of additive manufacturing processes using a bed of powder, is represented by the factor $Krit_{opt,mc}$. The bigger the cross section of the first manufactured layer and the more weight is put on it, the bigger the effect will be. Since all layers are based on the bottom layer, the mechanical curling increases over the height of the structure, influencing the shape deviation. Hence, the criteria $Krit_{opt,mc}$ is the area of the cross section in the orientation relative to the volume of the component.

Furthermore the component and endurance strength is contained with acceptance of conditions in the objective function. Here is an example to explain the spring rate k . Tests have shown that different spring rates in different orientations were present, see Figure 5. For this, samples were manufactured by Fused Deposition Modeling and subjected tension-pressure-experiments. This experiments have shown, if the component is manufactured lying, the spring rate higher ($k=2,18\text{N/mm}$) than the standing component ($k=1,23\text{N/mm}$). This physical effect is due to the anisotropy of the material or component. These scientific findings are integrated as constant values in the objective function f_{orient} . The minimization of the objective function is carried out to the optimum of the highest possible spring rates. The higher the spring rate, the lower the optimization criteria $Krit_{opt,cs}$.

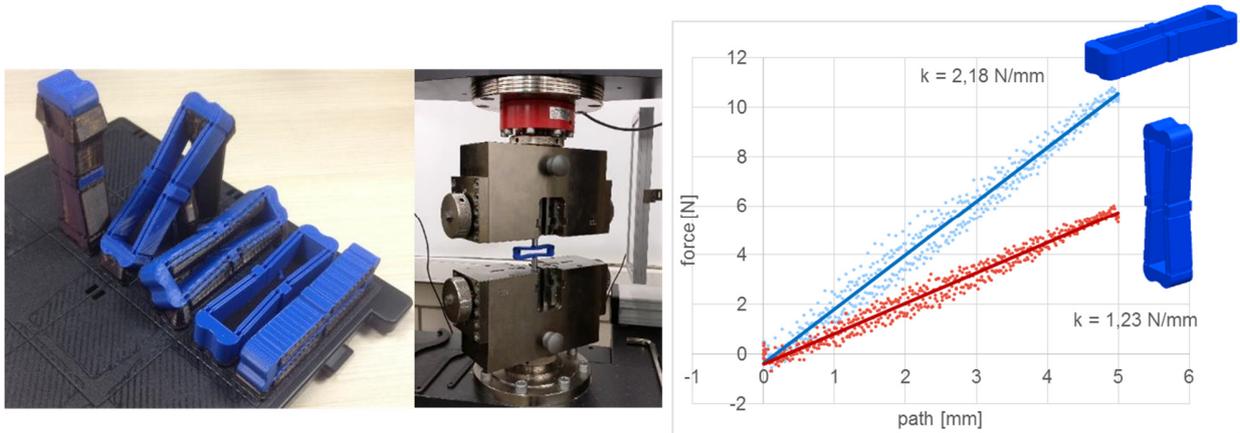


Figure 5: Influence of the orientation of the spring rate (left: example components, middle: test preparation, right: diagram with results for spring rates)

Optimization of the component positioning

As described previously, not only the orientation but also the positioning of the components in the virtual space can have a significant effect on the manufacturing process and the component's quality. The better placed, the less time will be needed to manufacture it and therefore, the more economically feasible it will be. The nesting and therefore, packing depends on various factors, as the number of components $Krit_{opt,nc}$, the compactness $Krit_{opt,cmpt}$, the volume utilization $Krit_{opt,vol}$, the packing height $Krit_{opt,ph}$, the relation of the positions $Krit_{opt,pos}$, and the component orientation $Krit_{opt,orient}$. Analog to the optimization of the component orientation, the optimization of the position is derived with an objective function:

$$f_{pos} = \sum_k g_k \cdot Krit_{opt,k} = g_{nc} \cdot (1 - Krit_{opt,nc}) + g_{cmpt} \cdot (1 - Krit_{opt,cmpt}) + g_{vol} \cdot (1 - Krit_{opt,vol}) + g_{ph} \cdot Krit_{opt,ph} + g_{pos} \cdot Krit_{opt,pos} + g_{orient} \cdot Krit_{opt,orient} \quad (2)$$

The genetic algorithm optimizes the positioning and nesting by minimizing the objective function f_{pos} . The number of components solely indicates how many components can be manufactured in one process and therefore, are a measure for the number of client's order can be accomplished ($Krit_{opt,nc}$). This criteria is calculated by dividing the components housed in the pack and all components to be manufactured. This result is always less than or equal to 1, therefore, it is withdrawn in the objective function of 1 ($1 - Krit_{opt,nc}$). The greater is the result of this division, the better is the optimization result.

Representing the packing height, the factor $Krit_{opt,ph}$ gives an approximation of the needed process time, which depends significantly on the number of layers and is proportional to the packing height. Based on the result, the packing height is derived, which then in relation to the total height of virtual space computes the optimization criteria $Krit_{opt,ph}$. The smaller the result of the division (packing height / space height), the better the optimization result.

The criteria $Krit_{opt,vol}$ quantifies the utilization of the space. For this, the approximate total volume of all packaging components shall be calculated on the space volume. Here also any space boundaries are considered. The result of this criteria is always less than or equal to 1. The optimum is also a great result for $Krit_{opt,vol}$.

Unlike the utilization of the virtual space, the criteria for the compactness of the nesting additionally considers the known packing height ($Krit_{opt,compact}$). The compactness of the approximate packing volume on the resulting volume of space area multiplied by the packing height. The criteria $Krit_{opt,compact}$ is thus a measure of the time efficiency of the manufacturing process and the result is always less than or equal to 1, therefore, it is withdrawn in the objective function of 1 ($1 - Krit_{opt,compact}$). The final criteria $Krit_{opt,orient}$ represents the average of the result of an algorithm for the orientation of the components in the virtual space. With this factor in the genetic algorithm, the quality of the component can be considered. In combination with the objective function of the optimization of the orientation and the number of components, the overall measure of the orientation can be computed.

Both objective functions f_{orient} and f_{pos} are minimised in the course of the implementation about the genetic algorithm. The thus determined optimum represents a compromise between the individual targets according to the weights g_j and g_k .

Prototype Implementation and Validation

Based on the shown concept a short overview of a prototype implementation is given. The prototype implementation is done using Matlab, see also [Fri214]. These are the subsystems implemented optimizations of the component orientation, optimization of the component positioning, and the user interface. The visualization of the program flow is shown in Figure 6. First, the STL files are loaded into the implementation (step 1). In the next step, the optimal x- and y-orientations are calculated by means of the genetic algorithm (step 2). Thereafter, the components about the z-axis are rotated and the optimum distances are calculated (step 3). This is done for all loaded STL files in the implementation. The calculation are then followed by the start of the optimization of the positioning of the components (step 4). When the optimization is completed, the best package is visualized. The result is the nesting as an STL file. Then support generating and the slicing can occur.

In the steps of the optimization of the orientation and the positioning come genetic algorithms used. The sequence of these algorithms is to look in the Figure 6 above right. For a better understanding now a digression on the subject genetic algorithm. In a genetic optimization a solution candidate is called individual. In analogy to biology is called an amount of solution candidates population. The genetic algorithm developed a population using evolutionary operators (recombination and mutation). This period is so long until a termination condition is met. The fittest individuals survive or form the basis for new individuals (selection). The fitness is determined by an objective function. For detailed information about genetic algorithms see specialist literature.

The optimization of the component orientation is divided here into two parts. Both parts, the x-y-orientation and the z-orientation work with the genetic algorithm. After loading the STL Files and the input of the parameters starts the optimization. Here the objective function on the genetic algorithm is minimized. By means of selection, recombination and mutation are found the fittest orientations for the respective components. If a predetermined termination condition is satisfied, the algorithm is terminated, this is not met further optimized, see also Figure 6 the upper right corner. If all components are optimally orientated start the optimizing of the positioning. Analogously to the first optimization a genetic algorithm is used here also. Here are necessary as input the file paths of the components as well as the results from the first optimization. Result is an array that contains all analyzed in the course of evolution component packages with associated indicative criteria, objective function values and matrices. About a function, the position

coordinates and the angle of orientation of the components are issued. Based on this data an STL file is created, which visualizes the optimized pack.

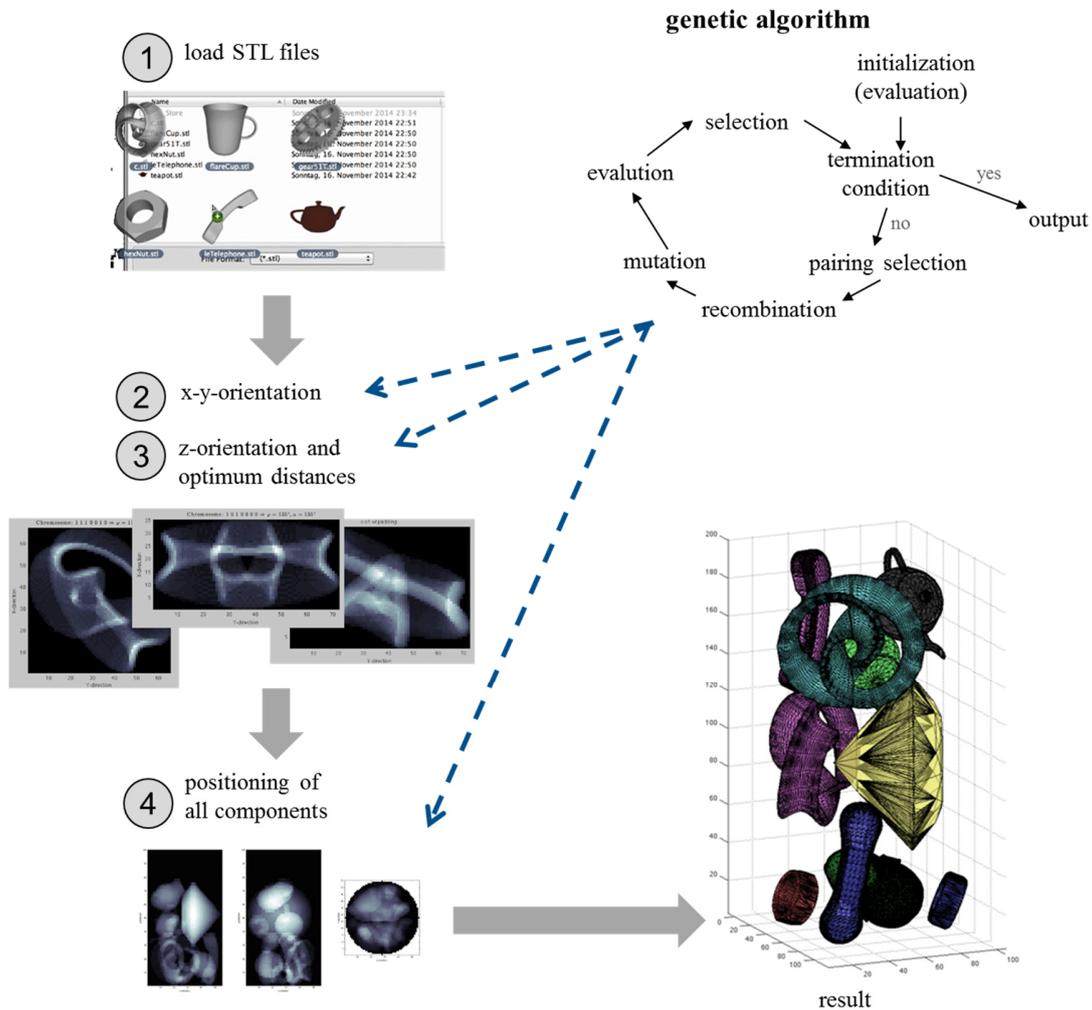


Figure 6: prototype implementation - programm flow. Adapted from [Fri14]

To validate serves the example of optimizing of the component positioning .To check the package optimization for plausibility the results of isolated optimization processes are considered and compared to individual target criteria. For example: in a cylindrical space twelve parts should be packed. However, this can not be all housed together due to their geometry. The algorithm should now solve succession with four different objectives, the packing problem.

1. As many parts to accommodate ($Krit_{opt,nc}$)
2. As compact pack ($Krit_{opt,cmpct}$)
3. As much of the total volume of the building space used ($Krit_{opt,vol}$)
4. The packing height minimize ($Krit_{opt,ph}$)

The weighting factors of the remaining optimization criteria have been set in this validation to zero. Figure 7 shows the visualization of the four different objectives.

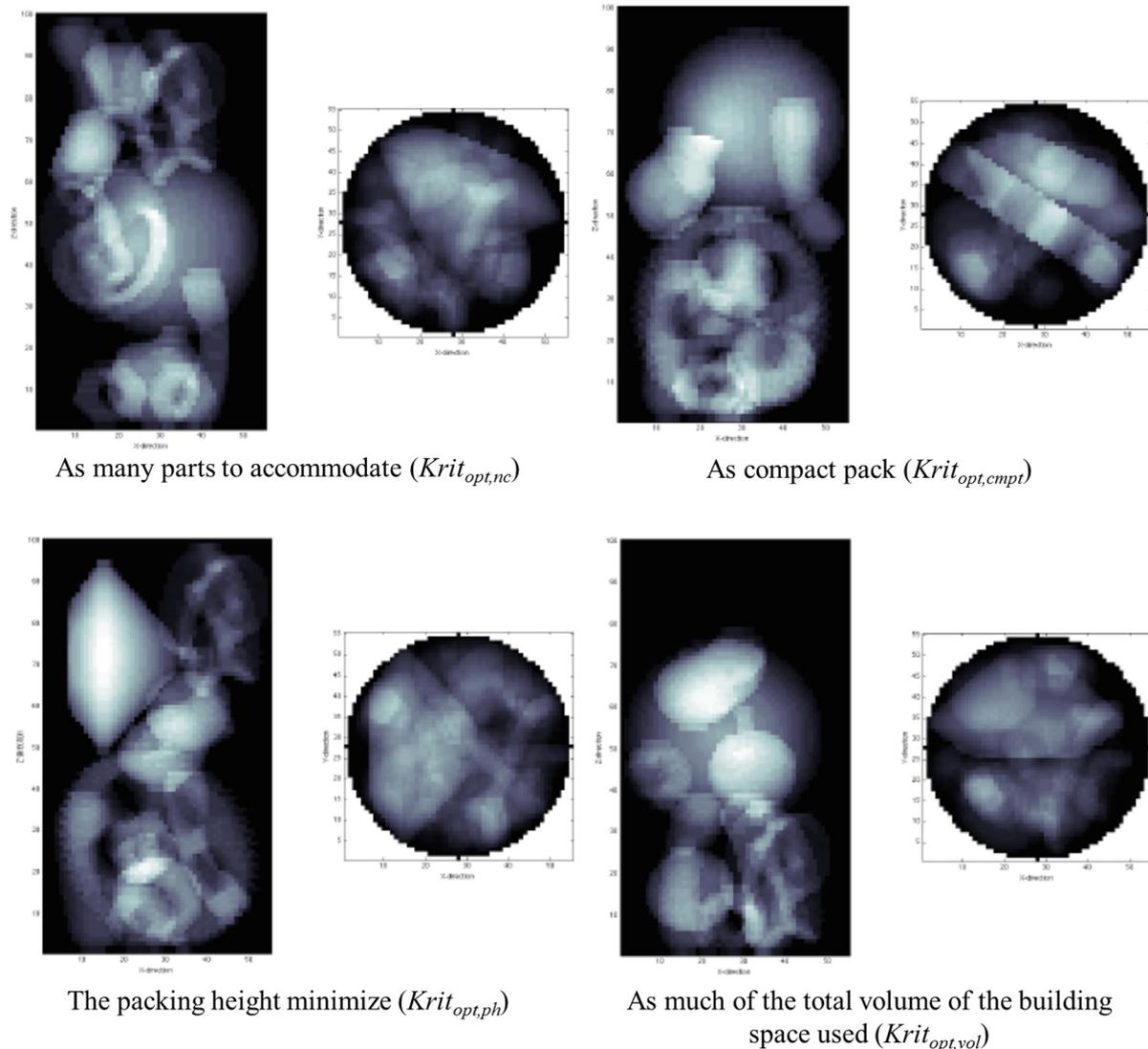


Figure 7: Component packages with different objectives. Left: side view in the y-direction; right: top view. Adapted from [Fri14]

The analysis of the algorithm shows that most of the parts (10) could be accommodated with alignment on the optimization criteria $Krit_{opt,nc}$ in the installation space. Similarly many components adapted to optimize the use of space $Krit_{opt,vol}$. This can be explained by the compactness of the components. These have only barely cavities. It should be noted, that was terminated at this plausibility checks the genetic algorithm after a relatively few generations. The results are thus to be seen only as a trend. It is to complete a detailed validation.

Conclusion and Outlook

The prototypical implementation confirms the function of the developed concept. The concept considers the optimization of the packing height, the volume utilization and the post-processes. Further, the consideration of the process-specific values is implemented.

This paper presents a rudimentary concept for optimizing the part orientation and arrangement of several components for additive manufacturing processes. At this point, pending steps and some development potential of this concept should be demonstrated.

- Within a next step, the developed mechanisms and introduced characteristic values should be thorough validated.
- Only certain effects which occur in additive manufacturing processes, e.g. the staircase effect, are considered in the here presented basic concept. Hence, in subsequent research a focus has to be put on extending the objective function of the genetic algorithm by the missing effects.
- For a user friendly field introduction of the algorithm, the profiles of the parameters are to be constructed on the base of the necessary machinery specifications.
- To improve the performance of the algorithm, it might be useful to implement it in a hardware-compliant programming language. Within the first parametrization of the two algorithms, standard values found in the literature are considered. In order to achieve a faster convergence, comprehensive adjusting of the parameters will be necessary. A known problem concerning the multi-criteria optimization is finding a local optimum instead of global ones. Simple compromise settlements of the single goals are often located far apart. Additionally, wide areas may exist, which are not covered. Through suitable modification of the evaluation function, this problem might be eliminated [Wei07].
- The investigation in this paper does not include a comparison to existing algorithms. This is an urgent need for further work.

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