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Adjusting the factory planning process when using immature technologies

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Abstract

Due to shorter product-life-cycles, innovations in production engineering have to keep pace with today's technologies. As a result, factory planning is more and more challenged by technologies being immature for series production. Usually, these immature technologies place special demands on production layout and quality management, for example. These demands have to be considered in the factory planning process. Moreover, technologies are part of the production process that is created by a series of technologies. Hence, a planning process has to ensure that the positive aspects of a new technology are not negated by arrangements to protect the technology chain against failure due to immature technologies.

With Selective Laser Melting (SLM) used as example for an additive manufacturing technology, this paper presents a method of planning a production system by taking the technology maturity into account. Possible requirements of an immature technology interacting with the process chain will be addressed as well as adjustments to be made to the factory planning process.

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Keywords: Technology maturity; Factory planning; Additive manufacturing; Selective laser melting; 3D printing

1. Introduction

There are a number of trends having an impact on the future design of factory planning and factory operation. Markets are more and more globally distributed, customer wishes are becoming more individual, new technologies and materials are used, life cycles of innovations and technologies are shortening [1]. In order to keep pace with competitors, more frequently, new and innovative products have to be introduced to the market with higher demands on component quality. Therefore, new technologies are essential for production facilities. The application of new technologies, however, involves technical and organizational risks [2]. For this reason, their use in production will only be possible economically once the technology reaches a treshold level of maturity [3].

As a consequence, existing factory planning approaches have to be adapted and further developed, so that they are capable to meet the technical and organizational requirements of new and innovative manufacturing technologies. Based on the example of the promising Selective Laser Melting (SLM) - a technology for additive manufacturing (AM) - a new approach for factory planning is developed that will deal with technological immaturity and reaches economic efficiency of the manufacturing process.

SLM offers the opportunity to bring individualized products with high functional integration from design to production within a short period of time and, thus, represents an innovative technology with high potential for development considering the industrial trends [4].

In general, the first step in every additive manufacturing process involves the creation of an accurate 3D CAD model according to the specific production requirements and design data. The realization of the structure with SLM technology layer-by-layer is characterized by steps such as powder application, local melting together of the layers according to the contour specifications of the 3D CAD model and lowering of building panel. After the actual production of the component, the supporting material and the excessive powder need to be removed in most cases. Before it can be used, the manufactured product is subject to post-processing steps such as manual grinding, deburring or sandblasting [4].

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The application range for SLM extends from the aerospace industry, benefiting most of all from the possible lightweight design, medical engineering and the production of individual dental implants, to the client-specific production in the automotive industry [5]. With Airbus A350 XWB, a component made of titanium manufactured by using an additive production method was applied in the aviation sector. The optimization of an aircraft engine bracket resulted in a weight saving of approx. 30% and a lead time reduction of 75%. For Airbus, this titanium component marks the beginning of series production of additive manufactured parts [6, 7].

This paper is divided into four parts: First, an overview of the related work is given and basic terms and methods for technology maturity assessment and factory planning are introduced. After that, the procedure for developing a new factory planning approach is presented. On that basis, the developed planning approach is applied to SLM technology and further elaborated. Finally, a short summary and assessment of the method is provided.

Nomenclature

AM	Additive Manufacturing
CAD	Computer Aided Manufacturing
DoE	Design of Experiment
NASA	National Association of Space Administration
SLM	Selective Laser Melting
TRL	Technology Readiness Level

2. Related Work

2.1. Technology maturity

In accordance with the guideline 3780 of the VDI (The Association of German Engineers) [8], the technology assessment involves the scheduled and systematic approach for examining the state of the art and its development opportunities, estimating and judging technical, economical and other effects and deducing from it possible actions and configurations. The technological maturity is an aspect of this assessment that was elaborated for the first time with the Technology Readiness Level (TRL) introduced by the NASA [2]. Building on this, numerous maturity level models have been developed [3, 9, 10, 11]. In this paper, the maturity level model of Reinhart & Schindler [3] which was developed for production technologies shall be used as the basis. This model offers the opportunity to express a maturity progress in the seven defined maturity levels on a percentage basis. Within every level, there are relevant technical and economic indicators which are evaluated with a questionnaire filled out by technology experts. Furthermore, the corresponding limits have to be exceeded on every TRL to show the necessary maturity for production. This model will serve as the basis for the factory planning approach presented below. The indicators to be collected meanwhile have to be specifically extended and adapted for every technology. For SLM, aspects such as component properties, process characteristics, economic requirements concerning system and material and the layout and function of the system have to be taken into account.

2.2. Methods for factory planning

The general task definition of factory planning is according to Greim et al. [12] that planning a factory must ensure a smooth production process without technical or economic problems combined with good working conditions for the employees. In a broader sense it means that ideal conditions should be created by taking into account various aspects and circumstances to reach operational objectives.

The exemplary planning approach according to the guideline VDI 5200 [13] consists of seven steps. Starting with target planning and analysis where basics of the planning process are identified. This is followed by the Structure and System planning where planning concepts are deployed and planned in detail. The next phases of preparing and monitoring the realization are leading to the last step being the startup support.

Due to the trends mentioned earlier, adaptations are made to conventional factory planning methods and new approaches are integrated. The principle of modularizing the planning process is pursued by Apel et al. [14] and further developed resulting in a separate method. By so-called freely configurable planning processes and their software-related support, the losses of effectiveness due to a planning that is divided into linear, deterministic and discrete phases shall be reduced. Within the individual modules of the factory planning object, planning activities are deposited which are applied as alternatives and generate case-specific results depending on information input.

The basic design of the production processes is created already during factory planning. If relevant requirements have not already been considered in the planning phase, resulting modifications with operations running can only be realized later at a considerable additional time, organizational and financial effort [15]. In order to avoid such a need for action and to first conduct a comprehensive and analytic technology maturity assessment of factory planning, a method shall now be implemented.

3. Methodology

The objective of this method is to combine the technology maturity assessment with an innovative factory planning method, to identify influencing parameters for an effective technical and organizational optimization of immature planning processes and to integrate relevant measures proactively into the planning process. For this purpose, a technology assessment and a comprehensive analysis of the production risks and problems is carried out first. Then, an effect analysis is performed with different indicators considered relevant. Based on the results, specific technical and organizational measures aimed at ensuring maturity and profitability of the manufacturing process are deduced and these will then be integrated into an innovative factory planning approach.

The sequence of this procedure for developing a planning approach is shown briefly in figure 1. Starting with a comprehensive technology maturity assessment by using the maturity level model of Reinhart & Schindler [3] for example, the actual state of the technological maturity is analyzed. In doing so, improvement potentials of the manufacturing process in terms of maturity level and technology shall be uncovered. Depending on the identified maturity progress the indicators can have a negative impact on the profitability of the manufacturing process and thus, have to be the main issue of optimization. The use of a technology that reveals a scrap rate of, for instance, over 5 % might not be advisable [3]. Certain indicators relevant for the maturity level are selected to illustrate in the next step the effect on performance of this manufacturing process with an effect analysis. In that regard, the design of experiment (DoE) method is applied to obtain a meaningful picture of the impact of the selected factors and their interactions with as little effort as possible. On this basis, specific measures to increase the manufacturing process's performance are subsequently deduced. The manifestation of significant influencing factors has to be optimized with highest priority. An effective and ideal impact of these measures shall be achieved by integrating them into the factory planning process in the final step. To this end, the modularized and freely configurable planning processes described in section 2 represent a suitable basis. Therefore, the factory planning contains the necessary amount of maturity related and technology specific elements.

Freely configurable planning processes offer the special feature that planning activities are deposited in the individual modules of the factory planning object which are applied as alternatives depending on the information input and generate case specific results. One single planning module contains several alternative methods and planning activities that differ in complexity and result [16]. Possible planning modules can be for example the layout, resources, quality control or the manufacturing process itself. This idea of individualized planning can be transferred to the context of immature manufacturing technologies. In this regard, information that serves as input is taken especially from the technology maturity assessment. The objective of this system that is based on digital tools is to choose automatically the technical and organizational measures and to implement interfaces to other planning methods on the basis of empirical values taken from similar and already evaluated planning projects. In doing so, a time and content related synchronization ensures the project progress towards an overarching goal. Unlike conventional planning approaches where the planning contents are determined by time, this approach allows to complement, parallelize or reprioritize the planning steps depending on the possible progression of the maturity level during the course of a project [14].

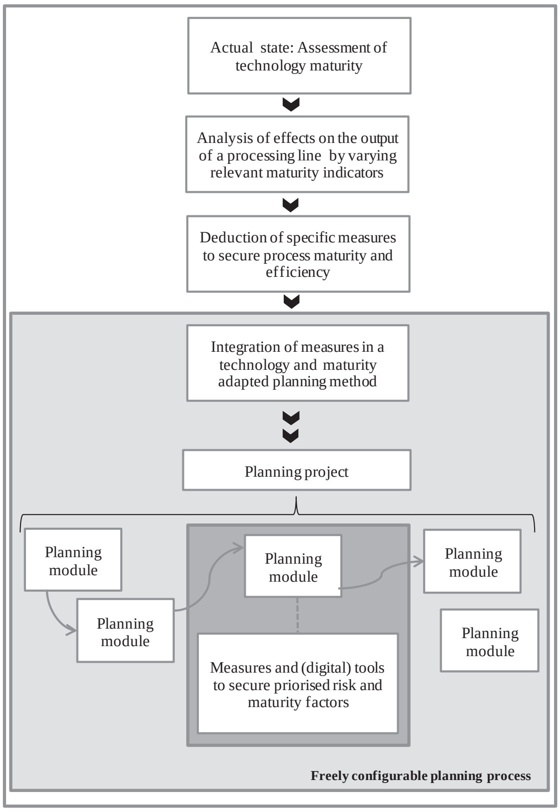

Fig. 1. Procedure for developing a new planning approach

4. Application for SLM

In the following, the previously presented methodological approach shall be applied to a simplified SLM production process. Economic and performance-related features of the SLM installations as well as the challenges that arise due to the immaturity of the technology [17] are considered when it comes to selecting the indicators determining the level of maturity.

The installation and material price (powder price) is integrated into the maturity model by Reinhart & Schindler [3] in terms of economic requirements. Further important technical indicators of the maturity level result from the desired component properties such as surface quality, dimensional stability and stiffness. Furthermore, the process capability must be integrated into the criteria catalogue as a reference value for the repeatable manufacturing accuracy as well as the degree of automation and the manufacturing speed.

In addition, employees must be professionally skilled and trained in the different areas of the SLM process [18]. Besides, factory planning is based on an unreliable data basis and different volume scenarios. Since the market for AM applications is rapidly growing [7] components which will be producible can only be specified insufficiently. The definition of technically adequate and economically reasonable test and measurement methods constitutes another challenge [19].

Meanwhile, SLM is undergoing a transition towards industrial implementation [20] where the mentioned inadequate criteria are to be implemented.

4.1. Influencing factors

The following performance indicators determining the level of maturity were exemplary defined for the manufacturing process with SLM.

Primary processing time und secondary processing time (A,B,C,D). The construction speed presents an evaluation criterion in the category of technical key figures [3]. Furthermore, it constitutes an important comparison criterion of additive processes within the process characteristics [21]. The processing time of SLM is divided into the primary processing time, which merely comprises the joining of the different layers, and the secondary processing time during which for example the powder layers are applied to the component and the cooling of the latter occurs [22]. It is at this point that the factors of the construction rate are consulted as the main influencing factors since they represent the primary processing time's main influencing variable. They result from the formula for the calculation of the construction rate: $\dot{V} = v_{scan} \cdot D \cdot \Delta y_s$, with v_{scan} standing for scan velocity, D_s for layer thickness and Δy_s for scan line spacing [22]. Consequently, the factors: scan velocity (A), layer thickness (B) and track pitch (C) as well as the secondary processing time (D) present influencing factors that need to be examined.

Setup time (E). The setup time, being an economic key figure, shall be minimized in order to achieve the most balanced ratio possible of value-adding and non-value adding production time. This parameter shall be examined as an influencing factor for the purpose of making the impact of an improved setup time visible.

Availability (F). The SLM installation's rate of availability shall be as high as possible to contain the risk of default.

The selected influencing factors are tested in the questionnaire on the maturity model by [3] at stage 5 (integration into equipment) and 6 (integration into production environment), consequently before stage 7 (application in serial production). Therefore, this selection covers the most important indicators of the relevant stages for SLM.

The influence of these factors shall be examined with reference to the target value **throughput** of good parts. This target value reflects the process velocity as well as the quality of SLM production. The measurement of the throughput consequently constitutes a relevant key figure of the process's economic efficiency and maturity.

4.2. Effect analysis

The DoE determines the effect of the selected factors on the throughput of a simulated and simplified reference process. Here, the advantage of the DoE lies in the fact that the examination of exemplary selected constellations of factor stages leads to the same results as a comprehensive test of all possible combinations. The so-called effect (also influence) of the factors describes the difference of the test results' mean values of the high and low factor stage. The effects for the effect analyses on the construction rate and thus the primary processing time of the reference process with the factors scan line spacing [mm], scan velocity [mm/s] and layer thickness [mm] are depicted in figure 2.

The graphical evaluation demonstrates that, in this simplified example, the scan velocity has the most significant impact (effect) on the construction rate and therefore the primary processing time. However, it should be noted that the effect on the target value is mainly determined by the selection of the factor stages. Consequently, the factor stages, in other words: the threshold values of the characteristic attributes, are to be determined by experts.

The standardized effects of the individual factors and factor combinations are compared to illustrate the impact of the influencing factors A-F of the throughput of the simplified reference process. The assessment of the results

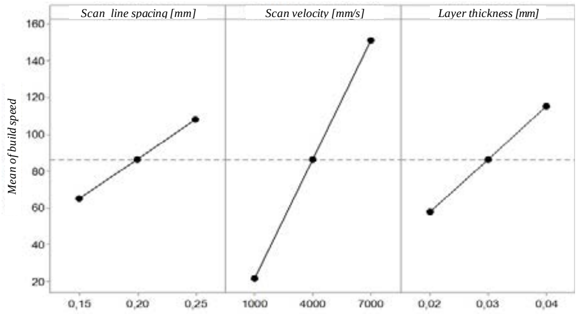

Fig. 2. Diagram of the effects of the influencing factors of the target figure construction rate.

is portrayed in the form of a Pareto chart of the standardized

The result demonstrates that scan velocity (A) has statistically the most substantial ($\alpha = 0.05$) impact on the throughput in the simplified reference process. This means, that the factor with a probability of error of less than 5 % is significant. Furthermore, layer thickness (B), secondary processing time (D), scan line spacing (C) and setup time (E) also have a relevant (since over 2.02) but less prominent impact on the throughput in this model.

4.3. Measures

The conclusions that can be drawn from the analysis of the results of the DoE of the simplified exemplary application are as follows:

- The most positive influence of the construction rate is achieved by increasing the scan velocity which constitutes a significant contribution in reducing the primary processing time.
- Further technical and organizational measures for optimizing the primary processing time can be implemented since the significant influence may also raise the throughput.

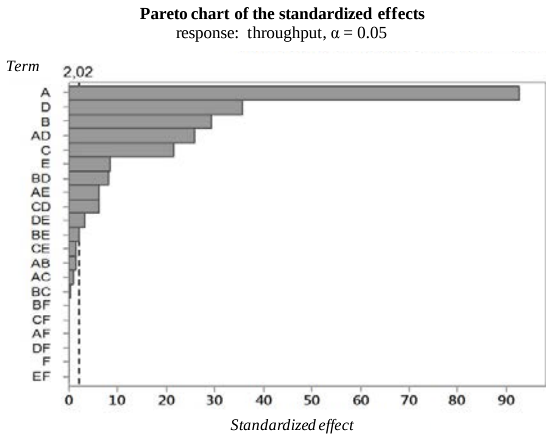

Fig. 3. Pareto chart of the effects on the throughput

- Secondary priority is attached to the optimization of the secondary processing time of the SLM process.
- As a general rule the following applies: The costs of the possible measures need to be compared to the expected increase of the throughput and individual threshold values for a viable balance must be determined.

The following technical and organizational measures have been or may be implemented for this purpose.
The so-called shell/core principle divides the component to be produced into the shell and the core area to which specific process parameters are attributed. Thus, this method is also referred to as adaptive SLM process management for increasing efficiency [23].

Measures such as two-sided powder coating as well as setting up and unpacking station which allow a parallelizing of the cooling down process and the construction process serve the purpose of reducing the secondary processing time. Furthermore, the automated powder management significantly reduce the setup time. However, a lower level of priority would be attached to its implementation in the case of a simplified application [24, 25].

Further organizational measures are elaborated by analyzing the components: man, material and method. Those factors are often use to classify the different influences on the production processes with an Ishikawa diagram. According to the Ishikawa clasification, the employees' qualification, capability and problem-solving skills, representing the factor "man", have a significant influence on the performance of any process in production. In an individual production scenario that is due to the great diversity of variants, strong problem-solving skills have positive repercussions on the process capability under the aspect of controllability. Predefined processes or checklists may prevent errors arising from monotony or excessive demand. Furthermore, studies on the implementation of innovation projects in production have demonstrated that early involvement and integration of employees in the form of workshops or training courses constitutes an essential factor of success [26].

A negative impact of the factor "material" on the performance of the SLM process may be reduced by using standardized and certified material [27]. In addition, supplier audits may be conducted to safeguard the quality of selected suppliers [28]. A positive impact of the subcategory "method" shall furthermore be aspired. To achieve this purpose, the instability of immature production technologies must be regulated with process parameters. The workpiece and application specific selection of standardized parameter sets improves the controllability and result of the throughput [27].

4.4 Integration into the factory planning method

In the last step, the derived measures shall be integrated into the freely configurable planning process or in other words: this innovative method shall individually be shaped according to [14]. The project's configuration is based on the selected planning tasks and planning modules which are required for the project presented here. For example, when an existing technology is substituted by an innovative production technology such as SLM, location planning no longer needs to be performed. Instead, the production area shall mainly be reorganized. According to the planning task, the "standard module" must then project-specifically be defined and particularized by allocating the identified measures to the respective modules. This way, for example, the management of human resources in the module also facilitates the recording of the demand for training. Thereby, the planning module may be dimensioned under consideration of existing resources, the available budget and in particular with respect to the progression of maturity. This means that the determination of the level of detail of planning as well as selection of adequate methods and workpieces is performed according to the technological maturity. Depending on the maturity of the technology, scenarios can be developed for the planning module quality management. Since in-line process control is urgently required in SLM production, because quality objectives have not yet been met, a simpler quality assurance measure may be implemented for more mature processes with higher process capability which for example could be performed by spot checks. The individual configuration of the planning object of standardized modules as well as the project-specific adaptation of the sequence allows the adequate planning of immature production technologies with SLM.

5. Conclusions

The developed planning approach lives up to the need to adapt installation planning based on the evaluation of technology maturity to the challenges and production risks of immature production processes. Freely configurable planning processes assure individual planning which can be elaborated specifically with regard to the degree of maturity as well as technology. A simple example of SLM application is used to demonstrate substantial influencing factors for the throughput of a reference process line and to derive effective measures. When using this method, the significant influencing factors fundamentally depend on the selected application case. Research presently deals with the further development of this method for achieving generic statements. The adapted planning method, which at the same time identifies optimizing approaches of an immature production line with SLM, constitutes another step towards promising future-oriented serial production with SLM.

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