Evaluation of Parts for Additive Manufacturing utilizing System Models of AM Plants

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Abstract. The objective of this study is to provide the design domain with knowledge about restrictive geometric parameters for AM-compatible part design. This knowledge is derived from the existing technical plant configuration and its component parameters. Parameter relationships between the AM plant configuration and the design parameters are derived from technical documentations and guidelines. The system model of an AM plant is built in SysML to formalise the complex relationships of the restrictive parameters relevant for part design depending on the AM system configuration. AM Manufacturing Models are introduced to calculate the technical constraints between AM plant components and restrictive design parameters. AM Plant Models are developed to formalise the configuration of a plant with the required parameters for the AM Manufacturing Models. A GUI is conceptualized for easy configuration setup of an AM plant.

1. Introduction and Objectives
Additive Manufacturing (AM) processes are a key technology in the development of innovative products. In an age of ever-increasing complexity of cyber-physical systems, AM can be applied to manufacture complex parts for which conventional methods are not sufficient. Due to its young age, the possibilities of the processes are constantly expanding. However, with every further development of the AM processes, the restrictions on part design must also be considered. For the successful application of these emerging AM technologies, manufacturing experts and designers need frequent communication and an exchange of expertise regarding Design for AM (DFAM) guidelines and dynamically changing process parameters must be assured. In order to produce high quality, functional parts, detailed knowledge about the existing AM plants, their configuration and the influence on design parameters is required already in early design stages.

Overcoming these hurdles, the support of Model-Based Systems Engineering (MBSE) is a promising approach. MBSE is a suitable framework for linking knowledge in a formalised way and making it tangible company-wide. It is obvious that bringing AM and MBSE together should be considered to clarify the relationships between the production domain and design parameters. This offers the potential to shorten product development phases and provide an economic benefit for companies.

2. State of the Art
In the following, the state of the art regarding part identification for AM by AI methods as well as the potentials of a MBSE approach will be discussed to disclose the need for research in this topic.
2.1. Artificial Intelligence in Part Identification for AM
A first study has shown that parts with high potential for AM can be automatically identified in a CAD database using AI algorithms that evaluate the part complexity [1]. In this supervised learning approach, the relationship between given CAD-files as input data and pre-assigned output values is learned by an Artificial Neural Network (ANN) as AI algorithm. The derived classifier is suitable for assigning parts to the clusters "AM potential" and "no AM potential" with an accuracy of over 90%. The procedure and used toolchain are presented in figure 1.

In order to train the AI algorithms for the part identification, a sufficient amount of data with known input and output measures (labels) is required. To reduce the manual effort for data labelling, the toolchain was extended by a method for the evaluation of the manufacturability of a part. The calculation of the Additive Manufacturing Feasibility Indicator (AMFI) allows a quantification of the manufacturability in a given AM process and the use of this value as a data label for the training of AI algorithms [2].

Figure 1. Toolchain for AI part identification for AM and manufacturability evaluation [2]

2.2. Additive Manufacturing Feasibility Indicator
The AMFI is developed to evaluate the manufacturability of a part in a specific AM process during the design process. By determining the AMFI of a part, the design engineer can already identify production-critical geometric elements of the part during the design process and adapt the design. The measure allows to derive a statement regarding the manufacturability on the basis of quantifiable design parameters. For the quantification of the manufacturability, critical features of a part are analysed regarding general and process-specific factors that promote or disqualify additive manufacturing (see table 1). Furthermore, the effect of recognized critical features can be adjusted by user-specific weighting [2].
Table 1. Overview of the most important restrictive design parameters determining the manufacturability of AM parts [3 - 8]

| General factors                        | Process-specific factors                  |
|----------------------------------------|-------------------------------------------|
| • Minimum wall thickness               | Powder-based processes                    |
| • Minimum gap width                    | • Critical hole diameter                  |
| • Minimum bore diameter                | • Cavities                                |
| • Minimum cylinder diameter            | Material extrusion processes              |
| • Part orientation                     | • Min. cross-sectional area               |
| • Build volume                         | • Critical overhangs                     |
|                                        | • Islands                                 |

General factors include criteria that can be analysed equally across all additive manufacturing processes. Focused parameters evaluated by the AMFI are part orientation and build volume, minimum wall thickness and gap widths as well as minimum bore and cylinder diameters. As the description suggests, process-specific factors depend on the selected AM process that is used for the manufacturability analysis.

Regarding the process-specific analysis three AM processes are focused to cover a wide range of industrial relevant applications. As representatives of powder-based processes, Selective Laser Sintering (SLS) and Selective Laser Melting (SLM or LPBM) are focused. Looking into powder-based processes, powder removal is one critical factor that needs to be considered. Holes with critical diameter for powder removal and cavities are identified during the manufacturability check. Fused Layer Modelling (FLM or FDM) is considered as material extrusion process using polymers. Parts with critical overhang angles or islands can only be manufactured in these processes by applying support structures (see figure 2).

The criticality of the individual general and process-specific features depends mostly on the process capability of the additive manufacturing system and thus on its configuration. The installed components of the AM plant have a direct influence on the design parameters that should be respected in the part design. A practical example is the diameter of the heated nozzle (1), which has a direct influence on the minimum wall thickness that can be printed. Furthermore, there are a large number of parameters which are not obviously connected to the design parameters but have a significant influence on the manufacturability due to complex interactions with other parameters in the AM plant [9]. The relationship between the components involved in the travel precision of the nozzle in the x-axis direction and their influence on the minimum gap width can be mentioned as an example of non-trivial relationships.

At the present time, the knowledge of interrelationships is restricted for production domain and can only be transferred to the design domain by an interdisciplinary exchange with a high communication effort.

2.3. Model-Based Systems Engineering

Today's increasing complexity of products due to the ongoing integration of electrical and software in technical products is leading to challenges in product development. To meet these challenges and reduce complexity, the use of a superordinate knowledge repository as a Single Point of Truth (SPoT) is a

Figure 2. Principle layout of an FLM plant [7]
solution. The approach of Model-Based Systems Engineering (MBSE) offers great potential for the modelling of the SPoT, as it also enables the comprehensible modelling of the links. Further, it represents a centrally available repository that is used for development in the MBSE framework instead of decentralised document-based processes. The structure of the system model and the included relationships is supported by tool-independent modelling languages such as SysML (Systems Modelling Language). This graphical modelling language enables the modelling of product and design knowledge as well as the relationships between the individual knowledge elements. The advantage of the graphical modelling languages lies in their formalisation. Syntax and semantics are clearly defined and can be understood quickly and easily thanks to the graphical representation [10].

The foundation for the representation of different contexts is the possibility in SysML to allow different views on the same knowledge without duplicating information. Changes to the element of a product structure affect all other representations of this element, regardless of the viewpoint. The different views considerably improve the availability, use and communication of knowledge in development [10]. The use of SysML in a system modeler, e.g. the Cameo Systems Modeler™, offers further advantages. One of these advantages is the feasibility of the modelled rules and standards. The system model can thus be used as a design tool in development and construction, in addition to the pure visual representation of knowledge. This advantage is particularly effective in the integration in CAD environments, as a linked knowledge base for configuration setup [11, 12] and in the control of complexity [13].

In conclusion, the development of a system model is recommended wherever complex knowledge relationships from different company domains like manufacturing are to be formalised and made available globally. However, the MBSE approach is currently still on the threshold of broad industrial use. Especially in the field of knowledge engineering in manufacturing models further research is needed.

3. Need for Research
The preceding remarks on the state of the art reveal the need for research in the field of manufacturability assessment of parts for AM and the potentials of a connection with a Model-Based Systems Engineering approach in the AM production environment. In order to make a more precise statement about additively manufacturable features than is stated in general guidelines, a method needs to be developed to formalise the complex knowledge of the dependencies between restrictive design parameters and the AM plant configuration. The following research question and hypothesis are derived to address the white spot in the specific research landscape.

Research Question
How can restrictive design parameters be derived from the technical AM plant configuration and the knowledge be provided to the design domain to support AM-suitable part design?

- How can the complex knowledge about the relationships between AM plant configuration and restrictive parameters be formalized?
- How does the configuration of components in an AM plant influence restrictive manufacturing parameters for AM?
- How can the knowledge of the influences be made available to the design domain to develop an optimized part design?

Research Hypothesis
Restrictive geometric design parameters for AM can be derived from the technical AM plant configuration and formalised using SysML. The complex dependencies of the plant components on each other and their effects on the restrictive design parameters can be represented with clear syntax and semantics within a system model. The knowledge can be transferred to the design domain by linking the formalized models to a graphical user interface in CAD to support part design for AM.
Objective of the Study
The goal of the study is the development of a SysML model of an AM system in which the technical conditions are combined with restrictive design parameters for AM. The model serves the purpose of realizing a knowledge transfer of the complex relationships from the AM domain into the design domain to support optimized design for AM. Based on this overall objective, the following sub-objectives are defined for this study:

1. Derived correlations between restrictive design parameters for additive production and plant technology (process, plant type, configuration)
2. Established AM Manufacturing Model for the calculation of the restrictive design parameters that depend on the components of the AM Plant
3. Representation of AM Plant in an AM Plant Model which displays the technical interdependencies in a configuration of an AM plant
4. Realisation of the connection of the system model to the toolchain for the calculation of additive manufacturability

4. Methodical Approach and Materials
To support the knowledge exchange between design and manufacturing, a system model is developed, which provides the knowledge about AM plant related manufacturing restrictions directly in the design process. The system model consists of the two parts AM Manufacturing Models deriving the restrictive design parameters and the AM Plant Models representing the configuration of an AM plant. The AM Plant Models provide the relevant parameters for the calculations in the AM Manufacturing Models. The methodical approach for the knowledge transfer between manufacturing and design domain is illustrated in figure 3.

In order to achieve this goal, the interfaces and limitations observed for this study are defined. Looking into the design domain, the most relevant restrictive design parameters given in Table 1 are considered to connect the system model to the GUI developed for the CAD software Siemens NX to determine the AMFI. This ensures that the production knowledge is transferred into the design process to support AM-suitable part design by indicating geometrical elements that are critical for manufacturing. The knowledge about the relationships between restrictive design parameters and the
determining components of the AM plant is extracted and formalised from technical documentations, guidelines, existing component portfolio and user experience. Once the identification of the correlations is done, the relevant modules of the AM plant can be defined which have to be represented in the system model. Furthermore, the specific configuration of these modules and the management of the configuration is considered in the design of the system model. An approach is taken to make the setting of the technical AM plant configuration user-friendly via a graphical user interface (GUI) for the production domain.

As example this study uses the Prusa i3 MK3S 3D-printer as representative of an FLM-process. Overall, the developed method aims at realising an easy extensibility in order to integrate additional AM procedures and further dependencies of restrictive design parameters, which are not considered in this study. The methodical approach of each individual step is described briefly in the following chapters.

4.1. Correlations of restrictive design parameters and plant technology

The relationships between the components of the AM plant with the restrictive design parameters are first identified and analysed. In a young manufacturing technology such as AM, a high degree of system complexity can be observed due to the level of integration of electrical and software elements in addition to the mechanics. In this study, the modelling of these dependencies is illustrated by the following idealised example of the AM Plant Prusa i3 MK3S shown in figure 4.

The components involved in the nozzle movement in x-axis direction are highlighted. A stepper motor (1) controlled by the system software is required to convert electrical energy into mechanical energy. The motor is equipped with an output shaft to which a toothed belt pulley (2) is attached. A toothed belt (3) is driven by this pulley, which moves a carriage in x-axis direction on which the print nozzle (4) is located. With the resolution of the precision of the traverse paths in x-axis direction, design parameters like the minimum realisable gap width in x-axis direction can be concluded.

![Figure 4. Prusa i3 MK3S with highlighted components relevant for the minimum gap width](image)

The minimum realisable gap widths depend on the precision of the nozzle travel in the x-axis direction. The nozzle on the carriage is moved by a transmission of the rotary motion of the stepper motor via the pulley to a linear travel path of the belt. The travel thus depends on the angle of rotation of the stepper motor, also known as step angle and the diameter of the pulley on which the belt runs. This relationship can be described with mathematical calculations that are part of the AM Manufacturing Models described in the following chapter.
4.2. AM Manufacturing Models for the calculation of restrictive design parameters

As described above, the restrictive parameters depend on the plant configuration through technical constraints. Since considering all calculations of the restrictive design parameters exceeds the extent of this study, the development of a model describing the technical constraints are limited to the abovementioned idealised example.

In order to create the link between parameters of the AM plant components, technical constraints and restrictive design parameters, the necessary calculations are carried out in AM Manufacturing Models implemented in SysML. The basic structure of the AM manufacturing models is shown in figure 5 using the example of the FLM Manufacturing Model for the Prusa printer for the calculation of the minimum wall thickness as general restrictive design parameter.

In principle, different process-specific manufacturing models (e.g. FLM Manufacturing Model, SLM or SLS) can be integrated into the AM Manufacturing Models. Each of the specific manufacturing models contains constraints for the calculation of each restrictive design parameter depending on the respective AM Plant Models. General factors of the restrictive design parameters need to be calculated in each specific manufacturing model. Therefore, a connection to each specific manufacturing model is necessary. The calculation of the process-specific factors is only carried out in the respective manufacturing model. Figure 5 illustrates the calculation constraints to derive the restrictive design factors. The Idealised Model Travel Precision from the Model Library is represented in detail in the FLM Manufacturing Model as one of the calculation constraints. The other constraints integrated in the Model Library that are also indicated in the FLM Manufacturing Model, are used for the calculation of the other restrictive design parameters but will not be discussed in detail.

![AM Manufacturing Models](image)

**Figure 5. AM Manufacturing Models for the calculation of restrictive design parameters**

All models used in the constraints can be integrated in different fidelity levels, depending on the goal of the system modelling. In the given example, the Idealised Model Travel Precision can be extended by additional parameters on higher model fidelity levels to increase the value accuracy if necessary. For example, the connection of the specific spring rate of the belt can be drawn from the component in the AM Plant Model, to be included into a more precise calculation. The constraint Idealised Model Travel Precision...
Precision can thereby be supplemented on a higher modelling fidelity by adding the specific spring rate of the belt and the acting force to define the positioning deviation of the nozzle.

For the modelling of high-precision industrial processes, the consideration of dynamic characteristic values is elementary and can be added to the FLM Manufacturing Model and be connected to other calculation constraints. However, due to the global tolerances of the considered AM process, they are not elaborated in further detail within the scope of this study.

The calculation models in the AM Manufacturing Models depend on values that are specified by the configured components in the AM plant. In the following chapter, the AM plant configuration and the determination of the required parameters derived from it are discussed.

4.3. AM Plant Models for the determination of relevant plant parameters

In the introduction of the AM Manufacturing Models shown above, parameters are used in the technical constraints that originate from a specific AM plant configuration. A plant configuration consists of a selection of components that are installed in the AM plant. These components possess the relevant parameters requested by the AM Manufacturing Models. If the configuration of the AM plant is changed, the resulting parameter values that are transferred to the AM Manufacturing Models must be adjusted accordingly. Furthermore, there are often technical dependencies between the components in the AM plant configuration that cannot be installed in any combination with each other.

With the development of AM Plant Models as digital twin of a physical AM plants, the configuration-specific parameters can be automatically updated and transferred to the AM Manufacturing Models. Furthermore, the representation of the AM Plant Model in SysML allows the definition of technical restrictions regarding the AM plant configuration. The following figure 6 illustrates the structure of the FLM plant as example for an AM Plant Model. It contains the derivation of the parameters required by the constraint Idealized Model Travel Precision in the FLM Manufacturing Model.

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**Figure 6.** Instantiation of AM Plant Models and their linkage to the AM Manufacturing Model
In the FLM Plant Model the technical restrictions for the configuration of the components stepper motor, belt and pulley are illustrated. The free combination of the component’s parameters for the calculation of the restrictive design factor is not reasonable for technical reasons. In the described example the pitch of the belt always depends on the chosen pitch of the pulley. The stepper motor is determined by the parameters step angle and shaft diameter. Similar to the pitch, the shaft diameter of the stepper motor has a direct link to the parameter of the inner diameter of the pulley to form a functional unit. The relevant pitch diameter \( \text{(pitch}_{d} \text{)} \) of the pulley now shows dependencies of parameters coming from both other components. On the one hand, the pitch diameter depends on the defined pitch and number of teeth. On the other hand, the pitch diameter depends on the shaft diameter of the stepper motor. These technical dependencies can be solved by creating two constraints. By the constraint \( \text{Diameter ratio} \) in the pulley it is defined that the pitch diameter always takes on a larger value than the inner diameter to ensure a realizable technical solution. Further the constraint \( \text{Pitch calculation} \) determines that the pitch diameter is calculated so that the required number of teeth with the appropriate pitch is achieved. In this way, the parameter values required by the \( \text{AM Manufacturing Models} \) can be determined and transferred by the \( \text{AM Plant Model} \).

The specific configuration of the FLM Plant is created as instance of a structure of the FLM plant shown in the bottom of figure 6. In the structure, components are shown that are relevant for the calculation of the restrictive design parameter in the example. Their options for the realisation of different product configurations can be integrated following the method described in [11]. In order to ensure expandability with further components for the calculation of the other design parameters, the structure is modelled according to Weilkiens' VAMOS method (Variant Modeling with SysML) [15].

In practice, the AM plant components are replaced regularly due to signs of fatigue, wear or defects. Each of the components is available in different variants with different technical specifications. Table 2 shows an exemplary selection of technical configurations of the three components in the FLM plant relevant for the calculation of the travel precision with their specification values. The three variants of the stepper motor allow different choices of shaft diameters and step angles. The pulley comes in four different variants that are differentiated in the parameters bore diameter, number of teeth and pitch. With regard to the belt, only the pitch is considered for the example, which is available in two different variants.

When looking at the parameters, it becomes clear that dependencies between the components are relevant as they are integrated in the FLM Plant Model. For example, the shaft diameter of the stepper motor directly influences the selection of possible pulleys. If a stepper motor with a 5 mm shaft is selected, only the first or third variant of the pulleys shown in table 2 can be mounted. By mapping these dependencies in the structure of the \( \text{AM Plant Model} \), the compatibility of the variants is checked directly and returned during configuration.

| Stepper motor \( \text{(shaft}_{d} \text{iameter; step}_{a} \text{ngle)} \) | Pulley \( \text{(bore}_{d} \text{iameter; number}_{t} \text{eeth; pitch)} \) | Belt \( \text{(pitch)} \) |
|---|---|---|
| • NEMA 14 (5 mm; 0,9°) | • GT2 (5 mm; 16; 2 mm) | • GT2 (2 mm) |
| • NEMA 17 (5 mm; 1,8°) | • GT2 (6,35 mm; 16; 2 mm) | • GT3 (3 mm) |
| • NEMA 23 (6,35 mm; 1,8°) | • GT3 (5 mm; 20; 3 mm) | |
| | • GT3 (6,35 mm; 20; 3 mm) | |

4.4. Interfaces for plant configuration setup
After the system structure and the determination of the restrictive design parameters are developed, the next step is to integrate the model into a usable tool chain. The fully automatic transfer of the calculated design parameters is realised using a Matlab code for the intermediate storage as comma-separated
values file in Excel. This file is then automatically imported when the AMFI calculation is queried, thus loading the existing design parameters into the tool for manufacturability analysis in the design domain.

Due to the currently still rather low distribution of SysML software in industrial companies, the design of an intuitive GUI for the configuration of AM plants is recommended. The mockup of a suggested GUI (a) that can be used in the production domain is shown in figure 7 with its linkage to the AMFI in CAD (b). The GUI consists of three areas, the general settings, a display of the calculated design parameters and an area for adapting the system configuration and components. In the general area, important metadata such as the configuration name, the date and the employee editing the configuration can be entered. Further in the configuration area different modules for configuration can be selected for adaption. In the example below, under the tab "Travel X" the components involved in moving the nozzle in the X-axis direction are listed. The relevant parameter regarding the components pulley, stepper motor and belt can be defined in this view. To simplify the AM plant configuration using standard solutions, selection fields for preconfigured components are provided. This means that the user does not have to specify each parameter individually, but only has to make a component selection. Incompatibilities between the choice of standard configurations, for example an incorrect pulley for the stepper motor, can also indicated by highlighting the parameters. For those components that cannot be pre-configured, the user is provided with illustrations of the parameter relationships via principle drawings.

(a) AM plant configuration GUI

(b) AMFI in CAD

Figure 7. Mock-up of (a) the configuration GUI and its linkage to (b) the AMFI GUI in CAD

5. Results
The developed system model formalises the production knowledge of experts from the production domain about the AM plant configuration and derives restrictive design parameters from it. This knowledge is automatically integrated by an interface into a tool for a manufacturability check of parts in the design domain.

It is possible to derive correlations between restrictive design parameters for additive production and plant technology from technical documentations and guidelines. The knowledge about the interrelationships can be represented in AM Manufacturing Models using SysML. By the representation of the AM Plant Models it is possible to mind the technical influences of different plant configurations in the AM Manufacturing Models. Also, by the utilization of the software Matlab it is possible to transfer the derived design parameters into the existing toolchain for the evaluation of manufacturability in AM.

Setting up the system model using the presented structure makes it easy to connect further existing structural models of AM plants. Furthermore, modelled AM plants can be easily extended with various component configurations. In an assembled model of an AM plant, the existing plant variant and also the variants of installed components on lower levels of the reference product structure can be easily
defined. The model structure is not only limited to the representation of additive manufacturing plants but can also be transferred to other manufacturing processes.

The structure of the AM Manufacturing Model allows an easy exchange of the interface between parameters of the production line and the design parameters. Furthermore, the automatic determination of the design parameters is ensured as well as the transfer of these parameters to interfaces to external tools such as the existing tool in CAD for the calculation of the AMFI. In this linkage, the currently existing AM plant can be set up automatically via the GUI of the AM Plant configuration and the resulting restrictive design parameters for the design domain can be considered in the component design for additive manufacturing.

6. Summary and Outlook
The developed AM Manufacturing Models enable the linkage of the structural and behavioural relationships of the AM plant with restrictive design parameters. In combination with the representation of the AM Plant Models an easy configuration of the AM plant components and parameters is allowed. The model structures can be successfully adapted for the other design parameters that are mentioned. By the combination of AM processes with the model-based product development steps are taken to overcome today's challenge of manual part and process evaluation. In addition, it is also possible to evaluate the manufacturability of a part already at early product design stages directly in the CAD software. In this way, the design engineer is supported in part design for AM, taking the company's specific production environment into account.

Nevertheless, the combination of the presented model structure with profound models for the behavioural description needs to be considered when applied to high-precise industrial AM plants. Based on the presented state, the system model can be further developed and supplemented with additional modules and components or by whole instances of AM Plants. The existing system complexity can thus be broken down step by step and the influences of the technical system configuration can be revealed.

The AM Manufacturing Models are also suitable for considering not only the technical plant parameters but also behaviour, process, material or cost models that can easily be connected to the system model. Thus, in addition to the components in the example, the extruder control, the temperature of the heatend or the material itself also have an influence on the width of the deposited polymer line in the FLM process and thus on the minimum realisable gap width in a part. These extensions of the system model need to be further explored in the future to further enhance the potential of this approach.

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