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TRIZ-based biomimetic part-design for Laser Additive Manufacturing

T. Kamps[a,*], C. Münzberg[c], L. Stacheder [b], C. Seidel[a,b], G. Reinhart[a,b], U. Lindemann[c]

[a]Fraunhofer-Institute for Machine Tools and Forming Technology, Beim Glaspalast 5, 86153 Augsburg, Germany
[b]Institute for Machine Tools and Industrial Management, Technichal University of Munich,Boltzmannstr. 15, 85748 Garching, Germany
[c]Institute of Product Development, Technical University of Munich,Boltzmannstr. 15, 85748 Garching, Germany

Abstract

Laser additive Manufacturing (LAM) possesses a great potential regarding part complexity and adaption for an innovative part design due to a layer-wise buildup offering multiple geometry variants form a broad design solution space. Thus, design optimization is a complex challenge for the designer that requires systematic design approaches.
A methodology for an application-oriented systematic part design development is introduced in this paper using TRIZ: TRIZ's wide collection of methods is analyzed with respect to easy applicability in order to identify a suitable set of methods to be used. This is augmented with databased biological solutions as an inexhaustible source of evolutionary principles and structures. Additionally, design restrictions for LAM are taken into consideration. Altogether an application-oriented methodology is introduced that systematically creates a solution space for a design problem specifically for LAM. The presented methodology is evaluated in a case study of an external reamer. The results obtained by the optimization process are compared to a conventional trial-and-error approach conducted by a practitioner. The use of the presented approach results in a reduction of mass by 10 % and increased functionality compared to a non-methodological practitioner solution.

Keywords: TRIZ; laser additive manufacturing; biomimetics; design for additive manufacturing; design optimization; reamer

1. Introduction

Designing for Laser Additive Manufacturing (LAM) is a challenge, especially for designers that are used to develop parts for conventional manufacturing technologies like casting or machining. Due to a layer-wise

* Corresponding author. Tel.: +49 821 56883 57; fax: +49 821 56883 50.
E-mail address: tobias.kamps@iwu.fraunhofer.de.

buildup of the part instead of a subtractive production process, LAM challenges existing design experience and methodologies by offering a large design solution space. This design freedom creates a vast solution space for technical design problems. Most approaches show a trial-and-error methodology by the designer relying on existing design experience. This results in the use of only a small area of the possible design solution space, which in the end leads to a suboptimal design approach. Hence, designer's mindsets have to adapt to a different way of production and design, as stated in the VDI status report of 2014 (VDI 2014). In summary, this makes design for additive manufacturing a high-complexity optimization problem. For a thorough industrial application of LAM, a systematic anchoring in design thinking has to take place.

Today, using evolutionarily optimized biological systems as an analogy for solving technical problems is well established. However, a systematic integration into an industrial innovation process lacks a substantiated knowledge base. Furthermore, the performance of biomimetic technical products is often underestimated (Oertel & Grunwald 2006). So far, only few companies employ the innovative principles of biomimicry due to a lack of resources. Especially in small and medium size companies, a profound use of biomimicry is not economically possible (Banthin 2014) due to a lack of application-oriented methodological approaches (Bogatyrev & Bogatyreva 2014) (Ponn 2007).

LAM offers a good opportunity for integration of biomimetic structures because of its advantage "complexity for free", which in general makes a rethinking of the part design process opportune. Transferring the observed biological principle into a technical application by means of abstraction is crucial for the exploitation of the biomimicry potential (Beismann & Seitz 2011).

This shows the need for a methodology that not only enables designers change their mindset to the new manufacturing possibilities through a layer-wise instead of a subtractive procedure but also helps exploit a maximum of given design freedom. Systematically employing nature's analogies in the part design process delivers a large design solution space to choose from. Likewise, in order to make it economical for small and medium sized companies, the methodology should be application-oriented to make it easy to use.

2. Research focus

The focus of this paper is to introduce an application-oriented methodology that systematically uses TRIZ (Russian acronym for "Theory of Inventive Problem Solving") as a methodological framework. TRIZ comprises multiple methods that can be used depending on the application. Thus, a selection of suitable methods is crucial to ensure application-orientation. Also, a focus on optimization of a given application of a part is advantageous factoring out other manufacturing technologies but LAM and the creation of entirely new products consisting of multiple components in order to reduce complexity. Methodological steps have to be comprehensible and reproducible. Solution space creation is supported by a systematic search for biologic analogies. Also, manufacturing restrictions have to be taken into account to ensure manufacturability via LAM. Within this framework, solution quality has to be maximized and evaluated.

Despite a lot of intersecting sets of the three considered disciplines LAM, biomimicry, and TRIZ as shown in figure 1, left, the exact reasonable intersections have to be identified. Ergo, an application-oriented combination of those disciplines is evaluated under the following given questions:

- How can suitable methods be picked from the TRIZ-methodology?
- How can the given part to be optimized be analyzed efficiently?
- How can the creation of a large solution space of biomimicry analogies for a given application or part be systematically done and where can it be found?
- How can suitable analogies be evaluated for technical applicability?
- How can solutions be evaluated for design restrictions dictated by Laser additive manufacturing?
- How can application-orientation be ensured without reducing solution quality?

A new methodological approach to biomimetic knowledge and its application-based use of suitable analogies will offer a new scope of utilization of the entire discipline of biomimicry. Consideration of popular scientific biomimicry projects often times displays a motivation of finding suitable demonstrative technical products for biological circumstances (Hacco & Shu 2002). A given biological phenomenon, like the fluid dynamical characteristic of shark skin, induces a search for potential technical applications. The opposite approach is focused in this paper: TRIZ is employed for solving technical problems and contradictions systematically for a given technical part using nature's analogies.

Nature offers excellent conditions for an adaption in TRIZ, since biological systems mostly demand an implementation of contradictory requirements (Hill 2005) like a light and at the same time high strength structure for plants.

3. State of the art

3.1. TRIZ

TRIZ was developed to support engineers and natural scientists solving inventive problems by using the knowledge of former inventors. For this purpose, TRIZ offers a comprehensive set of methods to analyze and solve problems by considering different perspectives. The practitioner can choose from a large amount of methods. Basic approach and central demand of TRIZ is solving inventive problems by its abstraction instead of approaching a direct problem solving (Orloff 2006). The abstracted problem is solved on an abstract level, which offers possible concrete solutions for the specific problem (Albers et al. 2014). The abstract solutions are finally converted into a concrete solution. The general methodology is shown in figure 1, right. Key methods are e. g. inventive principles, standard solutions or contradictions (Muenzberg 2014a).

In order to overcome technical contradictions, G.S. Altschuller extracted 39 technical parameters and 40 innovative principles from hundreds of thousands of patents. The parameters and principles are comprised in a technical contradiction matrix that serves as an elementary method in TRIZ for solution space generation. TRIZ as a general logic for application of interconnected methods also can be augmented with new methods. A project-group at the University of Bath, GB for instance added a methodology to integrate functions and effects of biological systems. 500 biological phenomena were analyzed (Bogatyrev & Bogatyreva 2009a), which were described by the use of the innovative principles of TRIZ. The results showed a great discrepancy between technical innovative principles provided by TRIZ-standard and nature's innovative principles. Thus, a new contradiction matrix resulting from the innovative principles was formulated. The newly introduced matrix makes working with biological and evolutionary innovative principles for technical problems possible, which is why it is entitled "Bio-TRIZ" (Vincent et al. 2006).

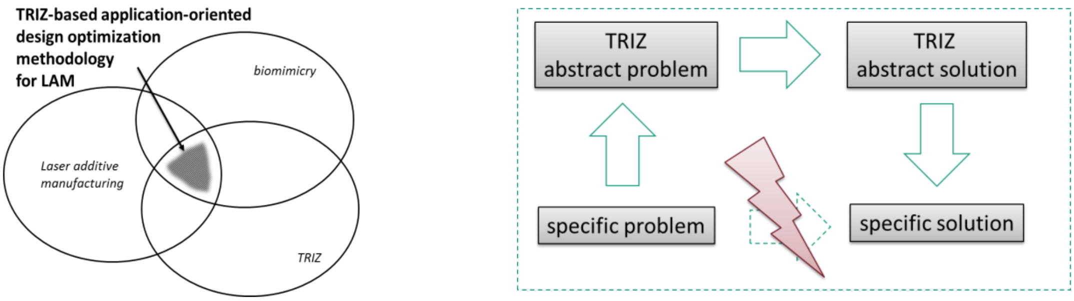

Fig. 1.left: schematic view of the considered disciplines focused for development of an application-oriented design optimization TRIZ-based methodology for LAM; right: general problem solving approach used in TRIZ

In summary, TRIZ as well as its variant Bio-TRIZ offer a suitable logical framework for part optimization. However, its catalogue of methods as well as its unconventional way of problem solving for many TRIZ-methods demands a thorough learning process (Deimel 2011). Thus, TRIZ-methods have to be analyzed and application-oriented methods have to be systematically selected. Also, new methods and methodologies have to be added to its holistic approach.

3.2. Biomimicry

Biomimicry aims at using biological analogies in technical systems as a stimulus of innovation (Nachtigall 2002). Thus, biomimicry introduces an interface between the disciplines technology and biology, hence, relying on harmonization on both sides. Ideally, biology provides principles and structures that can be employed in technical applications through biomimicry.

Biology as a whole offers a wide variety of solutions, principles, and problem-solving-methods for very versatile problems. Copying and adapting designs of natural systems has a long history. However, using biological models in high-complexity technical scopes demands methodological support.

On a structural level, an understanding of biological systems can be simplified, if pursuing a state of low energy consumption is assumed as an overall goal (Klein 2013). Biological systems seek a state of pure tensile load minimizing torque and flexural loads. Besides fiber-composite and sandwich structures (Riss et al. 2014), lattice structures offer a good structural solution resulting in a small density of biological structures (Teufelhart 2013). Ergo, according to Wadia 2011, natural design principles can be summarized as direct introduction and compensation of force, maximum moment of inertia and resistance, reinforcement of structures in main direction of load using the support effect of curvature, integral structural design employing fine textures and structural voids, and absolute exploitation of a specific design.

One example for analytically usable methods to improve structures according to the above is the method of tension triangles that reduces the amount of edges in a technical design according to a tree structure (Klein 2013). Simulation-based methods are for instance Computer Aided Optimization und Soft Kill Option (Beismann & Seitz 2011), that optimize a technical structure through load-adaption removing material at part segments with a reduced load.

In summary, biomimicry offers a large solution space for technical problems and part optimization. However, nature’s structures and functions may be designed with regard to different requirements than technical systems (Nachtigall 2008). This makes an analysis of natural systems for the use as analogies in technical part optimization difficult without an application-oriented methodology.

3.3. Design methodologies for LAM

The economical use of material is a commonality of nature and LAM-processes. Part design for LAM demands for both new intellectual approaches (VDI 2014) as well as a definition of guidelines and structures in consideration of design limitations. Literature shows different approaches: A large proportion of sources offer catalogues of design restrictions and guidelines for design for LAM. Depending on the applied process, process limitations are evaluated as a geometric framework for part design (Schulz 2008).

Also, existing works focus on determination of specific ratios for process or product performance measuring. Orientation of the part for additive manufacture influences costs and part quality of the product produced (Koehler & Danjou 2010). This is why some methods focus part modification for an optimal orientation. Besides orientation, other factors like for example complexity or massivity (Zhang et al. 2014) and (Macht 1999) are discussed.

Another method shows similarities to the one introduced in this paper. Namely, implementation of biomimetic structures is suitable for part topology optimization. Those have a focus in a design for LAM specifically for implementation of lightweight design and load-adapted structures (Emmelmann 2013).

A holistic approach is presented in the VDI-guideline 3405 (VDI 3405, 2015). Topics like part orientation, application of support structures as well as characteristics of material properties are covered in comprehensive recommendations that also cover post-processing. Recommendations for application-specific design approaches for LAM are discussed only rudimentarily (VDI 3405).

In Summary, those presented methods and guidelines for LAM are successfully used in common practice. However, so far a methodology that offers application-specific design recommendations for LAM with a focus of exploiting its biomimetic design potential is not state of the art.

4. Introduction of a TRIZ-based method for biomimetic design for LAM

4.1. General adaption of TRIZ

TRIZ as a collection of methods presents the logic framework of the entire methodology. The wide range of tools and methods within the TRIZ framework is reduced to those that are easy to use. TRIZ comprises multiple methods like the function analysis or contradictions (Muenzberg et al. 2014a), which can be employed depending on the application (Ilevbare et al. 2013). Thus, it is crucial to choose suitable methods for an application-oriented design problem. Suitability depends on whether the method can be characterized as analytical, reproductive, creative, and complex.

Reproductive and creative methods exhibit a greater application orientation assuming the extensive effort demanded by overall TRIZ-methodology mainly is due to creative and complex methods. Thus, focus lies on analytic and reproductive methods. This is seconded in a survey of experienced TRIZ-practitioners (Ilevbare et al. 2013). For analytic sequences the tools contradiction matrix and 40 innovative principles in combination with the methods technical contradictions are selected for abstracting the design problem. Functional analysis plays an important role, because it promotes a holistic understanding of the analyzed part. In order to provide good system clarity, a graphically enhanced functional analysis is used (Muenzberg et al. 2014b). The following interaction and effect analysis provides an overview of system's components and their interaction behaviour. For problem definition the contradiction matrix plays a crucial role. Typically for regular TRIZ, Altschuller's 40 innovative principles claim to represent the state of the art for technical problem solving due to their patent-based origin (Orloff 2006). Those innovative principles are used for solution space generation for the technical contradictions. Furthermore, the resource analysis is used as a basic element of TRIZ (Nachtigall 2010). Components contained by the system as well as boundary components are identified. Components can be fields (e. g. thermal and mechanical energy), material, time, or information. (Fend et al. 2003) Further steps provided by TRIZ are replaced by newly introduced methods described in the following.

4.2. Augmentation of TRIZ

The resource analysis is augmented with a part evaluation for suitability for LAM. If basic preconditions are not met, it is formulated as general problem, e. g. the part consisting of a not LAM-supported material.

In order to solve those formulated problems, idea generation is assisted by biological analogies. Specialized database systems (e. g. *ask nature*) are used that accept technical descriptions of phenomena. Afterwards, the identified solutions offered by an analogy database have to be evaluated for technical feasibility. The different system behavior of biology and technology has little problem solving methods in common, only about 12 % (Nachtigall 2008), (Wadia 2011), (Bogatyrev & Bogatyreva 2009b). This makes a mere copying of the presented approach by nature mostly not applicable. Thus, the innovative principles presented by the biological analogies have to be compared on a level that allows for systematic functional background information. This can be realized by comparing nature's analogies to the innovative principles that are suggested by TRIZ. This juxtaposition validates a theoretic feasibility. The theoretic feasibility then has to be checked for manufacturability. Indicators for process and part performance complete the presented optimization and evaluation.

4.3. Final general methodology

Schematically, the final version of the introduced methodology is shown in figure 2, left and can be described as follows: The entire methodology consists of the four macro-steps that are supported by separate micro-steps. Macro steps are part analysis, problem definition, creation of solution space, and solution.

Part analysis consists of a consideration of its components and their interactions paired with a functional modelling. A parallel analysis of the available resources is carried out. Resources may be for instance, energy or cooling lubricants. Also, a check for manufacturability via LAM is covered by the resource analysis. If the part is not manufacturable by LAM as it is, it is formulated as a problem to be solved later on, for example as a differential part design if the part dimensions are not supported. Part analysis is followed by the problem definition. An effect analysis is conducted clearly displaying negative and positive effects component has in interaction with other components. Negative effects are summarized and formulated in abstract problems. The problem formulation is met by the creation of solution space. The solution space is built through a characterizational description of each single problem and technical parameters and their analysis in a contradiction matrix. An analogy search in combination and feedback of the innovative TRIZ-principles and biomimetic principles delivers a selection of solutions. The solutions can be evaluated by an LAM-checklist for part and process performance ratios and indices.

5. Case study: design of an external reamer

The methodology was tested in a case study of an optimization problem for LAM of an external reamer. Overall goal was a design for LAM as well as a lightweight optimization. The case is based on a project conducted with the tool manufacturer MAPAL Dr. Kress KG.

This case is chosen for two reasons. Firstly, the methodology was checked for application-orientation. A practitioner with a lack of experience in biology and biomimicry had to be able to use the tool. Secondly, the case was used as a comparison with a state of the art trial-and-error optimization by a practitioner with experience in design for LAM. This way, a qualitative comparison is possible between a practical hands-on optimization and a systematic approach allowing for a quantitative evaluation of the methodology introduced. For the sake of clarity, only a selection of steps is presented here.

First, a component analysis was conducted followed by an interaction and resource analysis as well as functional modelling.

The resource analysis is conducted in a systematic view of the reamer. Substantial resource is the cooling lubricant. The amount of powder material provided for LAM is a procedural resource. Both may be used as means for a design change of the reamer. An initial check shows good LAM-manufacturability. As a field, rotational energy as well as changing ambient temperature is mentioned. As a space resource, the clamping dictates a fixture for the reamer. Also, the inner diameter is fixed due to its tooling standard. Other geometric figures are subject to change and are expected due to a use of biomimetic structures exploiting the design potential of LAM.

The part analysis allows for an effect analysis that may be summarized by the following independent characterizational description:

- Ensure shaft stiffness and increase specific stiffness of overall design (1)
- Low friction at sliding rails (2)
- Efficient cooling of the components and heat dissipation (3)
- Guidance of cooling lubricant without decreasing system stiffness (4).

The characterizational description is followed by an analogy search for solutions provided by nature. For this purpose the database *ask nature* was used (The biomimicry institute 2015). The combination of the results provides a first approach to a biomimetic design of the external reamer that is presented in figure 2, right.

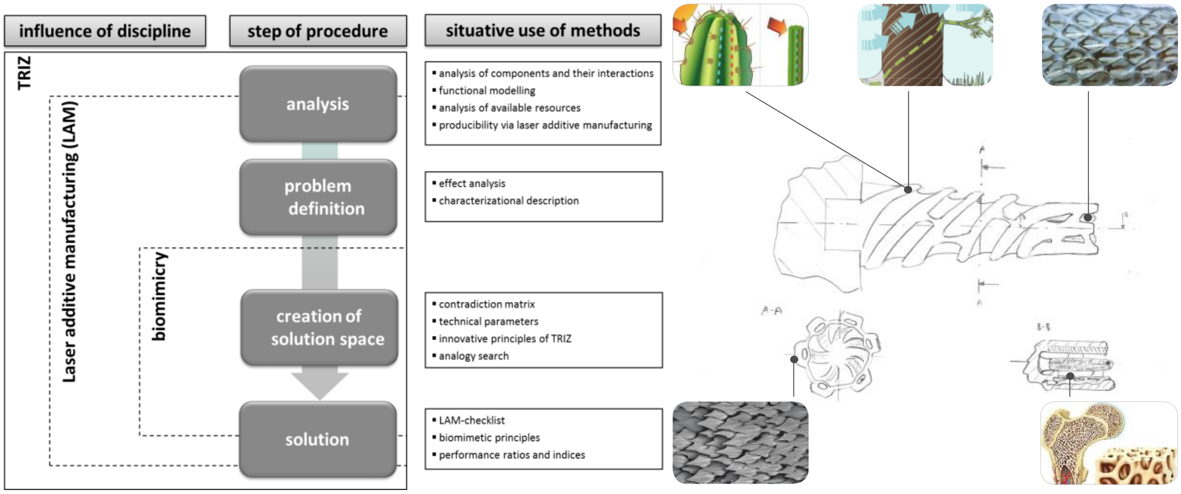

Fig. 2. Left: schematic view of the introduced TRIZ-based methodology for biomimetic part optimization for LAM, right: preliminary sketch of the reamer as a combination of technical feasible biomimetic analogies for part optimization specifically for LAM

The selection of feasible analogies was carried out using innovative principles and technical contradictions as provided. Each analogy was analyzed regarding innovative principles of TRIZ. The causative problem is analyzed in parallel. Applying the contradiction matrix of TRIZ method results in proposals for principles that are state of the art solutions based on patents. If a match between technical problem and biological analogy was found, this principle is referred as technically feasible.

The evolutionary CAD-design development is displayed in figure 4. Picture *a* displays the original reamer, *b* shows the design of a practitioner without methodological support, design *c* is the result of a systematic design for LAM using augmented TRIZ. As an example, the analogy search tasks (1) and (2) are explained. The bark of Norwegian *Scott's Pine* adapted to external loads in building structures that receive shear forces. This is covered by innovative principle 15. Also, the cactus is found as a structural solution for cooling. Its spiral structures ensure an optimized air cooling through circulation of ascending warm air. This is seconded by innovative principle 17 for technical feasibility. According to biological construction principles the whole structure is designed to be hollow. Resulting channels can be used for transporting cooling lubricant. This can be guided through porous structures that are inspired by human bone structures. Those designs were evaluated regarding achieved process and part performance through a comparison of key figures. The summary is displayed in table 1.

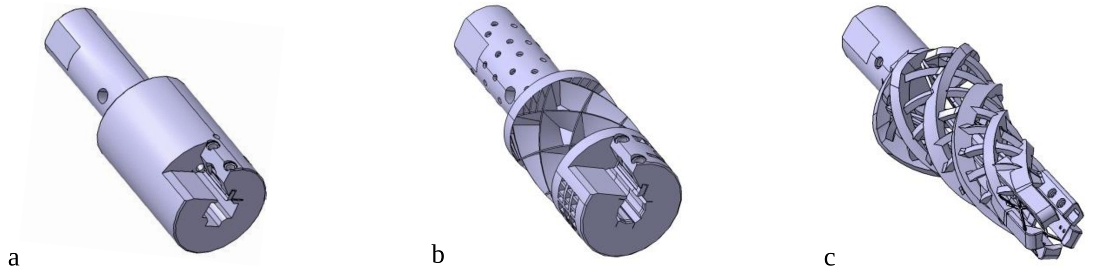

Fig. 4. Evolutionary development of the case study external reamer: (a) original reamer; (b) design of a practitioner without methodological support; (c) result of a systematic design for LAM using augmented TRIZ, (a) and (b) is the result of a topology optimization conducted together with MAPAL Dr. Kress KG (Schneider 2013)

Tab. 1. Qualitative comparison of original external reamer, LAM-practitioner design and optimization via introduced TRIZ-based methodology

		reamer conventional	reamer LAM-non-TRIZ-optimized	reamer TRIZ-optimized
PART-DATA				
mass (TiAl6V4)	**m** [g]	**232**	**107**	**86**
volume	$V_{BT}V_{BT}$ [mm³]	**52080**	**23980**	**19280**
surface	$O_{BT}O_{BT}$ [mm²]	**15000**	**33000**	**36000**
PROCESS-PERFORMANCE				
complexity-index	**KI**	**3,28**	**6,30**	**7,11**
massivity-index	**MI**	**0,82**	**0,66**	**0,56**
orientation-index	**OI**	**0,63**	**0,83**	**1,25**
PART-PERFORMANCE				
lightweight construction indicator	**LCI** [N/mm²g]	**0,03**	**0,09**	**0,49**
mass ratio	**MA**	**100 %**	**46 %**	**37 %**
safety-index	**SI**	**159**	**131**	**29**

The TRIZ-optimized model of the reamer shows the best figures regarding part date, process and part performance in comparison with the conventional and the practitioner solution:

Mass m was reduced to 86 g from 232 g by about 63 % compared to the practitioner solution with 54 %. A smaller volume V_{BT} in combination with a larger surface area O_{BT} proves a significant increase of complexity, which is displayed in a large complexity index KI. A reduction of the massivity-index MI to 0.56 proves the increased use of fine structures, thus. This is seconded by an increased orientation-index from 0.63 to 1.25 which expresses a good design for Laser additive manufacturing as well as a minimized amount of support structures.

Considering the safety-index shows the possibility of a large mass reduction without a significant reduction of performance via TRIZ-optimization. For static stiffness evaluation a value of about 1.5 is assumed to be sufficient (KLEIN 2013, p. 8). Thus, a value of 29 is assumed to offer a satisfactory and conservative value. Lightweight construction indicator was improved evolutionarily from 0.03 to 0.09 up to 0.49, which is an equivalent of a factor 16.

Using the methodology for the creation of an optimal design increases time needed for product design thus increases costs for personnel. It represents an additional step within the design sequence of a technical part as it is performed additionally to an actual CAD-design step extending the conceptual phase. Application-orientation ensures keeping added costs low. The methodology introduced can be carried out without the need for biological experience in about a day. Hence, for each part the value of an increased overall performance and thus the applicability of the method introduced have to be estimated.

All in all, the consideration of the calculated key figures proves an increased part and process performance when employing a systematic part design compared to a non-systematic practitioner design.

6. Conclusion

Using the introduced TRIZ-based methodology for the optimization of the case study external reamer is successful. After an analysis of the technical problem, suitable analogies is be found by a database search. Those analogies are evaluated and selected according to an analysis of their technical feasibility. After comparing the design with a non-methodological practitioner design, the key figures show an improved design quality when using the introduced methodology specifically for LAM.

The use of the introduced methodology is possible without profound experience in biology and biomimicry due to an application-oriented instrumentation within the timeframe of a workday. Also, a systematic preselection of single relevant TRIZ-methods was crucial for ensuring users' quick understanding while providing a deep system-based understanding of the problem. The search for applicable analogies efficiently offers a wide solution space.

The evaluation of process complexity within the framework of the methodology is a suitable instrument for the evaluation of manufacturing costs. However, a systematic analysis of the manufacturing costs is not included.

7. Summary and outlook

The constantly increasing degree of complexity in product design, specifically due to the emerging potential of LAM, is controllable by methodological means presented in this paper. TRIZ as a logical framework augmented with an analysis of design for LAM and a biomimetic analogy search offers a powerful application-oriented design methodology. Application-orientation demands a compromise between the creation of a maximum solution space and a minimum effort. The selection of suitable methods offered by classical TRIZ and the augmented methods shows a suitable compromise for the case study. This makes an industrial use economical.

Based on a given part to be optimized, the methodology offers an evaluation regarding LAM-potential. The degree of exploitation can be measured by use of introduced quality figures.

Potential of further developing the introduced methodology is versatile. Short term goal could be an implementation of an evaluation scheme for an economical potential estimation. A key figure for process complexity already covered by the methodology allows for an estimation of manufacturing costs. However, an implementation of a cost-oriented evaluation would improve an industrial applicability. Thus, the technically focused methodology could be developed into a holistic industrial approach for economical part design for Laser additive manufacturing. For overall cost estimation, manufacturing costs and personnel costs for applying the introduced methodology should be considered.

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