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A Cloud-based Platform for Automated Order Processing in Additive Manufacturing

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Abstract

Additive Manufacturing (AM) is increasingly used in the industrial part production. More than almost any other manufacturing technology, AM embodies the fourth industrial revolution (Industry 4.0). Even though AM allows a nearly direct manufacturing of parts out of their CAD data, the order processing still requires a lot of manual work. This paper addresses this issue by presenting a cloud-based platform, which has the intension to integrate and automate the order processing for additively manufactured parts. In addition to facilitating the order processing of the manufacturing service provider, the platform also serves as an interface to the customer. The focus of the platform is on an automation of the order acceptance, the offer calculation, and the part screening for the identification of appropriate AM parts. The paper builds an exemplary Industry 4.0 showcase by illustrating concepts and methods for an automation of the order processing and introducing the architecture of the implemented system. This includes web-based services for the management of parts and orders as well as an integrated analysis of geometry data for checking of manufacturability and quotation costing. The evaluation examines the efficiency and effectiveness of the platform.

Keywords: cloud platform ; automated order processing ; additive manufacturing (AM)

1. Introduction

Additive Manufacturing (AM) represents the fourth industrial revolution (Industry 4.0) more than any other manufacturing technology. AM allows a nearly direct manufacturing of parts out of their CAD data by building up parts layer by layer based on given 3D geometry data [1,2]. Within this paper, the focus is given to selective laser melting (SLM), which is the mainly used AM technology for metallic components.

One of the key components of Industry 4.0 is the Internet of Things and Services (IoTS), which enables services providers to offer their services via the internet [3–5]. The cloud platform, which is presented in this paper, connects the idea of an internet-based service platform with additive manufacturing. To have a clear understanding about the term of a cloud platform in the context of this paper, we define the term of a *cloud platform for manufacturing* as follows:

Definition 1 *Cloud-based Manufacturing Platform* describes a software application, which integrates and crosslinks several digital services for the manufacturing of physical goods (parts or components) in one web-based environment. It is hosted in the cloud (on web servers) and provides access to user or programming interfaces (for the customer and the service provider) via the internet.

Although AM is close to the principles of Industry 4.0, the order processing still requires a lot of manual work. Thus, one main objective of the integrated cloud platform is an automation of the order processing. Beside of presenting the workflow, concepts, and features of the implemented platform, the focus of the paper is given to an automated, web-based quotation costing, order acceptance, and part screening. The order acceptance process includes a checking of a part's geometry on manufacturing restrictions and design guidelines. A major difficulty in implementing AM is the

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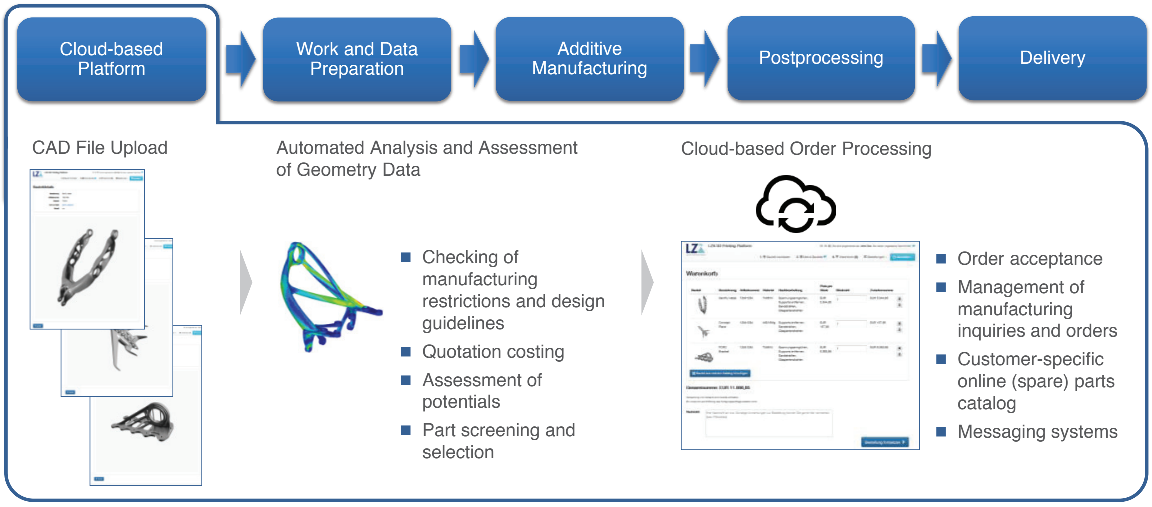

Fig. 1. Content and features of the cloud-based additive manufacturing platform (figure of optimized bracket: [6])

identification of appropriate parts. Therefore, this paper presents an easy-to-use part screening service, which is integrated into the platform.

The paper is structured as follows: Section 2 presents the related work and gives further background information. Section 3 describes the developed platform with a focus on methods and algorithms for an automated quotation costing, design checking, and part screening. Section 4 introduces the system's architecture and implementation. Section 5 evaluates the efficiency and effectiveness of the platform. Section 6 gives a conclusion and outlook.

2. Background and Related Work

In recent times, the first AM service providers offer the option to place orders online [7]. Examples for such commercial online portals are: i.materialise[1], Shapeways[2], and Sculpteo[3]. To the best of our knowledge, an integrated assessment of potentials (and part screening) is so far not state of the art. As introduced in Section 1, this paper presents an integrated approach for an automation of the quotation costing, checking of manufacturability, and part screening. The related work is presented in the following:

A comprehensive overview of published cost models for AM technologies is presented in [8]. Grund and Schmidt present analytical cost models for SLM in their theses [9,10]. The quotation costing, which is presented in this paper, adapts and expands these approaches to a generic model, which automatically calculates the unit costs for a part. Cost drivers, such as the build height of a part or the capacity utilization of a build job, are determined by a statistical method.

In order to ensure a fault-free AM process and provide required qualities (e.g. shape and position tolerances), certain manufacturing restrictions and design guidelines have to be considered. In recent research, process- and material-specific guideline catalogs have been developed [11–15]. We analyzed existing design guideline catalogs to select these guidelines, which allow an automated checking based on a part's STL file: part dimensions, wall thicknesses, gap dimensions, cylinder, and borehole diameters. For these guidelines checking algorithms have been developed.

Several different part selection and decision support methodologies have been developed in the past [10,16–18]. However, all these methods have in common that their application requires high manual effort and a lot of user input. This paper addresses this issue by presenting an automated part screening methodology, which tries to fulfil the requirements to be efficient, effective, transparent, and easy to use. Basis of the part screening is an automated cost calculation and comparison with conventional manufacturing technologies (milling and casting).

3. A Cloud-based Platform for Additive Manufacturing

The aim of the platform is an automation of the order processing for additively manufactured parts in a web-based environment. Fig. 1 gives an overview of the content and the features of the presented cloud platform. On the one hand the platform builds the communication interface between the customer and the manufacturing service provider. On the other hand it supports the service provider in the processing of orders and inquiries.

3.1. Workflow and Features

The customer can upload the geometry data of a part via the web browser by an online form (see Fig. 2). Afterwards, the geometry is analyzed and an offer is automatically calculated (on the web server). On basis of the offer, the customer can place a manufacturing order. Manufacturing restrictions and design guidelines are checked to decide, whether an order can be accepted or must be rejected.

[1]`https://i.materialise.com/`, Accessed: Dec. 2016
[2]`http://www.shapeways.com/`, Accessed: Dec. 2016
[3]`http://www.sculpteo.com/`, Accessed: Dec. 2016

Furthermore, the platform provides functions for the management of manufacturing inquiries and orders. After the customer has placed an order, he or she has the possibility to view and track the current status of his or her order online at any time. The main processing steps are: data preparation, additive manufacturing (or generation process), post-processing, and delivery. In addition to that, the customer has the option to create his own online (spare) parts catalog, from which he or she can reorder parts. Messaging functionality ensures the communication between customer and service provider.

As an additional feature, the platform provides an online part screening to compare AM with competing manufacturing technologies and identify appropriate parts with suitable AM business cases.

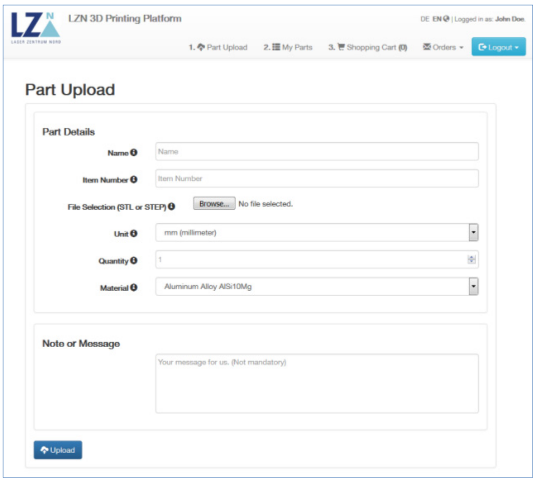

Fig. 2. Part upload via the implemented web-platform

3.2. Automated Geometry Data Analysis

The automated analysis of a part's geometry includes the determination of the volume, the surface, and the dimensions. These characteristic factors are used (as cost drivers) for the quotation costing, the part screening, and other analyses. The analysis is implemented on basis of the STL format (Standard Triangulation Language), which has establish as a de facto industry standard in AM [19,20]. In order to be able to handle CAD data (e.g. STEP), converters are used.

3.3. Quotation Costing

Input for the quotation costing is the analyzed geometry of the uploaded part (see Section 3.2), the material, and the number of pieces. The calculation is built upon the schema of a differentiating overhead calculation and an analytical cost model [21]. The total costs result from material, production, selling and administrative costs. A process cost calculation, which includes the part's generation and all necessary pre- and postprocessing steps, is used for the determination of the full production costs. To compute the build costs for one piece the following formula is used, which is composed of the build times for coating and exposure:

$$\begin{aligned} C_{Build} &= t_{Build} \cdot C_{mh} \\ t_{Build} &= t_{Exp} + t_{Coat} \\ &= \left(\frac{1}{v_{Melt}} + \frac{t_{Recoat}}{u_{BJ} \cdot h_{Recoat} \cdot l_{BC} \cdot w_{BC}} \right) \cdot (V_{Part} + V_{Sup}) \end{aligned} \quad (1)$$

where C_{Build} are the build costs for one piece, t_{Build} the build time for one piece, C_{mh} the hourly costs of a SLM machine, t_{Exp} the time for exposure, t_{Coat} the time for coating, v_{Melt} the melting rate, t_{Recoat} the time for one recoating, h_{Recoat} the layer height of one recoating, u_{BJ} the average capacity utilization of a build job, l_{BC} the length of the build chamber, w_{BC} the width of the build chamber, V_{Part} the volume of the part, and V_{Sup} the volume of the required support structures (estimated using an average factor on basis of a part's volume). The average capacity utilization describes the used average volume of a build job in relation to the potential total volume of a build job. It allows the modeling of different production contexts (e.g. build jobs with multiple mixed different parts), and may also depend on the build height of a part, which is estimated by a statistical model within the implemented cloud platform.

The preprocessing includes the data preparation (orientation in the build chamber and setting of support structures), and the machine setup. The postprocessing of a part consists of heat treatment, wire cutting (from the build platform), (manual) removal of support structures, and sandblasting for surface treatment [22]. The costs for the pre- and postprocessing are calculated using overhead rates and average processing speeds.

3.4. Order Acceptance - Checking of Manufacturing Restrictions and Design Guidelines

In order to have a common understanding, we define the terms *manufacturing restrictions* and *design guidelines* as follows:

Definition 2 *Manufacturing restrictions* describe restrictions of a manufacturing process or technology which prevent a part to be manufactured. A typical example for a manufacturing restriction of SLM is the size of the build chamber. In order to be produced a part must fit into the build chamber of a SLM machine.

Definition 3 *Design guidelines* describe recommendations for the designer or engineer, which should be considered in the design or work and data preparation phase, to ensure a flawless production and achieve the desired qualities (e.g. shape and position tolerances). Typical examples for design guidelines of SLM are wall and gap sizes, which should not fall below certain limits.

As part of the order acceptance for additively manufactured parts the cloud platform contains an automated checking of manufacturing restrictions and design guidelines (for SLM). Based on existing guideline catalogs [11,12], checking algorithms for a part's size, wall thicknesses, gap dimensions, cylinder and borehole diameters have been developed. The algorithms expect the data of a part in STL format as an input. The STL format describes an object by its triangulated surface geometry. For each triangle the three vertices and its normal vector are stored [20]. The developed checking algorithms use triangle distances and directions of the normal vectors to perform implicit feature recognition and detect critical areas. Based on the principle of convex (triangle normals diverge), concave (normals converge), and straight-lined structures (normals are nearly parallel to each other), cylinders and boreholes (for which other parameters apply) are distinguished from walls and gaps. Using the results, parts can immediately be accepted and go into production or rejected. More details about the algorithmic analysis of STL files can be found in [23]. Fig. 3 shows the result of the automated design check for test specimens.

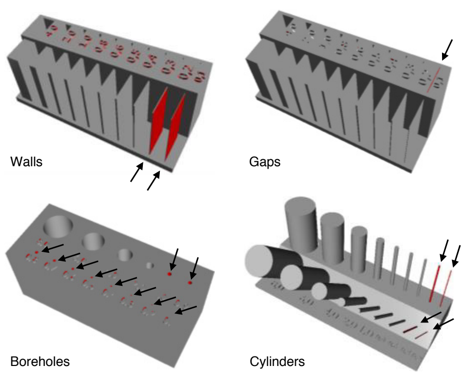

Fig. 3. Detected critical areas in the testing of titanium (TiAl6V4) on wall thicknesses, gap dimensions, borehole and cylinder diameters

3.5. Part Screening and Analysis of Potentials

The term *part screening* can be described by the following definition:

Definition 4 Part screening (in the context of AM) describes the process of analyzing (economic) potentials for a given set of parts to identify and select these parts, which have suitable AM business cases [24].

Since, especially for the industry (purchase department as a company function), the costs are the most decisive criterion for procurement decisions, the part screening methodology, which is presented in this paper, is based on an automated cost comparison of the additive manufacturing process with the competing manufacturing technologies machining and casting [10,25]. Based on the calculated costs, appropriate part candidates can be selected. The online upload of a part's geometry (as STL or CAD file) along with the information about the used material and the quantity to be produced forms the basic input for the part screening. SLM is one of the main representatives of AM technologies for the manufacturing of metal components. Within the presented platform, an automated calculation of the full production costs for SLM, CNC milling (representative for machining) and investment casting (representative for casting) is implemented. The calculation includes all necessary pre- and postprocessing steps. Fig. 4 shows exemplary a resulting line chart as part of the implemented web application. The chart allows a cost comparison of the three manufacturing technologies for different quantities.

3.5.1. Additive Manufacturing (SLM)

The cost calculation for SLM is based on the analytical cost model for the automated quotation costing, presented in Section 3.3. Since SLM can build multiple parts in one job, the capacity utilization of the build jobs is calculated using a two-dimensional packing algorithm [26].

3.5.2. Machining (CNC Milling)

The cost calculation for CNC milling (as subtractive manufacturing technology) is also based on an analytical cost modeling approach. One of the main cost components is the machining time. The calculation of the machining time is oriented on approaches of Bouaziz et al. [27] and Schmidt [10]. The total milling time is composed of times for roughing, finishing, and final machining of functional surfaces (boreholes, fits, …):

$$\begin{aligned} C_{Milling} &= t_{Milling} \cdot (C_{mh} + C_{wh}) \\ t_{Milling} &= t_{Roughing} + t_{Finishing} + t_{FinalMachining} \\ &= \frac{V_{RM} - V_{Part}}{Q_{Ro}} + \frac{A_{Part}}{Q_{Fi}} + \frac{A_{Part} \cdot p_{FS}}{Q_{FM}} \end{aligned} \quad (2)$$

where $C_{Milling}$ are the milling costs for one piece, $t_{Milling}$ the machining time for one piece, C_{mh} the hourly cost of a milling machine, C_{wh} the hourly labour costs of a worker, $t_{Roughing}$ the time for roughing, $t_{Finishing}$ the time for finishing, $t_{FinalMachining}$ the time for final machining of functional surfaces, V_{RM} the volume of the raw material, V_{Part} the volume of the part, A_{Part} the surface area of the part, p_{FS} the percentage of functional surfaces on the part's surface, Q_{Ro} the average volume rate for roughing (including idle machine times), Q_{Fi} the average surface rate for finishing, and Q_{FM} the average speed for the final machining of functional surfaces.

3.5.3. Casting (Investment Casting)

The production costs for investment casting mainly consist of the costs for tools and the costs for the casting process itself. The (tool) costs of the necessary injection molds for the creation of the (wax or plastic) models are estimated using a statistical approach of Chougule and Ravi [28]. For the calculation of the casting process costs a statistical model based on a linear regression, which gets a part's geometry as an input, is used:

$$C_{Casting} = \alpha_1 \cdot V_{Part} + \alpha_2 \cdot x_{Part_1} + \alpha_3 \cdot x_{Part_2} \quad (3)$$

where $C_{Casting}$ is the unit cost for the casting process, V_{Part} the volume of the part, x_{Part1} the longest edge of the part's dimensions, x_{Part2} the second longest edge of the part's dimensions, and α_1, α_2, α_3 the regression coefficients. Data of an analytical post calculation form the data base for the training of the linear regression. Due to the complexity of the casting process and the variety of potential influencing factors, we decide to use a statistically based approach for the modeling of the casting costs. The development and of an analytical cost model would be impracticable and expensive.

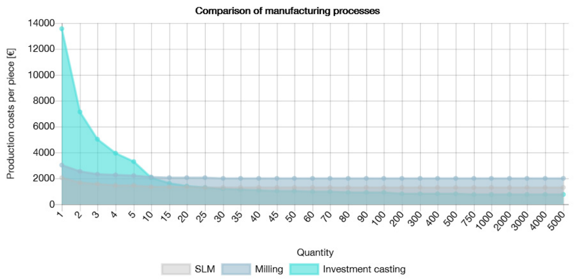

Fig. 4. Result of the part screening (part of application's user interface): Line chart showing a cost comparison of manufacturing technologies for different quantities

4. Implementation

Fig. 5 shows the system architecture of the implemented cloud platform as Fundamental Modeling Concepts (FMC)[4] block diagram. The architecture is oriented on the model-view-controller (MVC) software design pattern, which is widely used for web applications. The view builds the application's frontend and user interface to the customer, who accesses the platform via the web browser. It is implemented in HTML, JavaScript, and WebGL. The controller contains the business logic with modules for the management of manufacturing inquiries and orders, the geometry analysis, etc.. It communicates to the frontend and uses the business objects, described by the model. The model contains all necessary classes, e.g. customer or order, and stores the created objects into a relational database using an object-relational mapping (ORM) framework. CAD or STL files and pictures are stored in the file system. Controller and model are implemented in Java.

5. Evaluation

The evaluation focuses on the quotation costing and the part screening. First, the impact of the platform on the efficiency is examined. Afterwards, the effectiveness and accuracy of the presented methods is evaluated.

5.1. Efficiency

Fig. 6 shows the difference between a conventional (manual) quotation and the presented, automated, web-based method. It becomes clear that the conventional calculation process requires a lot of manual work and communication effort: For a manufacturing inquiry, the customer contacts the sales department of the service provider and sends the STL or CAD file of a part via email. The sales department forwards the inquiry to the production department (work and data preparation). There, the build height and support structures are specified. The results are returned to the sales team. Based on this, the sales team calculates an offer, which is send to the customer. The whole process can take up to four working

[4]`http://www.fmc-modeling.org/`, Accessed: Dec. 2016

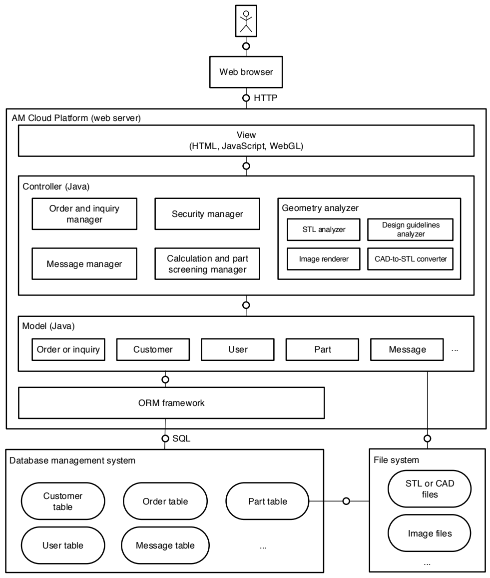

Fig. 5. System architecture of the implemented cloud platform as FMC block diagram

hours per inquiry. Depending on the workload a response to the customer may take several days.

In the automated, web-based quotation the customer can upload the part's STL file by accessing the online platform. On server side a price is automatically computed within seconds or a few minutes (depending on the amount of data), and the offered price is shown to the customer. Based on the offer, the customer can directly place an online order.

Compared to the conventional calculation the complexity of the process is significantly reduced. The price calculation is completely automated and communication overhead is avoided. The work and data preparation department as well as (ideally) the sales department are no longer involved in the calculation process. Since all necessary calculations, and processing steps are integrated into one digital platform, several software tools, which were needed in a conventional calculation (e.g. a calculation sheet, the data preparation or computer-aided manufacturing (CAM) software, and possibly a customer relationship management (CRM) or enterprise resource planning (ERP) system), are no longer required. The reduction of time from 4 hours to 1 minute corresponds to an increase in efficiency of 240 times, which shows the great advantage and potential of the presented platform.

5.2. Effectiveness

For the evaluation of the effectiveness the calculated results of the presented algorithms are compared to a post calculation, which is based on real process times. There, the cost calculation for SLM shows a mean absolute percentage error (MAPE) of 8.2% on the build time. Within the part screening, the calculation for milling has a MAPE of 21.0% on the milling time. The MAPE of the calculated costs for the investment casting process is 22.9%. This shows that the presented costing method is suitable for an accurate preliminary calculation and part screening.

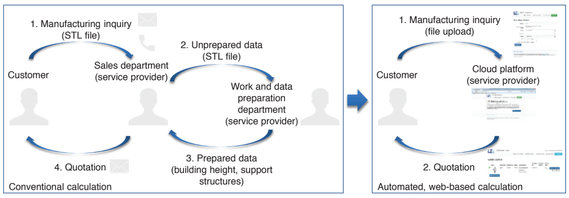

Fig. 6. Changeover from a manual quotation process to an automated, web-based method

6. Conclusion and Outlook

This paper presents methods and concepts, the implementation and the evaluation of a cloud-based platform for an automated processing in additive manufacturing. The focus of the paper is on an automated quotation costing, order acceptance (with checking of manufacturing restrictions and design guidelines), and part screening. In summary, a significant increase in the efficiency of order processing can be achieved by using the developed platform and the integrated algorithms. The evaluation shows the great potentials of a cloud-based platform.

Compared to conventional manufacturing technologies, AM offers a high degree of design freedom, which allows the manufacturing of complex lightweight structures [29]. Therefore, important topics for future research are the automated determination of a component's lightweight potential (through structural optimization) and the integration of design potentials in the part screening and selection.

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