Direct digital manufacturing – the role of cost accounting for online hubs to access industry 4.0

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Abstract: *Additive manufacturing is an established production method to realize Direct Digital Manufacturing in Industry 4.0. Especially for metal components, production requires high investment sums and high levels of know-how in the organisation. To make the advantages of the technology accessible even without high initial investment costs, co-called online hubs became an external and decentralised alternative to additive in-house production. After uploading the geometry to the online portals, material and post processing can be selected. The hub gives the customer a direct pricing response which is one of the main economic indicators for a purchase decision. The present paper focuses on the influence of the order quantity and the complexity of the components on the price algorithm. Therefore, sample parts of varying complexity and sizes are developed and uploaded to analyse data. Based on the in-depth findings of the study, the results are discussed.*

***Keywords**: DIRECT DIGITAL MANUFACTURING, INDUSTRY 4.0, ADDITIVE MANUFACTURING, COST MODELS, ONLINE HUBS*

1. Introduction

The paradigm of Industry 4.0 is digitally and technologically driven. The production environment is reacting to the changes in the consuming market. Product life cycles are shorting and individual solutions are getting more important [1]. Multiple approaches have been made to overall describe the paradigm. As one result of a bibliometric approach, Industry 4.0 could be defined as the implementation of cyber-physical systems for creating smart factories by using the internet of things, big data, cloud computing, artificial intelligence and communication technologies for information and communication in real-time over the value chain [2].

One of the key drivers for cyber-physical systems in Industry 4.0 is the production technology of additive manufacturing. The layer-wise production allows enormous complexity of objects as well as function integration and geometry-close contours. For metals, the process of Laser- Powder Bed Fusion (L-PBF) is one of the most popular production methods [3]. The process consists of applying a layer of powder and then melting the required cross section with one or more lasers. This is repeated until the desired object is generated [4]. In recent years, there has been increased research into the applicability and further technical development of additive manufacturing. Nowadays, a wide range of materials can be used, including various metallic materials such as Steel Alloys, Titanium and Aluminium [5]. Another technical aspect of the research was the implementation of additive manufacturing in the production processes with the help of computers, software, networks and big data processing [6]. The connection of the virtual and physical components throughout the entire product lifecycle leads to Direct Digital Manufacturing (DDM) [7].

On the economic side, DDM eliminates the need for tooling and moulds for conventional manufacturing processes which leads to very low investments per object, especially for small quantities [8]. The larger the number of identical objects to be manufactured, the less profitable the additive process becomes. The fixed costs for toolmaking at conventional manufacturing are thus better distributed to each produced object. Some studies confirm that DDM has a good economic chance, especially for low-volume production [9, 10]. Another aspect favouring DDM is the decentralized supply chain. Components can be manufactured locally on demand when they are needed. This also gives rise to new business models, for example, the so-called digital spare parts. This newly gained flexibility makes the model of DDM interesting from a quantity of one. Nevertheless, there are still higher one-time investments to do when considering in-house additive manufacturing both on the machine as well as the human side [10]. Training and knowledge must be acquired to supervise and manage the complex process. This is a huge challenge when it comes to adoption in the industry, especially for small and medium sized enterprises (SMEs) [11]. Alternatives such as external additive manufacturing on a flexible and fast basis are needed. Therefore, the business model of online hubs allows users to upload CAD geometry data via an online portal and select material and quantity (see Fig. 1). Then, the object can be ordered and is shipped to the customer after its additive production. The internal geometry processing algorithm and the cost modelling leading to the instant feedback of price and delivery times. Based on those data, the customer decides. These hubs follow the approach of a modular structure to effectively handle and manage the objects [12]. The key aspect of the decentralized solution is the optimal placement of components from different customers in the building chamber to keep costs as low as possible (nesting). Also, proper and accurate cost accounting is necessary to find the optimal way between own production costs and the offer for the customers. First studies have already dealt with the automated cost calculation especially for online hubs and have shown, that significant increases in efficiency of order processing can be achieved [13].

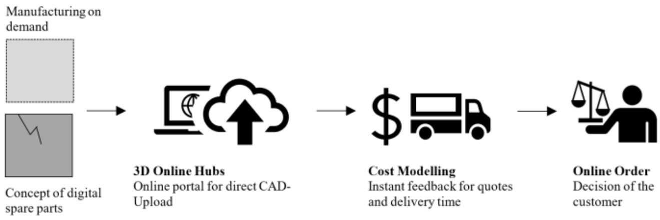

***Fig. 1** Process of Direct Digital Manufacturing via online hubs.*

In general, cost accounting for additive manufacturing is increasingly being discussed in the scientific community. Various cost accounting models have been developed, varying on the focus of individual equipment aspects [14]. The level of detail of the models also increased with the developments made. Aspects such as build time, energy consumption and orientation in the building chamber were included and became part of some cost models [15]. One of the main cost drivers is the number of ordered components. In addition, the complexity of the components is a decisive factor for reworking, since the individuality of the human worker is still required for most post processes.

As commonly agreed by researchers, the online hub model is characterized by several opportunities [16, 17]. Especially for urgent spare parts which are not in stock, this process is time- and cost-saving. Additionally, the external and decentralized model allows high flexibility for the customers. Geometry data could be adjusted and improved internally within hours when it comes to unforeseen damage or changed conditions or requirements. Despite the advantages, the model of hubs is more expensive compared to subtractive manufacturing with existing tooling. Also, the quality of the additive process still is in research and could lead to certification issues. Another problem is the smaller circle of available materials. Currently, Aluminium, Steel and Titanium are the most used materials. Besides the technological part, also the economic part is very important when it comes to decision making. Currently, cost models are not fully developed yet. Often, individual process steps are not sufficiently highlighted and cost accounting varies significantly. To strengthen the acceptance and uniformity of additive manufacturing online hubs, the present study investigates the role of cost accounting models of metal objects produced by L-PBF. Baldinger and Dutchi have done similar research in cost models for Polyamide 12 (PA 12) and Selective Laser Sintering (SLS) [18]. In contrast to their approach to plastic materials, the present study aims to evaluate metal material. Additionally, the methodology aims to select the online hubs more accurately.

Three research questions are more closely investigated in the following. Data is analysed whether cost accounting of metal parts for online hubs considers the complexity of the object and bulk orders in their pricing models. Additionally, the pricing difference between the several hubs is investigated. The results are systematically investigated and the generated data is analysed and presented. Afterwards, the results and the research questions are discussed. This novel approach leads to the first economic insights into the maturity of the online hubs.

2. Methodology

The methodology for the present research consists of two key aspects. On the one hand, test geometries have been developed. On the other hand, the functional scope of the online hubs is defined and systematic research is conducted to identify proper hubs. The data collection is then carried out manually. The test geometries consist out of three complexity stages and four volume sizes. To increase the complexity, the quotient of surface to volume is increased. This is done by including holes and shapes in multiple forms. Additionally, the holes are placed in multiple axes. This will increase the use of supportive structures during the process of production and the effort to remove the structures after the process by hand. As shown in Fig. 2, the complexity stages are low, medium and high. For one size, the volume of each dice, as well as the length of one edge, stays constant within the complexity levels. So, the change of the complexity will not affect the building height and the material price in the data analysis. The dimensions of the dice are "very small" (edge length of 6mm), "small" (12mm), "medium" (60mm) and "big" (120mm). As materials, Aluminium, Titanium and Steel (316L) are in the scope of analysis.

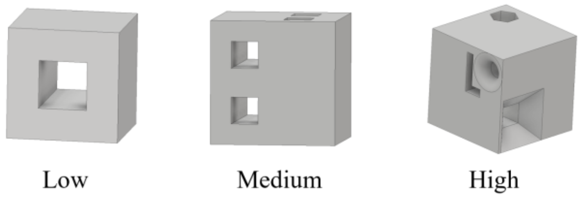

Fig. 2 *Developed complexity of geometries for the online hub analysis.*

To find the online hubs, a systematic web search is developed. The keywords are in English and German language and focused on internationality as shown in Table 1. In addition, further factors are determined which has to be fulfilled. These are a direct upload of the CAD file via an online portal, instant pricing feedback as well as a fully automated online ordering process without contact to physical persons. Within these boundaries, a systematic and methodical approach is developed.

Table 1*: Keywords for the systematic search of online hubs*

Technology	Material	Manufacturing Process
"3D Printing", "Additive Manufacturing", "Rapid Prototyping", "3D Druck"	"Metal", "Aluminium", "Titanium", "Steel", "316L", "Metall", "Titan", "Stahl"	"SLM", "DMLS", "Selective Laser Melting", "L-PBF", "Laser Powder Bed Fusion", "EBM"

Within the specifications of the systematic research, 32 hubs have been found. With further analysis, 4 hubs do not fully work as an online portal. The geometry has to be sent and transmitted via other tools. 12 hubs do not have instant quoting. Pricing feedback does not work for 2 online hubs (error message). As seen in Fig. 3, 14 out of 32 online hubs support online portals and instant quoting as defined in the methodology (44%). Overall, the online hubs have little transparency about the actual condition of the delivered component. Most of the hubs do at least remove the powder as well as the support structures. There are also minimum requirements for the size of the object as well as the minimum order quantity in terms of price. However, the developed methodology provides data of 14 different online hubs for every 3 materials, 3 complexities as well as 4 different sizes.

i.Materialise	Xometry
Shapeways	Protolabs
Sculpteo	Seedstudio
3D Hubs	3DActivation
ExOne	FacFox
Rapidobject	Materialise on Site
Protiq	3DCompare

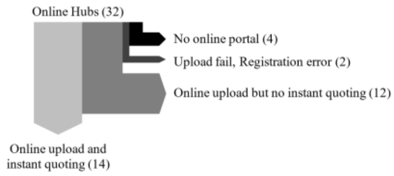

Fig. 3 *Available online hubs within the methodology.*

3. Results

Overall, 778 data sets have been generated by geometry uploads and analysed afterwards. One data set is defined as one geometry with one complexity and one size which is connected to one price. Therefore, most data sets with the material of Aluminium are available (335, about 43%). 316L is about 39% of all data (305) and Titanium about 18% (146).

The data was structured and analysed by using a statistical data program. The main focus was on the research questions beginning with the analysis of the complexity. As shown in Fig. 4, most online hubs do not consider the complexity within their calculation models. 87 pricing responses had a variation of 0%-1% if complexity is increased from low to high. 8 pricing responses had a variation of more than 4% in their pricing due to complexity. Additional, as shown, 4 prices have been decreased even though the complexity of the part was increased. It could be assumed, that most online hubs do not consider the complexity of the object, moreover the volume itself respectively the box volume is used for calculations.

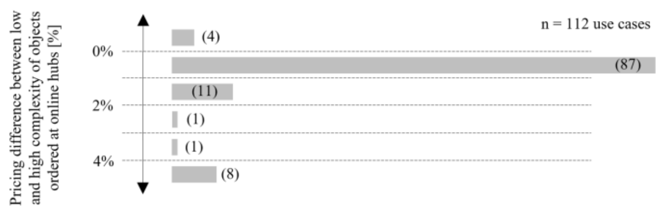

Fig. 4 *Pricing difference between low and high complexities of metal parts at online hubs.*

To analyse the economies of scale, prices per object for quantity one and quantity 500 were investigated. Therefore, the standardized price for one cm^3 is calculated. Fig. 5 compares the pricing differences for small parts orders (left) and big parts orders (right) for the defined quantities. The analysis shows, that prices mostly are not influenced by the number of ordered objects. Especially for big parts, constant pricing is not related to the number of ordered objects (iii, Fig. 5). For small parts, a little group of online hubs use the effect of bulk orders in their cost accounting models (ii, Fig. 5). Most hubs do not calculate with economies of scale (i, Fig. 5). This trend is not related to the materials of Aluminium, 316L or Titanium. It can be assumed that most cost accounting models for online hubs do not consider bulk orders in their pricing models.

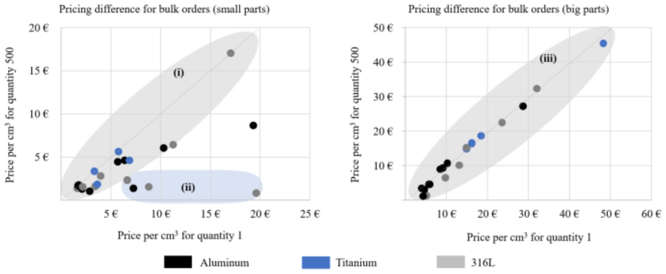

Fig. 5 Economies of scale for pricing at online hubs (small parts, left; big parts, right).

Moreover, Fig. 5 represents a reference to the average relative price (€/cm^3). Aluminium starts at about 2 €/cm^3 for small and 5€/cm^3 for big parts, as well as 316L. For Titanium, prices start at about 4€/cm^3 for small parts and about 15€/cm^3 for big parts (see Fig. 5).

For the analysis of the third research question, a boxplot of the prices for the three materials in relation to the multiple geometry sizes is illustrated in Fig. 6. The prices are calculated as an average of the complexity, whereas Fig. 4 has shown that complexity has very little influence on pricing differences. The lowest price for each size and material is used as a basis (100%, Fig. 6). Pricing differences show that especially for small parts of 316L and Aluminium there are high price ranges of up to 1,400%. For Titanium, the pricing ranges of bigger parts are higher than for small parts. In an absolute comparison, ranges are much lower than for 316L and Aluminium.

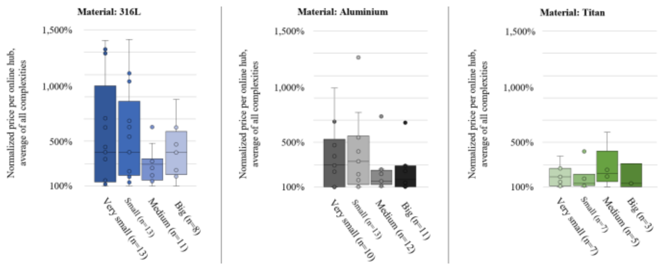

Fig. 6 Pricing range of online hubs for metal objects with multiple sizes at quantity one.

4. Discussion

Online hubs are a great opportunity for companies to benefit from the direct production of their components via additive manufacturing without high initial investments. To analyse the cost structure of these hubs, a methodology was developed and data analysed. Unlike Baldinger et al [18], the focus was on L-PBF as well as metallic materials (cf. SLS; PA 12). Prices of the materials Aluminium, 316L and Titanium were used as a data basis, with Titanium having a much lower weighting of 18% proportionally. This imbalance results from the offers of the hubs themselves, which on the one hand use Titanium only for larger components and on the other hand tend to offer Titanium less. For more detailed investigations, this deficit can be compensated by standardization. In addition, a rigorous and also limited methodology was used for data analysis. Due to the focus on the English and German languages in the research of the available online hubs, the Asian region may have been pushed into the background. In addition, the resulting larger database when considering the Asian region would enable a more substantiated statement. The rapidly developing field of DDM, additive processes and online hubs require constant new data collection and evaluation. In a further step, the selection of materials can also be increased. Nickel and Copper are playing an increasingly important role in additive manufacturing and can also be made accessible via online hubs. For a closer look at the cost models stored in the online hubs, it may also be useful to expand the methodology and use different geometries. This would highlight possible weaknesses as well as strengths even more clearly. However, this will not help the overall goal of improving the cost accounting models.

As shown in the present research, online hubs show a lack of transparency regarding the condition of the produced part, its post-processing and the shipping. Points such as the removal of the support structures, the alignment of the components in the build space, as well as the production parameters and the associated properties cannot be viewed. In addition, the de-powdering is not assigned to the price. Online platforms could provide the user with simple tools to define functional areas or apply for tolerances. This would allow the hubs to be directly integrated into the DDM.

When discussing the research results and research questions, it is clear that online hubs do not take complexity into account. Increasing complexity in all building directions requires much more complex rework and longer de-powdering. 78% of the reported prices for a rise in complexity increase by a maximum of 1% (see Fig. 4). This indicates that only the material volume and the box volume have an impact on the price in the cost model. Also, due to more complex geometries, more support structures are required which might lead to a little increase of 1%-2% in pricing. During post-processing, where the rising complexity is mainly reflected, this does not seem to be implemented in the model or a package price is charged. Especially cavitation and near-contour channels play a major role in de-powdering and especially in support removal.

Additionally, only a small group of price data takes bulk orders into account (Fig. 5, left). The effect of economies of scale is attributable to the distribution of fixed costs and should also be found in the additive process [19]. Cleaning costs, checking of the parameters and the machine hour rate can be distributed to all components in the building job. This effect is mostly realized when it comes to an increasing number of small components. In Fig. 5, it can be seen that only three price data have taken this into account, while for large components the effect did not come into play. However, the strategy of the online hubs also has to be critically questioned. If the building chamber of the machines is used to the maximum and components from different customers are placed in one order, all fixed costs are already distributed to the components in a standardized manner.

The price difference studied in Fig. 6 varies depending on the material and size of the component. Especially for 316L and Aluminium, enormously high differences of up to 1400% can be observed. Due to the higher availability, there are also greater differences from provider to provider. For Titanium, the differences are up to 500%.

Based on the findings of this research study, it is worthwhile for SMEs and customers to compare several online hubs. In general, however, enormously high differences can be seen. On the one hand, this may be due to the new technology and the different concepts of the hubs. On the other hand, however, an inadequate cost accounting model in the background can also lead to those large variances. Machine utilization and the degree of automation also play a major role. Despite the autonomous mode of the operating L-PBF systems, a lot of work has to be done manually, which can be classified as a cost driver.

Basically, the procedure shows that several online hubs might use different cost models for pricing their components. Since there is no transparent insight into the procedure, only conclusions can be drawn based on the available data. However, the wide price ranges and the failure to take complexity into account, in particular, is strengthening this thesis. The existing practice deficit has thus been proven.

5. Conclusion

Online hubs can fill the investment gap that has emerged for SMEs. Additive manufacturing via online hubs is an attractive option for companies. Nevertheless, the cost models used for pricing do not yet seem to be able to fully reflect the complexity of an additive manufacturing process and its post-processing. This is shown by the present research. Further priorities can therefore be placed on the development of a holistic cost accounting model. In addition, complexity and economies of scale must move into the focus to meet with acceptance in the economy.

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