ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)

https://doi.org/10.17559/TV-20210625150328
Preliminary communication

Design Principle for Additive Manufacturing: Direct Metal Sintering

Regina NOVAK, Filip VALJAK*, Nenad BOJČETIĆ, Mario ŠERCER

Abstract: Additive Manufacturing (AM) brought new design possibilities and freedom to the product design process. However, as the existing design rules and design limitations do not apply to the AM, designers require new methods and tools to utilise the full potential of AM. The stated is especially noticeable in the design of metal products made with AM, particularly with the Direct Metal Laser Sintering (DMLS) process. The research proposes a methodological approach for analysing the existing DMLS products made with DMLS to extract design knowledge. The methodology is applied to the pool of DMLS from which 15 design principles are extracted that formalise design knowledge about DMLS. The design principles are intended to be used in the early design stages of the design process as a source of design knowledge and inspiration for conceptualising new and innovative products that will be made using DMLS.

Keywords: AM models; design for additive manufacturing; design principles; direct metal laser sintering; metal AM

1 INTRODUCTION

In recent years Additive Manufacturing (AM) gained popularity in both academia and industry as it evolved from rapid prototyping technology to everyday manufacturing technology used for the production of final parts [1-3]. Reasons for the wide adaptation of AM technology are the many advantages AM brought over conventional manufacturing technologies, such as freedom of design, small-batch and on-demand production, the versatility of materials it can process and many more [4]. One of the widespread applications of AM is for producing metal parts, especially in industries with a high complexity of parts and small batches, like aerospace and medical industries. Among different AM processes that can produce metal parts, Direct Metal Laser Sintering (DMLS), based on laser sintering of a thin layer of raw powder material in a layer-by-layer manner [5], is one of the most common processes for metal AM [6].

As DMLS grew in popularity, nowadays, designers can see exciting-looking examples of metal AM designs created with DMLS (e.g., flow measurement probe [7], AM heat exchanger [8]) that utilise unique AM possibilities, but they often lack knowledge of how to design such parts [9]. The struggle arises from the different nature of AM compared to conventional manufacturing. Thus, a new design approach emerged to aid in the design and development of AM products - Design for Additive Manufacturing (DfAM). The DfAM, as design criteria, is focused on AM specificities and limitations and includes various methods and tools for guiding and assisting designers throughout the AM-oriented design process to create products that will utilise the advantages of AM [10].

In response to the growing use of AM, the research community started to develop various approaches inside the area of DfAM to assist designers who were faced with the challenge of designing their products to utilise the benefits of AM. Today, various DfAM approaches exist [11] that vary in their applicability to the design process and AM technology they are referring to. However, most of these approaches are focused on the later design phases, which are used to ensure the design's manufacturability. This is notable in the hitherto developed design rules and guidelines for DMLS that provide information on minimal wall thickness, necessary gaps, or gradient of the STL, as well as the influence of process parameters on stress relaxation, surface finish and rheological properties [12]. These rules and guidelines are precious for embodiment and detail design. Still, they utilise only a fraction of AM design possibilities as they have little influence on the functionality and layout of the future product. To truly utilise the possibilities of AM, the DfAM tools and methods need to be applied from the early phases of the design process, where the influence on the function and the form of a product is the greatest [13]. And while some DfAM approaches provide this support for early design phases, they are generalised to be applicable for all AM processes, thus, lack specific input and knowledge about DMLS needed for full utilisation of DMLS possibilities.

Hence, this research aims to define research methodology for extracting and formulating the design knowledge about DMLS and formulating an initial repository of this knowledge to be used in the conceptual design phase of product development. The methodology aims to enable the systematic capture of specific AM knowledge about DMLS and formalise it on a high level of abstraction through the construct of Design Principles (DPs), with an attended use of DPs for the conceptual design of metal AM products. This design knowledge in the form of DPs would assist designers, especially novices in design for AM, to design products that will be made of metal or metal alloys through the DMLS process, with a focus on conceptual design and early embodiment.

The paper is structured as follows: the literature review on existing DfAM approaches for early design phases and design approaches for metal AM parts design are given in Section 2. Section 3 presents the methodology used in this research, and Section 4 presents the list of developed DPs for DMLS. In Section 5, validation through a case study that utilises DPs is given. Overall research and the results are discussed in Section 6. Finally, the paper concludes with Section 7, where the conclusion and directions for future work are given.

2 LITERATURE BACKGROUND

Up to date, few approaches inside the DfAM act as a source of design knowledge for the conceptual design of AM products. One of the first developed approaches for this purpose was the Design Feature Database, which contains 106 different design features categorised into four categories (Ergonomics, Functionality, Part Consolidation and Aesthetics) [14]. Inside the database, various AM features are described with basic information on the application, functionality, AM system and material feasibility and are further shown through graphics. Perez et al. [15] developed a list of 23 design principles extracted from the designs available on crowdsourced platforms based on the Fused Deposition Modelling process. The principles were later developed into 27 design principles cards that provide design knowledge and guidance throughout the design process [16]. Weiss et al. [17] proposed the conception of design catalogues that will store AM-compliant solutions for common product functions based on functional classification.

Similarly, the conception of a broader AM design principles repository based on functional classification was developed by Valjak et al. [18], while Watschke et al. [19] developed a function-flow matrix containing 41 design principles based on the multi-material AM. Blösch-Paidosh and Shea [20] formed process-independent design heuristics that store AM knowledge needed to conceptualise a new product. The list was later refined into ten high-level heuristics [21]. The experimental study showed the benefits of using heuristics in early conceptual design, as they increased the utilisation of unique AM capabilities in developed concepts [20].

As shown, the DfAM approaches for conceptual design come in various forms, most often as design heuristics and principles. Some of the approaches are process independent ([14, 18, 20]), and others are focused on a particular AM technology ([15, 19]). Due to their broadness, these tools are suitable for conceptual design and can be used to conceptualise metal AM products. However, the lack of specific design knowledge about DMLS will reduce the utilisation of the DMLS potentials. Furthermore, the broadness of stored design knowledge and the lack of restriction rules can lead to the development of unfeasible concepts made of metal (e.g., the use of transparent material).

On the other hand, few DfAM approaches specifically for metal AM can be found in the literature. Atzeni and Salmi [22] proposed five general design guidelines for DMLS. These guidelines focus on avoiding design principles for conventional manufacturing, integration of parts and features, minimised use of material, freeform design, and correlation between functions and shape. Adam and Zimmer [23] developed an AM design rules catalogue with basic design shapes and transition elements for the powder bed fusion process for both metal and plastic. Using this catalogue, a designer can look at how to design parts of the overall product according to AM feasibility. Kranz et al. [24] created an extensive set of specific design guidelines for designing products from TiAL6V4 alloy using the DMLS process. Graziosi et al. [25] showed the benefits of using DMLS to manufacture sports equipment and emphasised the need to redesign the shape according to product orientation during the manufacturing process. Furthermore, they underlined the need to develop methods and tools for supporting the design process of metal parts with optimal trade-offs among functional, technical, and manufacturing requirements. Ranjan et al. [26] proposed a methodology for DMLS based on feature graphs that help designers identify critical features for AM and redesign them to avoid manufacturability constraints. These DfAM approaches for metal are developed for specific AM processes and even for specific metal alloys and are primarily oriented on manufacturability and process parameters. While this information is necessary for the manufacturing of the conceived design, they are primarily used in embodiment and detail design and are not suitable for a conceptual design where the product's functionality is the primary focus.

3 METHODOLOGY

To formalise design knowledge about the DMLS process for use in early design phases, the suitable knowledge construct must be identified, and the methodology for extraction and formalisation of knowledge must be established. During the product development process, designers use different sources of design knowledge formalised through various constructs such as principles, heuristics, rules, and guidelines [27]. In this research, the extracted design knowledge will be formalised in the form of Design Principles (DPs) as it is a construct with an appropriate level of abstractness for the conceptual design phase [28] and has been used previously for the similar intended purpose [16, 18]. Hence, Fu et al.'s formal definition of DP has been used: "*Design principle is a fundamental rule or law, derived inductively from extensive experience and/or empirical evidence, which provides design process guidance to increase the chance of reaching a successful solution*" [27].

Furthermore, to derive DPs, a formal process is needed to ensure systematic gathering and analysis of data and consistent formulation of DPs. DPs can be derived from various sources like existing principles, experience, design practice, expert observation, or existing designs [27]. The most common source of knowledge for the derivation of DPs are existing designs [27], as they are a record of design knowledge designers gathered during product development to solve the given design problem. This knowledge, implicitly embedded in the design, includes formal design knowledge from sources like textbooks and design catalogues designers used during the development process, but also knowledge gathered through experience, intuition, observations, or trial-and-error approaches. The accumulated design knowledge can be extracted from the existing designs through systematic examination and analysis [29] and formulated in the set of DPs. Furthermore, the inductive approaches are often used for derivation of DPs for various applications, such as "Tolerance design principles" [30] or "Transformation principles" [31]. Therefore, to derive DPs for metal AM an inductive process is used. The protocol used is made of multiple steps (Fig. 1) and is derived from existing protocols [16, 18, 31] found in the literature. The three key phases of the protocol are the collection of data, data analysis and extraction of patterns and formulation of theory based on the identified patterns [27].

In the first phase, the pool of existing DMLS designs was established. The primary sources were products and case studies available on web pages of AM companies (e.g., EOS GmbH, Materialise and Stratasys) and examples of AM designs found in scientific articles [32]. To enter the pool, product had to be manufactured with DMLS, and its functions improved by AM compared to conventional manufacturing technologies. In total, 15 products were gathered and analysed. The analysed products were mainly from the aerospace, automotive and medical industries, as seen in Fig. 2.

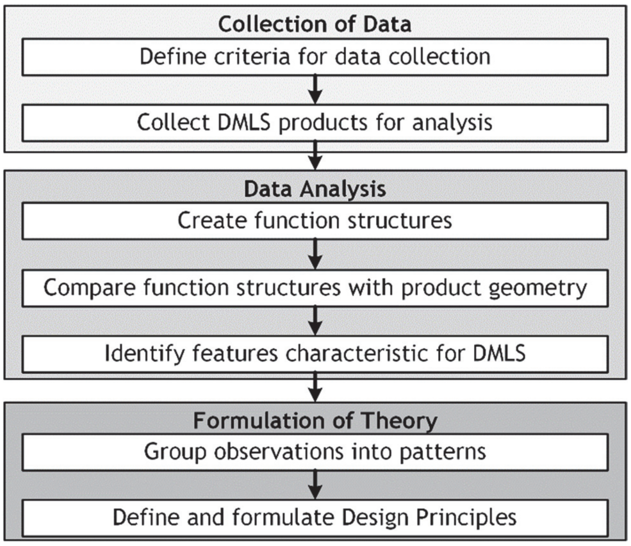


Figure 1 Protocol of methodology for derivation of DPs

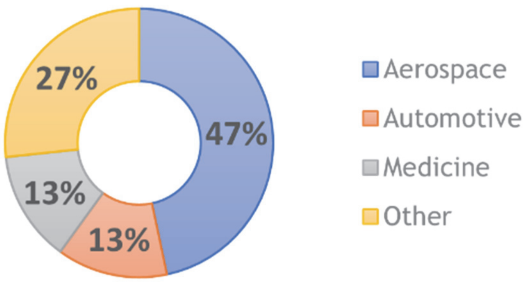


Figure 2 Analysed products by application

The second phase of the methodology was data analysis. The core of this phase was the functional analysis to facilitate the systematic analysis of existing designs. Hence the first step of this phase was focused on creating a function structure for each design from the pool of products. Function structure is a model of a product depicting the overall function of a product through its subfunctions in a solution-neutral way [33]. Its graphical layout is made of product subfunctions connected with flows of energy, material, and signal [13]. Hence, function structure is an abstract representation of the overall product function that does not suggest a technical solution. The solution-neutral representation of each design facilitated the comprehensive analysis of products on the same level of abstraction and eased their comparison in the process of deriving DPs. This was further enhanced by adopting a standard vocabulary of functions [34] that limited the number of possible expressions, thus simplifying the search for AM characteristic solutions [35].

Once the function structures for each analysed product were created, in the second step, they were compared with the geometry to analyse how individual subfunctions or blocks of subfunctions were solved. This enabled the identification and extraction of features typical for DMLS, as well as features that have improved performance or functionality. The features identified in this step were:

- integration of supporting material into the product,
- application of lattice structure,
- application of topological optimisation,
- application of internal structures,
- change of surface texture to suit the use case,
- adaptation of geometry to the individual user,
- integration of parts,
- use of layered structure to suit the use case.
- adaptation of geometry to the standard interface,
- adaptation of geometry to custom interface,
- feature size adjustment,
- enabled movement using multiple connected parts,
- conveying information through geometry.

The relations between function structures and identified features enabled an understanding of how AM is used to solve partial functions of a product. Through analysis of these relations, patterns of functions and connected features emerged, and from these patterns, DPs were identified and described in the final phase.

As the data analysis phase is a crucial part of the methodology, to illustrate the procedure described above, the example of analysis conducted on the bottle opener designed for DMLS is shown in Fig. 3.

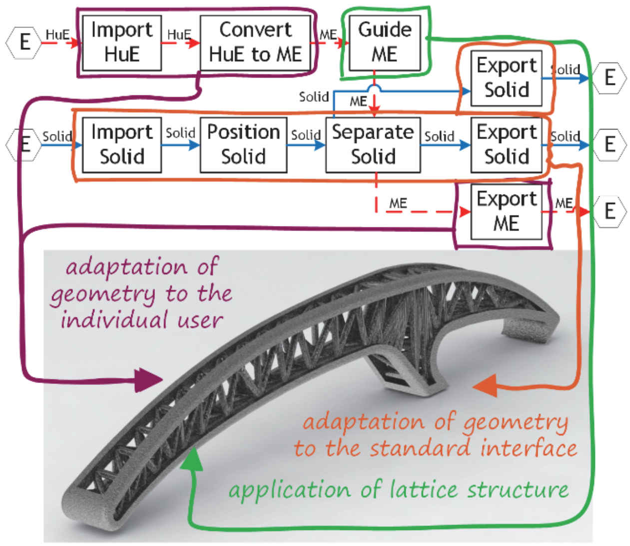


Figure 3 Analysis example

Bottle opener was chosen as an example due to simple function structure and clear depiction of geometry enabled by DMLS that does not hinder the steps of conducted functional analysis. Furthermore, it is often used as a demo and promotional product, so it is a common DMLS product. The analysis started with the creation of the bottle opener function structure. Its overall function is to convert human energy into mechanical energy that separates a crown cap from the bottle. The function structure comprises nine subfunctions connected with flows of energy (human and mechanical energy) and flows of material (solid). Next, it was observed how individual functions or blocks of functions were solved using DMLS capabilities. In this example following observations were noted. The block of functions for importing and converting human energy is solved using ergonomic shape and customisation of bottle opener to individual users (marked purple). The same geometry is also used for exporting mechanical energy (reaction forces) back onto the user's hand when they apply the energy needed to open the bottle. Finally, the function "Guide ME" is solved using a lattice structure that provides the required structural stiffness while being lightweight (marked green). Finally, all functions through which the flow of solid passes are solved using a standardised geometry that enables the grabbing of the crown cap and its removal from the bottle (marked orange).

The same analysis was applied to all products gathered in the pool of DMLS designs. Once all the products were analysed the results were compared, and observed relations between functions and DMLS design features were grouped into the patterns in the final phase of the methodology. The patterns were formed according to the functions' purpose and how they were solved and were consolidated through iterative analysis. In the final step of the protocol, the patterns were formalised into a set of DMLS DPs (described in Section 4). For the example described above, the purple observation became DP #6 (*Adapt geometry of the product to human ergonomics*), the green observation became DP #2 (*Use lattice structure to save weight and reduce the need for supporting material*), and the purple observation became DP #12 (*Adapt product to standard interface geometry*).

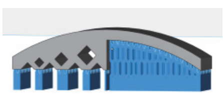
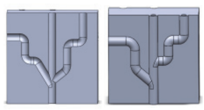
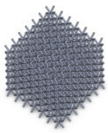
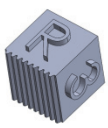
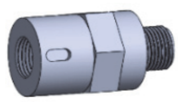
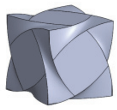
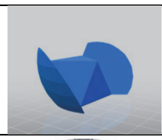
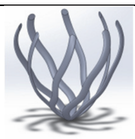
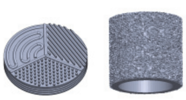
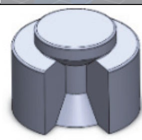
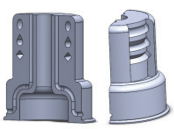
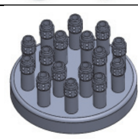
4 DESIGN PRINCIPLES FOR DMLS

Using the methodology described in the previous section, the analysis results were formed into a set of 15 DPs for DMLS (Tab. 1). To provide intended design support each DP must clearly communicate the embedded design knowledge about DMLS. Therefore, each DP is defined through a short descriptive statement [27] to express the purpose of DP. From a linguistic point of view, the descriptive form provides information about a concept, fact, or knowledge that can be applied to a given context [27]; thus, it is a suitable form for the intended purpose of using DPs in early design phases. Furthermore, the textual form of DP definition enables description through a high level of abstraction from which designers can perceive words as concepts and deduce their broad meaning necessary to understand DP [31].

In addition to the textual description of DPs, to ease the understanding and facilitate the utilisation of DPs during concept generation, each textual definition is supplemented with visual and tactile representation in the form of 3D models. The 3D models exist in two forms: as a virtual CAD model and as an embodiment of a virtual model in a physical form. Virtual CAD models help with the visualisation and perception of each DP. Furthermore, they enable a fast overview of all DPs and provide visual stimulation. They can also be used in a virtual environment, such as an online meeting of a design team or inside the virtual reality environment. The virtual models of DPs are shown in Tab. 1.

The virtual models are an intermediate step towards the physical models as they can be manufactured and thus transferred into a physical form. The use of physical models during the design process gives an insight into the sensitive aspects of DPs (e.g., surface texture, weight, shape) and, through the tactile dimension of representation, further support the designer's understanding of DPs. Hence, the physical models can enhance the understanding of the DPs and act as an intermediary between design and production [36]. The interaction with physical models accelerates the development of ideas in the early design stages of product development and expands the number of solutions designers can conceive [37]. The physical models can then be used with design methods that use physical embodiments of ideas in the design process [38]. Furthermore, the physical models enable the representation and testing of AM concept features and aid in representing functional and geometrical complexity, thus overcoming the drawbacks of virtual models that do not always adequately convey design intent [39].

Table 1 Design Principles for DMLS

1. Design products with integration of support material as a constituent part of the product. 	6. Adapt geometry of the product to human ergonomics. 	11. Use branched internal channels for flow distribution. 
2. Use lattice structure to save weight and reduce the need for supporting material. 	7. Transfer information by geometry. 	12. Adapt product to standard interface geometry. 
3. Use topological optimization to achieve structural performance while reducing weight. 	8. Incorporate aesthetic in the design. 	13. Adapt product to complex interface geometry. 
4. Use topological optimization to achieve biological structure. 	9. Shape product surface to increase performance and regulate surface roughness. 	14. Make functional mechanisms / products within one process. 
5. Adjust layer thickness in a way to improve the distribution of heat. 	10. Use internal channels that enable better fluid and energy transfer. 	15. Integrate multiple parts into one to shorten production time and increase product performance. 

In this research, for initial validation of DPs physical models' feasibility, the DPs were embodied through five physical models. Each of the five models contained and represented between two and four DPs. The models were manufactured on the EOS 290 machine using AlSi10Mg alloy and argon as an inert gas. The manufacturing process took 16 hours. The physical models showed the initial feasibility of derived DP and are shown in Fig. 4.

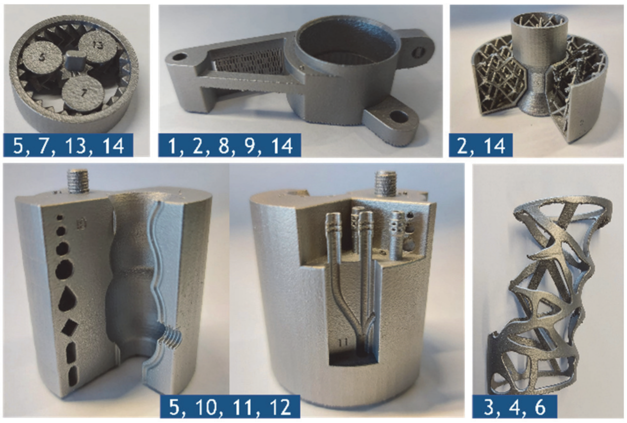


Figure 4 Physical models of Design Principles for DMLS

5 CASE STUDY

To verify the validity of using developed DP for metal AM to conceptualise new designs, the case study of redesigning automobile radiator to be made with DMLS was conducted (Fig. 5).

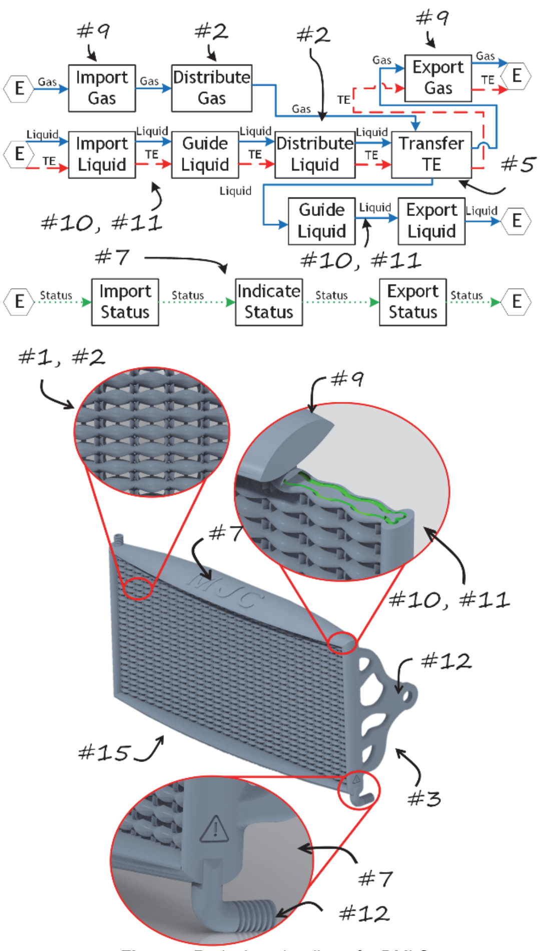


Figure 5 Redesigned radiator for DMLS

The case study aims to show the use case scenario of applying the DPs in the design process. The radiator is chosen because it is a metal product with complex geometry and multiple functions, whose performance is critical for an engine's overall performance. The radiator is a heat exchanger used to cool internal combustion engines by enabling coolant circulation and heat transfer on the air passing over a large surface area. Radiators are usually made of metal alloys and are assembled from many components like core, tubes, and flanges. The core is typically made of multiple metal sheets to create a large surface area and to form channels through which coolant circulates. Therefore, the radiator has a complex geometry and multiple requirements regarding performance, weight, and size, thus will clearly depict the application of DPs and the potential benefits of using DMLS as a manufacturing process.

The redesign process started with the creation of the radiator function structure. It consisted of 12 subfunctions connected with the energy flow of thermal energy, material flows of liquid and gas, and status information flow. Once the function structure was created, DPs were mapped onto individual subfunctions or blocks of subfunctions as a potential partial solution. Here more than one possible combination of mapping could exist, and the designer should be encouraged to iterate the process and explore the design possibilities. However, due to simplicity, only one possible combination is shown, where DPs were mapped onto function structure through the mapping process.

Once the DPs that could be applied were identified and mapped, the concept of a radiator was created. The redesigned radiator can be manufactured as a single part (DP #15) to eliminate the need for assembly and remove the need for sealing between components of a radiator, thus reducing the risk of coolant leaking. Because the radiator is a single part, it incorporates the internal channels to guide coolant throughout the product (DP #10 and DP #11). This enables a good coolant distribution, and optimised trajectories will reduce the flow losses by avoiding sharp turns. An aerodynamic surface increases the airflow through the radiator (DP #9) by guiding air over the lattice structures (DP #2). The lattice structures increase the surface area and enhance heat transfer from the coolant to the air. Furthermore, they reduce the part's weight and the need for supporting material (DP #1). The radiator incorporates standard attachment points (DP #12) for the hoses and the attachment onto the chassis. The flanges on which the attachment points for the chassis are located are topologically optimised to reduce the weight (DP #3). On the top of the radiator is an embedded logo, and on the side, a marking containing warning information is incorporated (DP # 7). Finally, in the production process, the part is oriented, and layer thickness is adjusted to improve heat distribution (DP #5).

6 DISCUSSION

The paper presented two main contributions. First is the methodological approach for deriving DPs for metal AM, and second is the initial set of 15 DPs for the DMLS AM process that store specific design knowledge for designing products that will utilise the possibilities of DMLS technology during the conceptual design.

The methodology presented in Section 3 provided a systematic analysis of existing DMLS products. The methodology is built on previous approaches [18], but the novelty is the use of functional analysis to identify DMLS features used to solve the product functions. The functional analysis enabled the solution-neutral representation of analysed products, and thus easier comparison of DMLS enabled form and solutions used to solve a block of functions or individual functions. Consequently, this provided support for the extraction of DMLS design features, and observation of relations between product functions and DMLS features, which enabled the formulation of DPs. The proposed methodology, while focused on the analysis of DMLS designs, can be adopted to extract different design knowledge from existing designs by changing the data pool inclusion criteria.

The proposed methodology was used on the pool of 15 DMLS products that enabled the derivation of 15 DPs that formalised design knowledge about DMLS. The primary intended purpose of the DPs is to provide support for early design phases and conceptualisation of new products or redesign existing ones that will be manufactured with DMLS. The application of DPs should enable the utilisation of unique DMLS possibilities and improve the functionality and performance of the product being designed. When the set of developed DPs is compared to existing DfAM knowledge constructs for early design phases [16, 15, 20], it is comparable in the level of abstractness and formulation of design knowledge, as their intended purpose is similar. However, the DMLS DPs set is smaller, with only 15 derived DPs. The significant reason for this is the specificity of the derived DPs for just one AM technology; thus, DPs are limited to only a part of the possibilities AM can provide as a group of technologies. Nevertheless, when compared to design heuristics [20] as one of the most comprehensive sources of AM design knowledge, all DPs can be mapped onto one or more heuristics, leaving out only heuristics based on AM features not feasible with DMLS (e.g., transparency or multicolour).

Furthermore, when DMLS DPs are compared to design rules and guidelines for metal AM a difference in intended purpose can be observed. The rules and guidelines are focused on the embodiment and detail design phases, thus containing specific and detailed knowledge about the DMLS, such as process parameters, feature dimensions, etc. On the other hand, developed DPs contain knowledge on a higher level of abstraction as their purpose in the conceptualisation phase, where functionality, layout and basic form of the design are established [13].

In accordance with the purpose of the DPs, they are represented through two description elements, textual definition and 3D models (both virtual and physical). Both elements aim to store design knowledge about DMLS and stimulate the designer's creativity during conceptualisation. As the previous studies on design creativity showed that designers seek inspiration mainly in the early stages of the design process [40], it is essential to represent the DPs and the design knowledge they contain adequately. The existing elements of DP description follow existing research on design creativity and should aid in conceptualisation of new designs. Nevertheless, the representation could be further expanded to DP's broader textual description at a higher level of abstraction. Such textual description can help designers to comprehend words as concepts and obtain the broader meaning of the DP [41]. This can be complemented with supplementary visual descriptions in the form of sketches and schematics, as some ideas are not expressible through written words [41]. The representation elements can be additionally expanded to include examples of designs and products where utilisation of DP can be seen. The examples are often used throughout the design process as a source of inspiration, initial validation, and a reference to a solution, thus supporting the design team communication [42].

Here it is important to reflect on the lack of manufacturing data in the description of DPs. While manufacturing data such as layer thickness, laser power, or required resolution of STL [12] is valuable data for every designer, such data in conceptual design can have a negative effect as the designer could focus on manufacturing details rather than functionality and the overall form of the products. For this reason, the manufacturing details were not observed in the conducted analysis and were not integrated into the DPs description. However, there is a possibility to relate DPs with appropriate design rules and guidelines that will provide the manufacturing data when needed in later design phases.

Finally, the presented research has limitations that need to be elaborated. The first limitation is the number of AM products made with DMLS technology that were analysed. The total number of products is relatively low, but as the analysed products are mostly demo products designed to utilise as many DMLS possibilities as possible, they captured the majority of DMLS specific design knowledge. Furthermore, the number of newly derived DPs is compared to the number of analysed products through convergence analysis (Fig. 6) that is often used to determine the size of data pool in knowledge extraction approaches [27]. The number of derived DPs quickly converged with only a handful of analysed products, suggesting that the finite set of DMLS DPs could be derived.

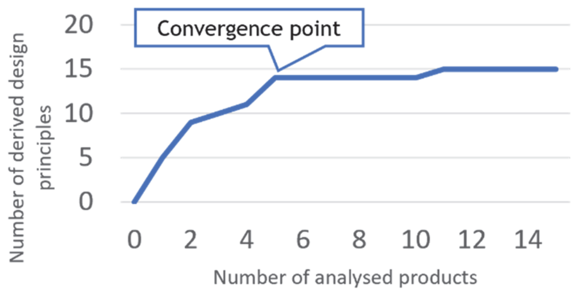


Figure 6 Number of analysed products versus number of new design principles obtained from each product. The products are listed in order of total number of DP they contain.

Convergence analysis, together with comparison of DPs with existing literature sources, gives confidence that the set of derived DPs, while not a definitive set, is comprehensive. Nevertheless, expending of the analysis is planned for future research.

An additional limitation of the research is the validation of the DP. When the four-step procedure for validation of early-phase DfAM design support is followed, the DMLS DPs are validated partially through two steps [43]. Firstly, the DPs are verified through conducted case study that demonstrated their feasibility in a use case scenario for providing design support for early design phases. Secondly, the comparison of DPs with other validated DfAM approaches indicated their comprehensiveness and validity for the intended purpose. However, to fully validate the DPs, a user study in controlled environment and project validation is needed, but such studies will be outside the scope of this paper.

7 CONCLUSION AND FUTURE WORK

The research presented in this paper addresses the growing need for specialised support for the conceptual design of DMLS products that will help designers in the utilisation of unique possibilities of DMLS from the beginning of the design process [9]. The first contribution of this paper is the methodology for deriving DPs. The proposed methodology follows literature recommendations on knowledge extractions [27], and was derived from existing protocols based on functional analysis [18]. The novelty of the methodology is using functional analysis for the identification of DMLS features that are used to solve product functions. The identified DMLS features and their relations with product functions are the basis for the derivation of DPs.

The second contribution is the derived set of DPs for DMLS developed using the proposed methodology. The set is made of 15 DPs, where each DP is defined through a short descriptive statement [27] to express the purpose of the DP. This enabled the representation of design knowledge extracted through the conducted analysis in a concise form that can be easily used and applied by designers. Furthermore, the representation of DPs is supported with virtual and physical models of DPs that enable their visualisation to convey the stored design knowledge to the designer.

While this research is focused on the derivation of DPs for DMLS, it contains the initial validation of DPs. The physical models of DPs were manufactured on EOS 290 machine from AlSi10Mg alloy to demonstrate their feasibility. Furthermore, the conducted case study where the existing product is redesigned using the DPs, provides initial validation of the developed set of DPs.

However, the physical models and case study are not complete evidence of DPs validity, only an initial step. Therefore, future research, besides expending the analysis on new set of products and investigation of DPs modality, will be focused on the broader and comprehensive validation through user studies.

Acknowledgements

This work has been supported by Metal Centre Čakovec under the project KK.01.1.1.02.0023.

8 REFERENCES

[1] Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Martina, F. et al. (2016). Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Annals*, *65*(2), 737-760. https://doi.org/10.1016/j.cirp.2016.05.004

[2] Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., Zavattieri, P. D. et al. (2015). The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design*, *69*, 65-89. https://doi.org/10.1016/j.cad.2015.04.001

[3] Patalas-Maliszewska, J., Topczak, M. (2021). A new management approach based on Additive Manufacturing technologies and Industry 4.0 requirements. Advances in Production Engineering & Management, 16(1), 125-135. https://doi.org/10.14743/apem2021.1.389

[4] Gibson, I., Rosen, D., & Stucker, B. (2016). *Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing*. New York, NY: Springer. https://doi.org/10.1007/978-1-4939-2113-3

[5] Diegel, O., Nordin, A., & Motte, D. (2020). *A practical guide to design for additive manufacturing*. Singapore: Springer. https://doi.org/10.1007/978-981-13-8281-9

[6] Wohlers, T. T., Campbell, I., Diegel, O., & Kowen, J. (2022). *Wohlers report 2022*. Wohlers Associates.

[7] EOS (2018). *Flow measurement probes from Vectoflow - highly robust thanks to additive manufacturing and EOS*

[8] EOS (2018). *Leverage the full potential of a heat exchanger with additive manufacturing.*

[9] Pradel, P., Zhu, Z., Bibb, R., & Moultrie, J. (2018). Investigation of design for additive manufacturing in professional design practice. *Journal of Engineering Design*, *29*(4-5), 165-200. https://doi.org/10.1080/09544828.2018.1454589

[10] Laverne, F., Segonds, F., Anwer, N., & Coq, M. L. (2015). Assembly Based Methods to Support Product Innovation in Design for Additive Manufacturing: An Exploratory Case Study. *Journal of Mechanical Design*, *137*(12). https://doi.org/10.1115/1.4031589

[11] Wiber, A., Persson, J., & Ölvander, J. (2019). Design for additive manufacturing - a review of available design methods and software. *Rapid Prototyping Journal*, *25*(16), 1080-1094. https://doi.org/10.1108/RPJ-10-2018-0262

[12] Kozior, T. (2020). The Influence of Selected Selective Laser Sintering Technology Process Parameters on Stress Relaxation, Mass of Models, and Their Surface Texture Quality. *3D Printing and Additive Manufacturing*, *7*(3) 126-138. https://doi.org/10.1089/3dp.2019.0036

[13] Pahl, G., Wallace, K., & Blessing, L. (2007). *Engineering design: A systematic approach*. Berlin: Springer. https://doi.org/10.1007/978-1-84628-319-2

[14] Maidin, S. B., Campbell, I., & Pei, E. (2012). Development of a design feature database to support design for additive manufacturing. *Assembly Automation*, *32*(3), 235-244. https://doi.org/10.1108/01445151211244375

[15] Perez, K. B., Anderson, D. S., & Wood, K. L. (2015). Crowdsourced design principles for leveraging the capabilities of additive manufacturing. *International Conference of Engineering Design*, 1-10.

[16] Lauff, C. A., Perez, K. B., Camburn, B. A., & Wood, K. L. (2019). Design Principle Cards: Toolset to Support Innovations with Additive Manufacturing. *13th International Conference on Micro- and Nanosystems*. https://doi.org/10.1115/DETC2019-97231

[17] Weiss, F., Binz, H., & Roth, D. (2016). Conception of a design catalogue for the development of functionalities with additive manufacturing. *DS 85-2: Proceedings of NordDesign 2016*, *2*, 002-011.

[18] Valjak, F., Kosorčić, D., Rešetar, M., & Bojčetić, N. (2022). Function-Based Design Principles for Additive Manufacturing. *Applied Sciences*, *12*(7). https://doi.org/10.3390/app12073300

[19] Watschke, H., Bavendiek, A. K., Giannakos, A., & Vietor, T. (2017). A methodical approach to support ideation for additive manufacturing in design education. *DS 87-5*

Proceedings of the 21st International Conference on Engineering Design (ICED 17), *5*, 041-050.
[20] Blösch-Paidosh, A. & Shea, K. (2019). Design Heuristics for Additive Manufacturing Validated Through a User Study. *Journal of Mechanical Design*, *141*(4). https://doi.org/10.1115/1.4041051
[21] Lindwall, A. & Törlind, P. (2018). Evaluating Design Heuristics for Additive Manufacturing as an Explorative Workshop Method. *Proceedings of the DESIGN 2018 15th International Design Conference*. https://doi.org/10.21278/idc.2018.0310
[22] Atzeni, E. & Salmi, A. (2012). Economics of additive manufacturing for end-usable metal parts. The International *Journal of Advanced Manufacturing Technology*, *62*(9-12), 1147-1155. https://doi.org/10.1007/s00170-011-3878-1
[23] Adam, G. A. & Zimmer, D. (2014). Design for Additive Manufacturing - Element transitions and aggregated structures. *CIRP Journal of Manufacturing Science and Technology*, *7*(1), 20-28. https://doi.org/10.1016/j.cirpj.2013.10.001
[24] Kranz, J., Herzog, D., & Emmelmann, C. (2015). Design guidelines for laser additive manufacturing of lightweight structures in TiAl6V4. *Journal of Laser Applications*, *27*(S1). https://doi.org/10.2351/1.4885235
[25] Graziosi, S., Rosa, F., Casati, R., Solarino, P., Vedani, M., & Bordegoni, M. (2017). Designing for Metal Additive Manufacturing: A Case Study in the Professional Sports Equipment Field. *Procedia Manufacturing*, *11*, 1544-1551. https://doi.org/10.1016/j.promfg.2017.07.288
[26] Ranjan, R., Samant, R., & Anand, S. (2017). Integration of Design for Manufacturing Methods with Topology Optimization in Additive Manufacturing. *Journal of Manufacturing Science and Engineering*, *139*(6). https://doi.org/10.1115/1.4035216
[27] Fu, K. K., Yang, M. C., & Wood, K. L. (2016). Design Principles: Literature Review, Analysis, and Future Directions. *Journal of Mechanical Design*, *138*(10). https://doi.org/10.1115/1.4034105
[28] Valjak, F. & Lindwall, A. (2021). Review of design heuristics and design principles in design for additive manufacturing. *Proceedings of the Design Society*. https://doi.org/10.1017/pds.2021.518
[29] Kurtoglu, T. & Campbell, M.I. (2009). Automated synthesis of electromechanical design configurations from empirical analysis of function to form mapping. *Journal of Engineering Design*, *20*(1), 83-104. https://doi.org/10.1080/09544820701546165
[30] McAdams, D. A. (2003). Identification and codification of principles for functional tolerance design. *Journal of Engineering Design*, *14*(3), 355-375. https://doi.org/10.1080/0954482031000091095
[31] Singh, V., Skiles, S. M., Krager, J. E., Wood, K. L., Jensen, D., & Sierakowski, R. (2009). Innovations in Design through Transformation: A Fundamental Study of Transformation Principles. *Journal of Mechanical Design*, *131*(8). https://doi.org/10.1115/1.3125205
[32] Novak, R. (2021). *Razvoj konstrukcijskih principa temeljenih na mogućnostima DMLS proizvodnog postupka, in Croatian* (eng. *Development of design principles based on DMLS manufacturing process*). Master Thesis, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture.
[33] Erden, M. S, Komoto, H., van Beek, T. J., D'Amelio, V., Echavarria, E., & Tomiyama, T. (2008). A review of function modeling: Approaches and applications. Artificial Intelligence for Engineering Design, *Analysis and Manufacturing*, *22*(2), 147-169. https://doi.org/10.1017/S0890060408000103
[34] Hirtz, J., Stone, R. B., Mcadams, D. A., Szykman, S., & Wood, K. L. (2002). A functional basis for engineering design: Reconciling and evolving previous efforts. *Research in Engineering Design*, *13*(2), 65-82. https://doi.org/10.1007/s00163-001-0008-3
[35] Borgue, O., Müller, J., Panarotto, M., & Isaksson, O. (2018). Function modelling and constraints replacement to support design for additive manufacturing of satellite components. *DS 91: Proceedings of NordDesign 2018.*
[36] Sass, L. & Oxman, R. (2006). Materializing design: The implications of rapid prototyping in digital design. *Design Studies*, *27*(3), 325-355. https://doi.org/10.1016/j.destud.2005.11.009
[37] Neeley, W. L., Lim, K., Zhu, A., & Yang, M. C. (2013). Building Fast to Think Faster: Exploiting Rapid Prototyping to Accelerate Ideation During Early Stage Design. *Volume 5: 25th International Conference on Design Theory and Methodology; ASME 2013 Power Transmission and Gearing Conference*. https://doi.org/10.1115/DETC2013-12635
[38] Rias, A., Segonds, F., Bouchard, C., & Abed, S. (2017). Towards additive manufacturing of intermediate objects (AMIO) for concepts generation. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *11*(2), 301-315. https://doi.org/10.1007/s12008-017-0369-0
[39] Valjak, F. & Bojčetić, N. (2019). Conception of Design Principles for Additive Manufacturing. *Proceedings of the Design Society: International Conference on Engineering Design*, *1*(1), 689-698. https://doi.org/10.1017/dsi.2019.73
[40] Gonçalves, M., Cardoso, C., & Badke-Schaub, P. (2014). What inspires designers? Preferences on inspirational approaches during idea generation. *Design Studies*, *35*(1), 29-53. https://doi.org/10.1016/j.destud.2013.09.001
[41] Goldschmidt, G. & Sever, A. L. (2011). Inspiring design ideas with texts. *Design Studies*, *32*(2), 139-155.
[42] Eckert, C. M., Stacey, M., & Earl, C. (2005). References to past designs. *Studying designers*, *5*(2005), 3-21.
[43] Blösch, K. (2020). *Design heuristics for additive manufacturing*. Doctoral Thesis, ETH Zurich.

Contact information:

Regina NOVAK, mag. ing. mech.
Faculty of Mechanical Engineering and Naval Architecture,
Ivana Lučića 5, 10000 Zagreb, Croatia
E-mail: rnovak@fsb.hr

Filip VALJAK, PhD, Postdoctoral Researcher
(Corresponding author)
Faculty of Mechanical Engineering and Naval Architecture,
Ivana Lučića 5, 10000 Zagreb, Croatia
E-mail: fvaljak@fsb.hr

Nenad BOJČETIĆ, PhD, Full Professor
Faculty of Mechanical Engineering and Naval Architecture,
Ivana Lučića 5, 10000 Zagreb, Croatia
E-mail: nbojcetic@fsb.hr

Mario ŠERCER, PhD
Development and Educational Centre for the Metal Industry -
Metal Centre Čakovec,
Bana Josipa Jelačića 22 D, 40000 Čakovec, Croatia
E-mail: ravnatelj@metalskajezgra.hr