

Digital design and manufacturing process comparison for new custom made product family – a case study of a bathroom faucet

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Abstract. The demand to fulfil a wider range of customer requirements is increasing constantly as well as the need for the customizable production tools. At the same time, the product life cycle as well as the lead time for product development shortens. To respond these changing needs, digital product development enables faster development of complex products but challenges the communication and the data management. Digital design methods and manufacturing processes enable this development and decrease the need for expensive prototyping. In this research, digital design and manufacturing process means such a process where design and manufacturing can be done even over long distances between physical location of designers and the production line. An empirical case study of a configurable bathroom faucet was performed. The digital design for manufacturing using sand casting and laser additive manufacturing as alternative digital manufacturing technologies were researched in this study as possible methods for manufacturing these configurable products.

Key words: configurable product, product development, parameterized modelling, laser additive manufacturing, sand casting.

1. INTRODUCTION

The challenge, facing the manufacturing industry today, is the growing demand of being able to fulfil a wide variety of the customer requirements fast and flexibly. By being able to answer directly to the customer needs, the market share can be

increased, an existing customer base can be maintained or even increased, a better coverage and profit can be achieved and the companies can operate more cost-effectively [¹⁻⁴]. The European industry has to invest in product development processes and in the designing of high-end and unique products to be able to compete with the low production costs of the developing economies. Generally, a unique product means a large variety of the parts in different geometries and high production costs per unit (low production efficiency, high amount of wasted time in the set-up and less opportunity for the automation of the process, etc). On the other hand, modularity and configurability can be used to reduce the total number of the required unique components, speed up the production and form a base for customizability even in the highly variable end-products. The product development projects can be collaborative. The design can be decentralized and the communication between the different disciplines is challenging [²]. The up-to-date information should be available for everybody to allow a smooth cooperative design process. This is why the digital design process can be an answer for this challenge. The additive manufacturing process for its part can be the technology to enable the digital design process by its flexibility and “degree of freedom” in the design.

In this study, the digital design process was used in a case study of manufacturing a bathroom faucet. Digital design and manufacturing are defined as a process where the design of the workpiece and the actual manufacturing can be done remotely. The term “digital” describes the ability of the process to handle such a digital data of the designed workpiece that it can be transferred from company to company digitally, e.g., via email. In addition, the requirements of the manufacturing methods include the ability to use the workpiece data in digital form.

The primary targets of the case study were to design a configurable CAD model of an electronic bathroom faucet and to study the effect of the selected manufacturing method on the design process. The studied manufacturing methods were the laser additive manufacturing (LAM) and sand casting.

For the process, the faucet design was chosen as the target design since in this research project the information on faucets was easily available through industry partners and as such the consultation on detail level made by professional faucet designers was engaged on the research goal. Also, a faucet as a product was considered to be globally so intuitively known that it would offer a good starting point to deliver new knowledge on the design process possibilities of a customer modifiable custom product manufacturing chains.

There are only few studies about comparison of the conventional manufacturing technology and the new generation manufacturing technology in terms of “additive manufacturing”. An important point of this study was to include such a conventional manufacturing method that fits into the concept “additive manufacturing” and in this study this was the sand casting. To be able to compare the physical properties of the example case of faucet and the demand of manufacturing metallic material, the new generation manufacturing method in this study was the laser additive manufacturing.

1.1. Background

Traditionally, prototypes in the industry are built for many purposes, but their building can be time-consuming and expensive, especially if there are different versions of them. Their time frame is large, when small series products are considered. The use of simulation decreases the need for the physical prototypes and speeds up the design and the manufacturing process [⁵]. In addition to the simulations, through the utilization of the virtual prototyping tools, the design can be optimized with the virtual prototypes without the real life prototype related manufacturing costs and delay times [⁵]. When the virtual prototypes are used as a part of the development process, the prototyping costs are reduced typically through time saving, and not so much through the material costs. On the other hand, many of the innovations that would be figured out through playing with the real life prototypes may be missed. So in this sense, there really is no one “best practice” scenario. This is why the physical prototyping, for example, through utilization of the additive manufacturing methods can be included as a part of the “virtual” prototyping processes.

To be able to use the virtual models as a part of the prototyping process or to be able to simulate the models, the part or product to be developed has to be modelled in a computer aided environment. The digital design can be used to help a faster development of the products and the computer aided design (CAD) allows the fast representation of ideas. This enables digital design of the complex products and product families, and the creation of the needed documents and the files for the digital manufacturing, e.g., for the LAM. The simulations of the virtual prototypes can be effectively done by the use of computer aided engineering (CAE) tools. The product data management (PDM) and product life-cycle management (PLM) systems permit to store and distribute a huge amount of information, created during the development processes.

In the group of the additive manufacturing methods, LAM is one of the techniques to build up the end-product through adding material on the base “layer” or on an empty base platform, and thus enables the manufacturing of complicated 3D products starting from the “scratch”. In the LAM process, the product is manufactured from fine grained metal powder layer by layer. The shape of each powder layer is melted by a laser beam, and at the same time, attached on top of the previous layers of the solid material structure. When this process is repeated multiple times, the workpiece with the desired 3D structure is achieved [^{6,7}].

Traditionally, the process of making a 3D model has been treated as a special technology of the well-educated and well-trained professionals, where the general public had no idea at all how the “magic” happens or they just did not have the tools available for them either to start to learn the art. As such, the development of user-friendly software and the quick and easy transformation from the digital product to the physical one via the manufacturing of a CAD drawing to a finished part has made additive manufacturing (AM) interesting for the prototyping and the modelling for larger masses than ever before. In addition,

the development of the laser technology to a new generation of fibre lasers with a better beam quality, with better energy efficiency and with a lower price has made this technology more usable even for the serial production. A wide pallet of the materials and an improved quality of the parts has decreased the gap between the end-product and the parts, manufactured with the additive manufacturing machines. This is mainly due to the development of more accurate machines and of the advances in the used materials [8].

Nowadays, it is possible to manufacture functional parts directly and the method of achieving this is not just for the manufacturing of prototypes and the conceptual models. For example, the aerospace company General Electric uses the additive manufacturing to manufacture fuel injectors: “*Technicians at General Electric weld together as many as 20 separate pieces of metal to achieve a shape that efficiently mixes fuel and air in a fuel injector. But for a new engine coming out next year, GE thinks it has a better way to make fuel injectors: by printing them.*”¹ The growing trend is towards making the parts in small batches and the end-use functional parts with long-term consistency [6].

Currently, typical application fields for the additive manufacturing, especially for the LAM, are concept models, light weight and complex hollow structures and diverse applications used in mechanical engineering, e.g., some of the Airbus A350 metal parts are made by using metal 3D printing methods and additive manufacturing². The reason why the additive manufacturing methods are not as widely spread as could be expected, considering the almost limitless freedom in the part design, is related to the manufacturing costs, which are higher in the new technology than in the traditional manufacturing processes [9]. As such, it is understandable why the first application areas are special cases, e.g., in the aerospace industry where the weight of an airplane is one of the most significant factors in the total life cycle costs. For example, the extra weight that could be avoided is expensive for the aviation companies, e.g., in additional fuel costs.

The LAM process can be used in the production of functional parts with a long-term usability. The method is currently reliable and ensures the mechanical properties and the geometrical accuracy of the workpiece. On the other hand, one of the bottlenecks of the wide industrial implementation of the LAM technology is the high price of the functional parts. This is mainly due to the process speed, which is relatively slow and the cause of the high production costs. The high cost of the end-product is nearly linearly related to the high cost of the machinery time in LAM. This is why the process needs to be fast enough to ensure the economic performance [6,9]. In this context, the speed is the total speed of the process, which is the unit of inspection. The lower manufacturing speed of the LAM, which is based on the manufacturing machine itself, can be accepted, if

¹ 15th Jan. 2012, WB Engineering: 3D Printing: Billion Dollar Industry Almost Ready to Go Mainstream, URL = <http://www.wb-3d.com/2012/01/3d-printing-is-a-billion-dollar-industry-and-is-almost-ready-to-explode-into-the-mainstream/>

² 24th Oct. 2011, Airbus.com, News & Events, Bringing new dimensions to Airbus production through Additive Layer Manufacturing, URL = <http://www.airbus.com/news/events-single/detail/bringing-new-dimensions-to-airbus-production-through-additive-layer-manufacturing/>

time can be saved in the design processes, in the set up times, in the finishing processes and in the quality control, as well. The meaningful speed in this sense is the total time spent from the idea to the end-product, and not just the speed of a sub-process in the case of unique, small batch products that are tailor-made to meet the customer specification [¹⁰].

1.2. Research problem

This paper in the field of the engineering design discusses the designing of a configurable product by digital systems. The initial challenge in the designing of an electronic faucet is to involve intuitiveness and user-friendliness. In addition, the data transfer and the communication between the designers with different professional backgrounds were studied. The requirements of different manufacturing technologies had to be considered when configuring the created CAD model. The challenge of a configurable design was to maintain all the requirements with each configuration throughout the designing and manufacturing process.

1.3. Aim of the research

The primary targets of the case study were to design a configurable CAD model of an electronic bathroom faucet and to study the effect of the selected possible manufacturing methods on the design. In this research, configurability was defined as the ability to parametrically modify the design of the model with only limited number of variable parameters to maintain similar appearance. The secondary target was to design the CAD model so that the manufacturing documents, i.e., the files for the manufacturing, could be produced for each of the configurations. The requirements and the challenges in this product development project were reviewed from the point of view of engineering design. The development of the faucet was limited to the configurable design of the spout. The requirements set by the selected manufacturing methods on the design were studied but the manufacturing of the product was excluded, it was to be carried out later.

2. METHODS

A commercial electrical bathroom faucet was used as a reference layout (Fig. 1) for the project. During the design of the configurable faucet the research team used the product design and development process model defined by Ulrich & Eppinger [²]. It was used, because it was familiar to the research group, but other possible design and development process methods can also be used.

The process of the faucet development project was divided into five different stages: 1) planning, 2) concept development, 3) system-level design, 4) detail design and 5) testing and refinement (Fig. 2). The planning stage was considered to be performed before the decision to start the design process and is not discussed here.



Fig. 1. Spout and internal components of the reference bathroom faucet.

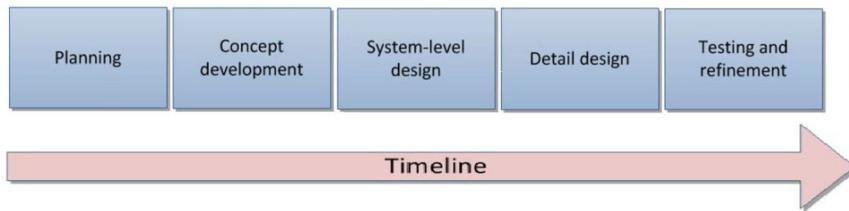


Fig. 2. Stages of the process timeline according to Ulrich and Eppinger [2].

The process is examined from the point of view of engineering design. The focus was defined during the concept development stage. The aim, set in the planning stage, was to design a configurable electric bathroom faucet family, to build prototypes and to compare the additive manufacturing techniques from the design, productivity and manufacturing points of view. Configurability was defined in the concept development stage as the ability to parametrically edit the size and the external shapes of the faucet spout, but still maintaining the original design outlook. As a further development of this concept, future versions of the model or models could then be used, e.g., by appliance sales people in end-user appliance stores.

The internal components of the reference electronic faucet (Fig. 1) were decided to be used in the new faucet design. To be able to create a working model of the faucet, the internal components were modelled with Pro/Engineer Wildfire (Pro/E) software. The team used these 3D CAD models as a reference in the concept development stage with Rhinoceros³ as well as in the system level and in the detailed design stages with Pro/E. The 3D models were transferred between these software in the STEP file format [¹¹].

The use of the existing internal components set restrictions to the faucet spout design. The components had to fit into the new spout. The positions and the inter-

³ Rhinoceros, Modelling tools for designers, <http://www.rhino3d.com>

faces of the water feed pipe, the thermostat controller, the sensor, and the fitting screw were also fixed, as well as the thread of the nozzle. Another requirement for the spout was to design the outlook so it would be intuitive to use. The outlook of each configuration has to guide the user to put the hands into the operation zone where the sensor recognizes the hands and to where the water jet is aimed at.

In this case, the system-level design can be considered to be divided into two steps: gathering of precise information and the CAD modelling. The requirements set by the two selected manufacturing methods, the sand casting and the LAM, were studied. The pattern for the sand casting was designed to be manufactured by 3D printing and the core box by NC milling. In the future, it may be possible to use patternless moulding, e.g., by milling the mould form directly into sand [12].

The CAD modelling of the spout started in Rhinoceros where the surface model of the final outlook was created (Fig. 3). The Rhinoceros model was then transferred into Pro/E. The model was entirely recreated in Pro/E, because the parametric configurability had to be enabled (Fig. 4). The used version of Rhinoceros did not support parametric modelling. The industrial designer, who made the first models, had long experience in working with Rhinoceros, so to have smooth start it was decided to use it in the first step of the modelling. Rhinoceros is widely used by the industrial designers, in general.

The imported geometry from Rhinoceros was used as the reference for the precise modelling in Pro/E. The profiles were approximated as lines, constant radius arcs and splines with a minimal set of control points. Certain geometric entities were first constrained to the imported geometry to maintain the original design and the constraints were then removed to allow the parametrical editing. This made the dimensioning easier, because the released constraints obtained automatically a correct dimension value from the software. These dimensions could then be used in the parametric model creation.

Based on this parametrical solution, a simple CAD model without any internal features was modelled. The demand for ability to modify the size of the spout was set earlier. The size could be edited by changing two parameters: the height and the length. To avoid the change of the desired outlook when editing the parameters, certain dimensions and geometric entities were set to change relatively to

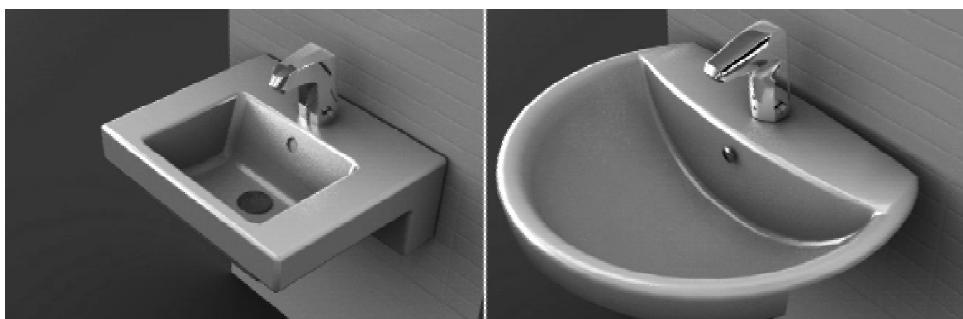


Fig. 3. Proposed concept models created with Rhinoceros software.

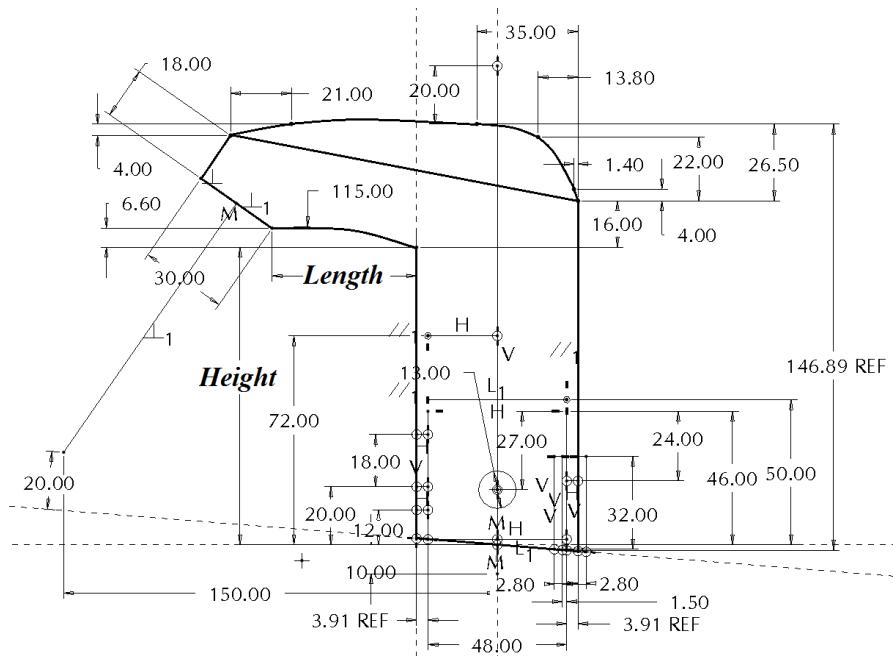


Fig. 4. Parametric model of the chosen concept. *Height* and *Length* can be modified by the design algorithm.

these parameters. If the length of the spout increases, the point, where the water jet is aimed at, does not increase as much, but remains in the hand washing area. In addition, a larger spout without relative sizing could look thinner than it was intended, so several dimensions were set to be in relation to the length parameter with a set of equations to maintain the original outlook with different parameter values.

Two types of relations were used. The first types of relations are the geometrical relations that keep the entities parallel, perpendicular, tangential, horizontal or vertical to each other. The second types of relations used were the dimensional relations, which change the chosen dimensions, based on the programmed formula, in a relation to the changes the user makes on the model. The setting of the relations was started with the easier geometrical relations. The designers then discussed, which shapes were desired to remain constant, and after that, formulas for dimensional relations were tested by giving different values for the height and length parameters and observing how the outlook of the design was changing. In this process, the examination was done to determine, what dimensions had to be related to the main parameters and how much they should change in relation to each other to maintain the desired form and shape, e.g., several of the dimensions were related linearly to the length parameter. The finalized parametric model is illustrated in Fig. 5, where 9 different sized instances of the spout model are shown.

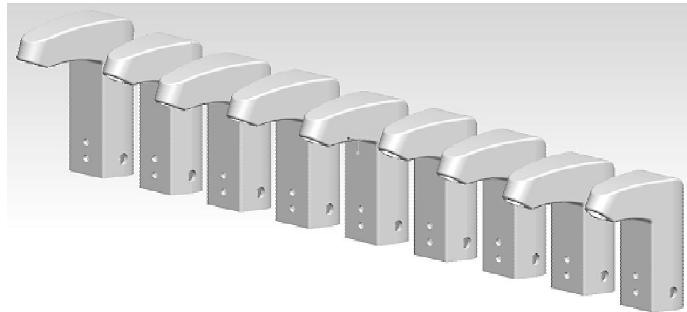


Fig. 5. Illustration of different sized instances of the faucet model.

In the detail design, the first prototype was made by ZCorp binder jetting machine. The purpose of the prototype was to ease up the discussion and the design of internal features, to see and to feel the designed models physical counterpart and to be used in the testing of the sand casting process itself. The prototype was binder jetted into two halves to see its internal space and to avoid the usage of cores in the possible sand casting tests.

The designers decided to build two separate CAD models, one for the sand casting and the other for the LAM to optimize the model for both manufacturing methods. The model designed in the system-level served as a master for both of these manufacturing-oriented models. The CAD models of internal components were used for designing the interfaces and the fittings of the spout. The required tapers for the sand casting and the overhang supports for the LAM set the major requirements for the CAD models. The LAM process itself sets some limits to the product design, because all the features with a lower building angle than 45° cannot be built (Fig. 6) without separate supports. This limitation is a result of the fact, that the powder material itself does not give enough support to the structures above it. Especially challenging are all the internal structures that need supports if the building angle is less than 45° since the later removal of them can be challenging. This was the reason to design all the structures for the LAM process as self-supporting, i.e., all the building angles were over 45° .

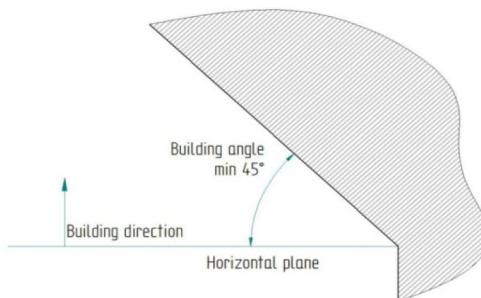


Fig. 6. Building angle in LAM processes.

A product model and a billet model were needed for both methods. The product model had all the machining features and it was a CAD representation of the final product. The billet model did not have the machining details. It was a model of the billet, produced by sand casting or by LAM. The cast billet had extra features as well, such as the offset taper faces and the fillets, which did not exist in the end-product model. The product and the billet features were modelled to the same CAD model and grouped into machining and billet groups. Additionally, a core box and a pattern had to be designed for the cast spout, which are needed by the casting method itself. To design them associatively, a CAD model of the core was created.

3. RESULTS AND DISCUSSION

The casting plan was designed collaboratively with casting experts. The joint line was the symmetry plane of the spout (Fig. 7). The casting gutter was designed to be connected to the water feed mount of the spout.

The sand casting set requirements for the tapered surfaces. All taper angles were set to 3° to allow easy removal of the pattern. The external surfaces of the cast billet were offset before tapering in Pro/E to take the required machining allowance and tolerances into account. Only the free hole for the water jet nozzle was designed to be cast but the nozzle thread and all the other holes were features, which would be machined on the casted billet afterwards. The machining features are illustrated in Fig. 8 (left).

The LAM process set different requirements for the design and the manufacturing. To minimize the number of the overhangs and to minimize the need for additional supports in the LAM model, the spout was designed to be built in the upside down position. This orientation minimized the number of the overhangs and allowed the structure to support itself in the build process. The only overhang is formed in the hollow water chamber. The machining features are illustrated in Fig. 8 (right). The counter bore will be machined after the LAM, because the connection with the water feed pipe has to be leak-proof. The challenge in making all the holes in xy direction (z direction is the building direction) with the LAM is that the overhangs without supports form droplets on the top surface of

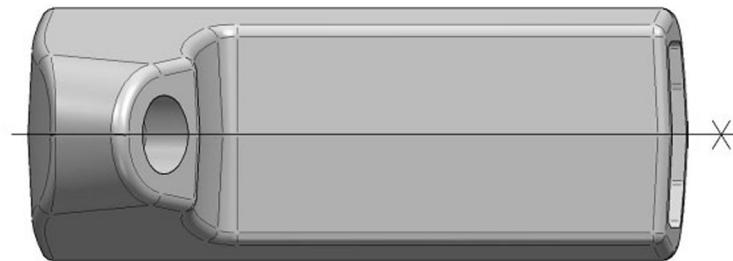


Fig. 7. Joint line of the cast model.

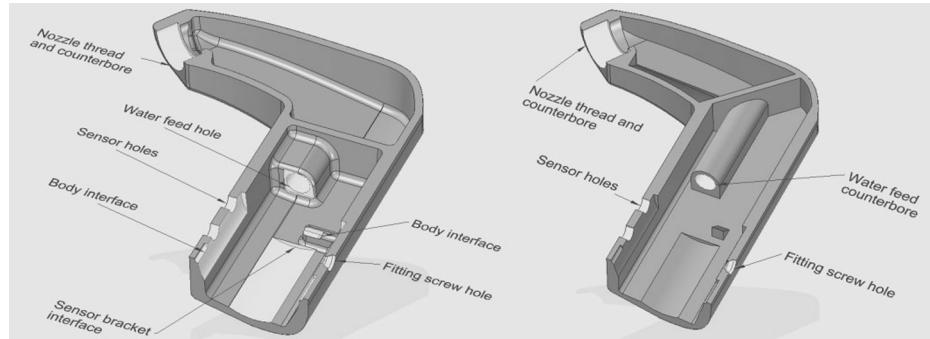


Fig. 8. Machining features of the sand cast spout (on the left) and of the LAM spout (on the right).

the holes [^{9,10,13}]. This is why it is advisable to manufacture them with conventional machining methods. Comparisons of duration of different design stages for the sand casting and for the LAM are represented in Table 1.

The consulting time includes the discussions with casting and LAM experts to optimize the geometries for the manufacturing methods. This time will be significantly reduced with the growing experience of the designer. Also, the time spent on the other stages will be reduced. The time to design the configuration model consists of the modelling of the configurable product model and the associative billet model. The reason for designing the family instances is to create and to select the customized models from the product family. The associative core, the core box and the pattern models were included in the tool design.

As Table 1 shows, time saving with LAM, compared to sand casting, is 46%. Since the time spent for each design stage linearly correlates to money, spent for

Table 1. Duration of different design stages of faucet geometry for sand casting and LAM in hours

Stage	Casting		LAM		Time saving by LAM of total time, %
	h	% of total time	h	% of total time	
Consulting	11	24	7	28	9
Configuration model	21	45	14	56	15
Family instances	2	4	2	8	0
Tools	7.5	16	0	0	16
Trail files ⁴	5	11	2	8	6
Total	46.5	100	25	100	46

⁴ Trail files are files made by Pro/E and contain the design steps made by the user. They were used for the automation process of the different instances of the faucet.

a certain design stage, it can be concluded that design stages of sand casting take much more time and money. Thus LAM can be stated to be economically more feasible if a product with small manufacturing pieces and custom made variable geometry is considered.

In practice, this means that if the size of the manufactured batch has to be taken into account when considering the cost of a single produced item. The cost efficiency of the LAM can be much better in small batches when compared to the one of a production technology, which requires tool design, e.g., sand casting, and this fact is the real promise of the LAM in the future. This is an issue, authors will study further and will provide publications of the topic.

4. CONCLUSIONS

The motivation for this research on configurable, i.e., parametrical, product was to apply digital design processes in a case study, and to study the effects of a conventional and of an additive manufacturing method on the digital design process. For this, a configurable CAD model of an electronic bathroom faucet was designed for two different manufacturing methods. The studied manufacturing technologies were sand casting and laser additive manufacturing. The current CAD systems are effective in designing complex and configurable products, which was also shown in this study. The used software tools were not the latest versions available, but they represent the typical high-end versions used by the industry.

The direct import of the CAD data in the STEP file format from Rhinoceros to a parametric model in Pro/E was not possible, because the software (Rhinoceros) used by the industrial designer did not support the parametric modelling, and thus made the remodelling in Pro/E necessary. The latest or upcoming versions of Pro/E software or software also from other vendors may provide a solution for this. The new version of Pro/E called Creo⁵ has the ability for parametric editing, which would be useful in modifying the model created in other 3D software, but the new version was not available for the team during this research.

As it was shown in the benchmark data, the design process for the sand casting was more time consuming than the design for the LAM: the manufacturing technique which requires tool design needs more time than the process which does not. In this case the geometry for the sand casting was more complicated, which can be seen in the consulting and in the configuration model creation times. The designing of the internal geometry of the cast spout as well as the planning of the casting orientation were relatively time consuming. The CAD modelling for the LAM did not need as much time, because no tools were required, but understanding of the process limitations of the LAM is required.

⁵ See PTC web page: <http://creo.ptc.com/>

Such limitations are, e.g., the support requirements and the design challenges of the overhangs.

Judging by the results of the study, it is reasonable to assume that in the future, if the build or the print costs of items using the LAM process will keep going down, many of the small batch custom products or components are manufactured using this sort of additive methods, because of the high costs related to the design, tool manufacturing or machining times of the products when using more traditional manufacturing methods. On the other hand, if the manufacturing by sand casting remains cheaper than that of the LAM, it is also reasonable to assume that it will remain the more dominant manufacturing method from these two for the larger batch products as there the design costs per item are small compared to the total manufacturing costs and the time used.

The authors aim to study further techno-economical aspects of manufacturing custom-made products with the help of sand casting and LAM. Also, configurability and effect of batch sizes to the feasibility of the processes are evaluated as they are important factors for the evaluation of the manufacturing technologies.

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Kohandatud tootepere digitaalne disain ja tootmisprotsess – vannitoa valamusegisti näide

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Tulemaks toime klientide järjest laienevate nõudmistega ja suureneva tootearendusele ning tootmisele suunatud ajasurvega, on artiklis vaadeldud digitaalset tootearendust ja tootmist. See võimaldab kokku hoida prototüüpimisega seotud kulutusi ja vähendada selleks kuluvat aega, ent samas nõuab see teatud pingutusi kommunikatsiooni ning andmehalduse vallas. Käesolevas uurimistöös toimusid digitaalne tootearendus ja tootmisprotsess geograafiliselt erinevates kohtades paiknevate inseneride koostöös. Reaalse näitena vaadeldi vannitoa valamusegisti arendustööd. Segisti digitaalne tootearendus ja tootmine sisaldasid tänapäevaste raalprojekteerimisvahendite kasutamist ning tootmistehnoloogiaid, nagu metallivalu liivvormi ja alternatiivse protsessina lasertehnoloogial baseeruvat digitaalset otsetootmist.