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Additive Manufacturing Production Shops: A Requirements Analysis

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Abstract

Additive Manufacturing (AM) technologies become increasingly relevant for manufacturing companies. Despite having the highest share of AM applications, end-use parts are mostly used for spare or special parts and rarely within series applications. This paper addresses the challenge of practically implementing AM series production into industrial environments by means of a requirements analysis. It proposes a methodology on how to record, prioritize and meet requirements for AM production shops.

Successful implementation demands understanding of the requirements for AM production shops from both a factory and an AM perspective. Quality Function Deployment (QFD) is chosen as a methodology for the requirements analysis. It offers a framework for structured collection and weighting of the requirements identified through expert interviews with AM users and system manufacturers. Subsequently, measures and a basic plan of action on how to implement AM series production into production shops are defined.

The analysis reveals seven requirements for AM production shops within the categories spatial organization, process chains and flow systems. Most of them concern process chains, making these primary obstacles towards additive series production on the technical side. Substantial requirements are high process stability, fast process chains and the reduction of manual post-processing.
Different advancements are necessary on the AM and the factory side. On the factory side, measures that form synergies to conventional manufacturing technologies, such as cross-usable quality assurance systems, are favorable. On the AM side, focus lies on the enhancement of physical and digital process chains.
The results show that implementing AM production shops requires joint and interdisciplinary developments by AM users and system manufacturers. Further research and a larger sample are needed for validation as well as practical realization and advancement of the identified measures.

Keywords

Additive Manufacturing; Additive Manufacturing Production Shops; Additive Factory Structures; Quality Function Deployment; Requirements Analysis

1. Introduction

Conventional manufacturing technologies have reached full process maturity. They struggle to address the complexity of global market structures and customer requirements on individualization. To fulfill customer requirements and remain competitive, the flexibility of production systems becomes critical to success for manufacturing companies. These demands necessitate technological development and a redesign of production shops. [1]
In this context, additive manufacturing (AM) becomes increasingly relevant for manufacturing companies. AM technologies facilitate cost- and time-efficient as well as tool-free part production allowing for individualization and complexity for free. Profound development of AM technologies has led to a shift from prototyping and special part applications to industrial manufacturing of end-use parts [2]. Despite having the

highest share of AM-applications by now, end-use parts are still rarely produced within series applications [3,4].
Therefore, this paper addresses the reasons preventing the implementation of AM series production in industrial environments by means of a requirements analysis for AM production shops.

2. State of the Art

This chapter gives an overview on industrial AM and applications. Further, research on the implementation of AM series production in production shops is introduced.

2.1 Industrial AM

AM technologies produce parts from 3D model data by joining material layer by layer, as opposed to subtractive and forming manufacturing technologies [5]. The technologies are classified in seven process categories according to DIN EN ISO/ASTM 52900 [6]. Additional to the mere manufacturing process, AM requires pre- and post-processing operations, inter alia for meeting part requirements, resulting in AM process chains. Though differentiation depending on the AM technology, Figure 1 displays a generic AM process chain.

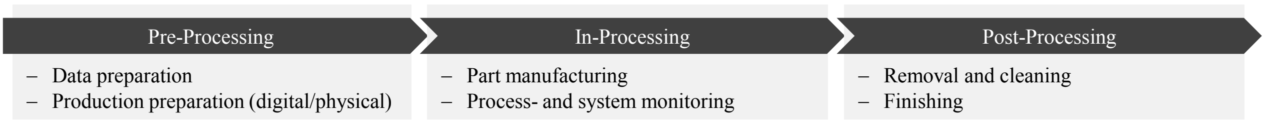


Figure 1: Generic AM process chain based on [7]

Industrial AM describes process chains with a maturity level high enough to compete with conventional manufacturing processes [8]. As of today, AM finds industrial use in highly complex and variable product programs or small batch sizes, for example in mass customization and mass complexity manufacturing applications. Further, AM facilitates strategies such as spare parts on-demand and digital warehouse. Additionally to these end-use part applications, low-volume series parts also begin to establish. The degree of the industrial integration of AM significantly depends on both industry and use-case [9].

2.2 Additive Series Production in Production Shops

According to Haleem and Javaid, large-scale integration of AM series production in production shops necessitates the consideration of AM as a digitized manufacturing technology and the fulfillment of the principles of modern, networked factories [4]. Breuninger et al. identify needs for adaption in the following fields of a production system for the implementation of AM series production: Spatial organization, product design methodology, quality, organization of logistics, handling of material and process flow [10]. Yi et al. address the integration of AM into manufacturing systems in the form of a holistic enterprise approach, emphasizing the need for quality assurance (QS) systems [11]. The main obstacles identified are a lack of know-how and high risks associated with the introduction of not yet widely established technologies. According to the authors, further research is needed regarding process chain and manufacturing-related barriers as well as counteractions. Kynast et al. identify the use of automated process chains planned over the entire manufacturing process as a requirement on a continuous additive process chain integrated into a manufacturing system [12].
Deradjat and Minshall record requirements for mass customization within the segments technology, operations, organization and internal and external influencing factors through case studies. Identified requirements are, inter alia, front-end software solutions, simplification of material handling, speed and stability of process chains, part design, employee trainings as well as supplier chains and business models. [13]

2.3 Interim Conclusion

The state of the art shows the relevance of AM for series production. Requirements for the implementation of AM series production already exist. However, approaches lack a methodology for the assessment of these regarding priority, applicability, usability and specification. This causes a gap between the weighting of the requirements and the defined targets, making the implementation of AM production shops more difficult. Previous research does not holistically consider the role of factories as production systems in fulfilling requirements, but rather focuses on the optimization of mere AM processes. This research approach closes the gap by using Quality Function Deployment (QFD) to record, prioritize and meet requirements for AM production shops from both an AM and factory perspective.

3. Methodology

Following, the pursued methodology is introduced through the QFD, the application of a house of quality (HoQ) as well as the data collection.

3.1 Quality Function Deployment

QFD is a methodology developed for planning products and processes. It focuses on the voice of the customer as the foundation for product design. First, customer requirements on the usability of a product are recorded and considered in the product development process. Second, based on customer requirements, design specifications and competitive analyses are carried out. Additionally to the design and optimization of products, QFD represents a methodology for planning tasks along the entire company value chain. QFD facilitates the accomplishment of planning projects, such as strategy, organization and technology planning. [14] The results determined through QFD can be illustrated through a HoQ.

Building on the results, measures for the optimization and development of products and planning processes can be derived by applying QFD, making it a favorable methodology to conduct a requirements analysis for AM production shops.

3.2 Application of a House of Quality

The general setup of the HoQ is shown in Figure 2 and follows the subsequent steps [15,16]. Depending on the planning object, not all steps must be performed. In this research approach, the planning object consists of the integration of AM series production in a production shop. Two HoQ are built due to the separate consideration of measures on the AM system manufacturer and user side.

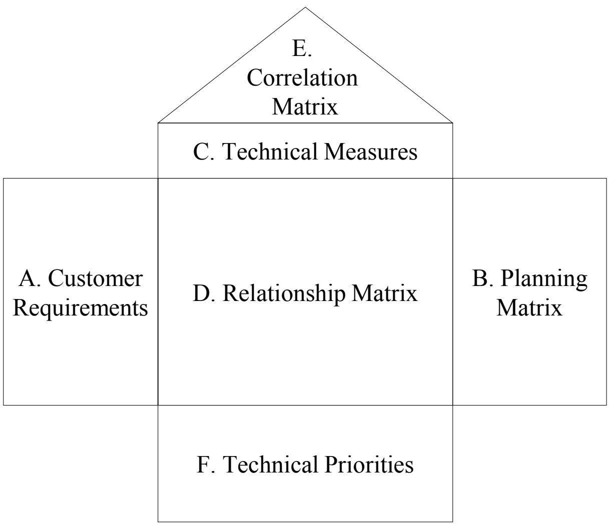


Figure 2: General setup of the HoQ

A. Customer requirements

Firstly, requirements that must be met to enable the use of AM in series production are recorded. Data collection tools serve this purpose. Secondly, the requirements are analyzed and interpreted to avoid doubling. Thirdly, sorting of the requirements into groups defined by the topics of the planning object takes place. Lastly, weighting of the requirements selected for the HoQ is conducted, taking into consideration additional data from market analyses.

B. Planning matrix

The planning matrix contains different representations, depending on the planning object. In the context of this research proposal, it reflects whether requirements must be implemented on the AM system manufacturer or on the factory side.

C. Technical measures

To fulfill the customer requirements recorded, technical measures are defined which are directly related to the requirements. Further, each measure requires measurable development potential. A target value and an optimization direction are assigned to each measure.

D. Relationship matrix

The relationship matrix shows the extent to which the technical measures contribute to meeting the identified customer requirements. Data from market analyses support this estimation. Predefined symbols represent the relationship between technical measures and customer requirements.

E. Correlation matrix

The correlation matrix, representing the roof of the HoQ, shows how the change of one technical measure affects other measures. Negative influences are considered separately in this step and taken into account during the planning phase. They represent the basis for trade-off decisions regarding the implementation of measures.

F. Technical matrix

In the final step of the QFD, a competitive comparison is carried out between the measures. For this purpose, market analysis data is evaluated with regard to target fulfillment of the measures. Following, their target fulfillment level is weighted against competing products.

3.3 Data Collection

Additionally to systematic literature research, expert interviews are conducted for the recording of requirements for the QFD. These are conceptualized on the semi-structured interview method, facilitating the obtainment of exclusive expert knowledge in the field of AM series production in industrial environments [17]. To integrate perspectives from different industrial sectors and companies into the requirements analysis, respectively four experts of both AM system users and system manufacturers are selected. To ensure optimum contribution to the research proposal, all interview partners have direct relation to either additive series or final part production.

A structured expert survey is conducted through a questionnaire in an online survey tool. Data collected through this method are used to quantitatively evaluate the aspects relevant to the research question. The design of the questionnaire is based on the elements of the HoQ with aspects to be collected mainly relating to the planning and relationship matrix. For measureable and comparable results, the questionnaire consists of only closed questions [18].

The majority of the questionnaire is based on an ordinal scale, describing the contribution of technological advancements to the fulfillment of requirements for AM series production. As a common instrument to determine the position of ordinal scales, the median of the results is used for evaluation. For a congruent data basis, questions with an interval scale are also evaluated using the median. The sample size is N=22, which consists of industrial AM users (27.3%), AM users in research institutions (36.4%), AM equipment manufacturers (22.7%) and other AM users and experts (13.6%). Most participants are AM department and project managers, as well as employees in research and development.

4. Results

The presentation of the results is structured according to the HoQ, including customer requirements, planning matrix, technical measures, relationships, correlations as well as a holistic integration.

4.1 Customer Requirements

As the aim of this study is the design of development measures for the integration of AM series production, only requirements relating to areas with further development needs are considered. All parties directly involved in the concept implementation for AM production shops are considered stakeholders of the planning object. The focus is on AM system users on the production shop and AM equipment manufacturers on the technological side. The identified requirements are weighted on a scale from "1" to "5" according to the results from the expert survey, with "1" having lowest and "5" having highest priority. Table 1 visualizes the recorded requirements, their classification according to structural factory areas as well as their weighting.

Table 1: Requirements identified through expert interviews

Structural Area	#	Requirement	Definition	Weighting
Spatial organization	i	Good integrability into existing processes	Adaption of manufacturing and post-processing operations of AM and conventional manufacturing	3
Process chains	ii	Fast process chains	Minimization of lead times	4
	iii	High process stability	Avoidance of unplanned downtimes and repeatable part quality	5
	iv	Little manual post-processing effort	Part separation from build plate, removal of support material	4
Flow systems	v	Simple material handling	Easy material supply and avoidance of material loss & contamination	2
	vi	Automated material flow	Integration of AM materials into an automated in-plant material flow system	2
	vii	Continuous information flow	Avoidance of information losses and media discontinuities within stations	2

4.2 Planning Matrix

Based on the requirements recording, the planning matrix states whether the responsibility for addressing the requirement is assigned to AM users (production shop) or AM system manufacturers (AM processes). According to the results, process chain related requirements must be addressed through AM processes. In particular, "fast process chains", "high process stability" and "little manual post-processing effort" are assigned to the AM process side by the survey participants. Flow system related requirements however are more likely to be addressed within the production shop. Material handling is identified as an important requirement. The fulfillment of simple material handling has a weak tendency towards implementation on the production shop side. The described tendencies remain mostly unchanged even under separate evaluation of the results from AM system manufacturers and users.

4.3 Technical Measures

In order to address the fulfillment of the requirements, measures for further developments on the AM system side (Table 2) and production shop (Table 3) are derived, dividing the analysis. For each defined measure on either side, a matching measure on the other side is defined to facilitate a comparison of both analyses. The definition of a target value and optimization direction enables the evaluation of the development status of each measure. These values are based on the results of the expert interviews and directly related to the previously defined requirements.

Table 2: Measures on the AM system side

#	Measure	Definition	Target	Optimization Direction
1	Communication capability of manufacturing equipment	Increasing degree of automation through interfaces enabling intelligent networking	Versatile interfaces	Improve
2	Software solutions of manufacturers	Software solutions to be integrated into PPS system	Cross-process planning and control	Fix target value
3	Machine robustness	Shielding of workspace against external influences (humidity, contamination)	No external influences	Fix target value
4	Integrated post-processing	Include post-processing steps, e.g. part cleaning or support removal into machine	Comprehensive	Improve
5	Material supply to machine	Improvement of interfaces for material supply to and material removal from machine	Closed materials cycle	Fix target value
6	In-situ quality control	Detection of defects during manufacturing process	Real-time analysis of production data	Fix target value

Table 3: Measures on the production shop

#	Measure	Definition	Target	Optimization Direction
7	IT infrastructure communication capability	Adaption of ERP system to simplify the integration of new	Versatile interfaces	Improve

		technologies and resulting planning tasks		
8	Product design software	Tools to optimize product design for AM processes	AI optimization of manufacturing data	Improve
9	Machine environment	Avoiding temperature and humidity fluctuations as well as contamination	Clean room	Fix target value
10	Peripheral post-processing equipment	Camera systems to automatically detect and initiate necessary post-processing steps on assigned machines	Comprehensive	Improve
11	Material supply	Automated material flow on the production shop, e.g. through automated guided vehicles	Automated	Improve
12	Post production quality control	Automated quality control using non-destructive methods to detect e.g. surface finish, dimensional accuracy	Line-integrated	Fix target value

4.4 Relationships

The relationship matrix represents the body of the HoQ. Therefore, it is an important step within the final evaluation of the QFD. Input data for this step are derived from the results of the questionnaire. Participants answer the question, “How does an improvement of the following design fields contribute to the fulfillment of requirement X?” The response options are “not”, “weak”, “medium” and “strong”, resulting in an ordinal scale. Measures assessed as non-contributing are not displayed in the correlation matrix. Measures influencing the fulfillment of requirements are marked with symbols based on a common representation of the HoQ:

- Weak correlation: △
- Medium correlation: ○
- Strong correlation: ●

The implementation of measures with strong correlations is recommended for prioritization to meet requirements. Figure 3 shows the relationship matrix between requirements and measures for AM processes and production shops.

Requirement \ Measure	1	2	3	4	5	6
i	●	○	△	○	○	●
ii	●	●	△	●	●	●
iii	○	○	●	△	○	●
iv	△			●		
v	△	○			●	
vi	●	○			●	
vii	●	●			△	○

Requirement \ Measure	7	8	9	10	11	12
i	●	○		○	○	●
ii	○	○		○	●	○
iii	○	○	○	△	△	●
iv		●	△	○		○
v	△	△		△	●	
vi	○				●	
vii	●				△	○

Figure 3: Relationship matrix for AM processes (left) and production shops (right)

4.5 Correlations

The correlation matrix shows how the measures influence the fulfillment of each other, both positively (+) and negatively (-). It is developed based on data of today's industrial manufacturing processes and findings from the expert interviews. The correlation matrix for AM processes and production shops according to the defined measures in Table 2 and Table 3 are visualized in Figure 4.

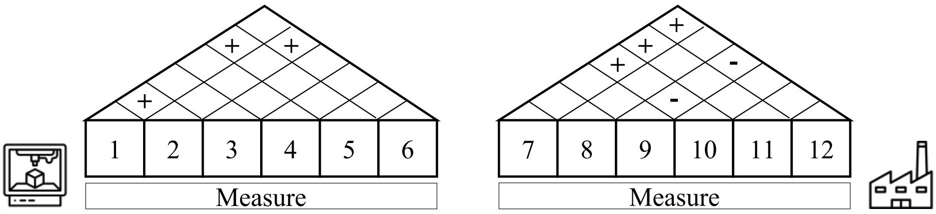


Figure 4: Correlation matrix between measures for AM processes (left) and production shops (right)

4.6 Integration of the Results

For integration and analysis of the results, the absolute weighting of the measures is determined. For this purpose, the symbols of the relationship matrix are assigned numerical values:

- Weak correlation "△" – 1
- Medium correlation "○" – 3
- Strong correlation: "●" – 5

To determine the total weighting of a measure and therefore the prioritization for implementation, the respective entry of the relationship matrix is multiplied by a requirement's weighting. The results are added up to the total weighting for each measure. Following formula is used for calculation:

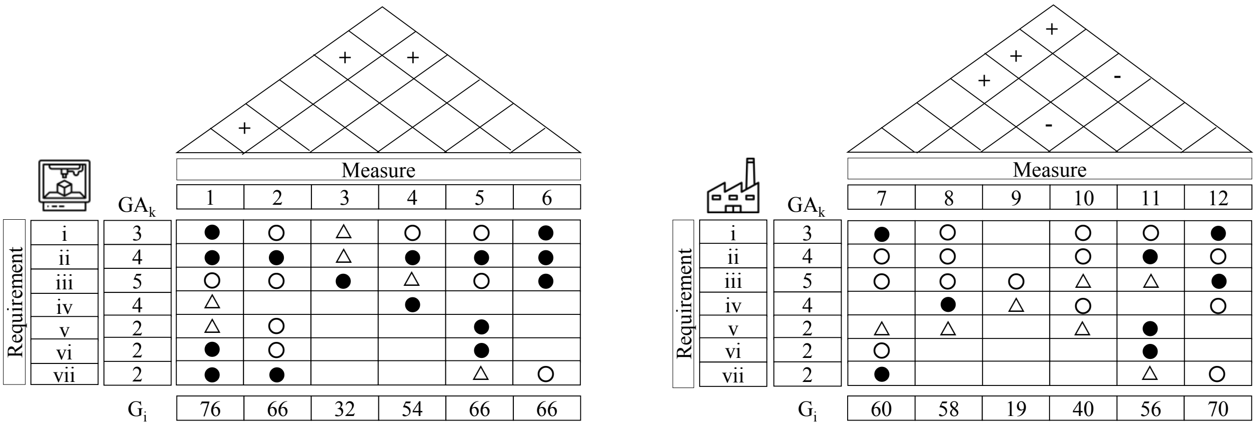
$$G_i = \sum_k GA_k * B_{ki} \quad (1)$$

G_i = Absolute weighting of measure i

GA_k = Weighting of requirement k

B_{ki} = Relationship matrix entry

The results are displayed in Figure 5.



Requirement	GA_k	1	2	3	4	5	6
i	3	●	○	△	○	○	●
ii	4	●	●	△	●	●	●
iii	5	○	○	●	△	○	●
iv	4	△			●		
v	2	△	○			●	
vi	2	●	○			●	
vii	2	●	●			△	○
G_i		76	66	32	54	66	66

Requirement	GA_k	7	8	9	10	11	12
i	3	●	○		○	○	●
ii	4	○	○		○	●	○
iii	5	○	○	○	△	△	●
iv	4		●	△	○		○
v	2	△	△		△	●	
vi	2	○				●	
vii	2	●				△	○
G_i		60	58	19	40	56	70

Figure 5: HoQ for measures in AM processes (left) and production shops (right)

5. Discussion and Conclusion

The evaluation of the requirements analysis reveals that requirements for an AM production shop must be met primarily through the development of process chains. The greatest need for further development is seen in the requirement for high process stability. Requirements for fast additive process chains and little manual post-processing effort also have high priority for the industrial use of AM. On the technical side, the development status of process chains within a production shop represents the greatest obstacle towards additive series production. Lower development need is attributed to requirements relating to flow systems within a factory.

This analysis allows drawing of initial conclusions on the greatest challenges in implementing an AM production shop at the current state. However, the derivation of further technological developments requires the consideration of sectors and technologies influencing the fulfillment of the requirements. Therefore, measures are evaluated revealing that further developments must be designed differently on an AM system manufacturer's perspective (AM process side) and AM system user's perspective (AM production shop).

Analyzing the weighting of the requirements, measures on the AM process side are mostly weighted higher than those on the AM system user side. The highest weighted measure is improvement of the communication capability of manufacturing equipment (measure 1). On the production shop side, measures that form synergies to conventional manufacturing technologies, such as cross-usable quality assurance systems, are favorable. Non-destructive quality assurance of every part is critical to additive series production, but can also be used for conventionally manufactured parts. On the AM process side, the main focus lies on the enhancement of digital process chains. Another focus area is the automation of physical processes. Additionally to the fully automated printing process, development activities by AM system manufacturers should lead to automation of up- and downstream process steps.

The results allow the identification of focus areas for further technological development for AM system manufacturers and users. They show that implementing AM production shops requires joint and interdisciplinary developments by AM system manufacturers and users. However, due to qualitative data collection, subjective bias of the results may occur. Therefore, the results must be examined with regard to the qualitative quality criteria of intersubjectivity and indication of the research approach. Further research and a larger sample are needed for validation as well as practical realization and advancement of the identified measures.

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