Chapter

Development of a Quality Gate Reference Model for FDM Processes

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Abstract

Additive manufacturing (AM) enables industries to accomplish mass customization by creating complex products in small batches. For this purpose, fused deposition modeling (FDM) is widely used in 3D printing where the material is applied layer-by-layer from a digital model to form a three-dimensional object. There still exist problems in FDM processes regarding the failure rate of printed parts. Failures vary from deformed geometry, clogged nozzles, and dimensional inaccuracies to small parts not being printed that may be attributed to various process steps (e.g., poor quality CAD models, converting issues, overheating, poor quality filament, etc.). The majority of these defects are preventable and are caused by imprudent try-and-error print processes and troubleshooting quality control. The aim of this chapter is to propose a quality gate reference process with defined requirement criteria to prevent the occurrence of defects. The framework shall be applied in quality control and in-situ process monitoring to enhance overall manufacturing quality.

Keywords: additive manufacturing, fused deposition modeling, reference process, quality gates, quality control

1. Introduction

Customer demands on products and services are constantly increasing in the global and local market and the competitive conditions of companies are in constant flux. As a result, companies are faced with changing market conditions in which they have to assert themselves against increased competitive pressure, greater product complexity, and an ever-increasing variety of products [1].

Industrial 3D printing or additive manufacturing (AM) is considered the key technology for mass customization. This allows the individual production of complex components and offers various possible solutions for increasingly complex requirements [2]. Additive manufacturing is an umbrella term for manufacturing processes in which components are built up element by element or layer by layer directly from computer-aided design (CAD) data without component-specific tools [3].

Fused deposition modeling (FDM) belongs to the AM technologies, which enable incorporation of cavities in a part's design and have little changeover cost compared to conventional manufacturing processes, potentially enabling individualized production and new possibilities for light-weight products [4].

The first step of state-of-the-art FDM processes involves a so-called slicing software that is used to generate machine-executable instructions (G-code), approximating a virtual product in the form of a CAD model. The desired product geometries are decomposed (sliced) into stacked layers of equal height along a specified axis, called the build orientation. Furthermore, for each of the layers, a closed two-dimensional path is planned, incorporating print head velocities set by the user. In the production step, the FDM machine follows the defined path while extruding heat-liquified raw material threads. Starting on the build plate, for each layer, the respective trace is followed by the machine, and so the whole part is fabricated. During the process, the machine must highly accurately control the correct material flow, the build plates state, and the correct positioning and velocity of the print head [5, 6].

While the concept seems straightforward to realize, practitioners long since report that reproducibility and reliability issues persist, demanding effective quality control measures [7–9]. Achievement of the aforementioned demand requires controlling for influences from the 5M-domains during pre-process and in-process stages: man, machine, milieu, material, and method affect the success of a print [10].

To achieve a successful production result, a set of numerous interrelated process parameters must be determined, some of which have been mentioned above. Finding appropriate parameters can pose a challenge to beginners, leading to failure in almost every second print [11]. Even expert knowledge does not necessarily lead to a good print result, but their experience helps them to avoid easily preventable mistakes. Many man-hours and unnecessarily wasted material could be saved by the prevention of simple mistakes. The reason lies in the fact that there is almost no recognized or approved reference process in which defined requirements serve as a quality control measure.

As of now, there are only few works that serve as a reference process for additive manufacturing. There is a lack of standards and norms that ensure high process and product quality. A lot of previous academic literature focuses on particular printing defects such as warping or oozing. Performed research indicates that comprehensive guidelines regarding failure prevention in the overall printing process ought to be developed. Additionally, there is a lack of in-depth documented requirements to achieve high quality in process and printed products.

This paper proposes a reference process model including 10 quality gates that serve as documented requirements to prevent defects and failure prints beforehand instead of costly troubleshooting. Section 2 describes related work and shows up the gaps upon which this present scientific work further elaborates. In Section 3, various failure types are introduced and considerations to prevent them. Section 4 contains the proposed reference process model including quality gates. Section 5 summarizes the results and discusses the advantages of the proposed approach and concludes with future research potentials.

2. Related work

An extensive list of FDM print issues and their causes have been published by Loh et al. [12]. Qualitative expert knowledge has been formulated in natural language and lacks precise arguments. Each failure is assigned to a category which is either "printer-associated," "deposition-associated," or "print quality," but no reason nor meaning for an assignment is given. Livesu et al. provide a detailed description of the main process starting with the CAD model and ending in the G-code, but they focus mainly on software issues [13]. Baş et al. describe print conditions that sufficiently lead to faults by the application of a fault tree analysis (FTA) [14]. Many faults are described and their dependencies are formally expressed. The German Norm DIN SPEC 17071 proposes a print flowchart, leaving open the actual events of quality checks [15]. Oropallo et al. name error control in a list of 10 challenges in 3D printing. A distinction is made between errors during printing and errors before printing, which is partially avoidable [16]. Bähr and Westkämper divide a print into three stages: pre-process, in-process, and post-process. The importance of cooling is emphasized and divided up into a sinter phase, crystallization phase, glass transition phase, and a shrinkage phase, which are bounded by corresponding temperature values. Additionally, a table is provided that relates process parameters to their manifestation in component properties. Martinez-Marquez et al. developed a detailed quality control procedure including 18 quality gates but tailored to the production of patient-specific medical implants [17]. The process assumes the use of a laser-based AM system and error control is only briefly described. Fu et al. provide literature research and an overview of sensor technologies for in-situ monitoring of FDM processes [18]. Their flowchart is limited to in-situ printer health and product quality monitoring. Oleff et al. do systematic literature research in order to find quality-related research gaps, giving examples for a few FDM-process errors [19]. Song and Telenko examine FDM-print failures in a university makerspace [20]. They categorize these into user errors, machine errors, and designer errors. Also, a poll has been carried out to determine failure rates dependent on the user's experience level. The results show wastage levels of about 34% of the total material and a print failure rate of 41.1%. Gibson et al. provide a rough overview starting with the CAD model, ending in the application. An in-process view, as well as defects, is not considered.

To the best of the authors' knowledge, no publication at present exists wherein a generic reference process is determined in which quality gates serve as requirements for quality control to prevent printing defects.

3. Defects in additive manufacturing

Defects that occur later in the process chain are harder to assess, as this presumes that no defect has occurred in a preceding process step.

In the following, examples of failures are explained which can either be pre-process, in-process, or post-process. Also, dependencies among failures are illustrated and research hypotheses for their assessment are formulated. Most of the enumerated defects have already been explained by Loh et al., whose work is extended in the following.

3.1 Pre-process defects

The following shows defects that may occur in the pre-process steps and are possibly preventable through quality control measures.

3.1.1 Tangled filament

If the end of the filament thread on a roll has been guided through under itself, a knot will eventually form on this roll, making proper unwinding impossible. This can happen after a user has unloaded filament from a printer. A proper loading process of filament should therefore be examined and verified.

3.1.2 Gaps

In all instances of this kind of defect, print segments are not properly connected and small gaps are recognizable by the naked eye. Loh et al. distinguish between three kinds "walls not touching," "gaps between Infill and outline" or "gaps between thin walls." Such gap appearances are introduced by the slicing software, affected by the extrusion line width. Thus, gap defects are avoidable if slicing errors are being determined.

3.1.3 Small features not printed

This defect highlights noticeable differences between the provided CAD model and the production instructions executed by the printer. Two distinctions between affected features can be made: A vertically standing wall whose width is smaller than the extrusion line width and a feature parallel to the build plate, whose height is smaller than the layer height. Material waste can be prevented if the slicing software informs the user about deviations between the CAD model and the generated G-code.

An example part that is susceptible to these kinds of defects is given in **Figure 1**, along with G-code paths generated by a slicing software using different parameter settings. The part consists of a block, a thin wall whose depth is 0.35 mm on its top, and a thin feature whose height is 0.1 mm in parallel to the build plate and is shown in (a). If a layer height smaller than the height of the thin feature of the CAD model and a line width smaller than the wall depth is chosen, then both the wall and the thin feature are not included in the generated G-code path, as demonstrated in (b). Conversely, if the layer height is smaller than the thinnest feature and the line width is smaller than the wall depth, then the sliced result matches the expectation of the

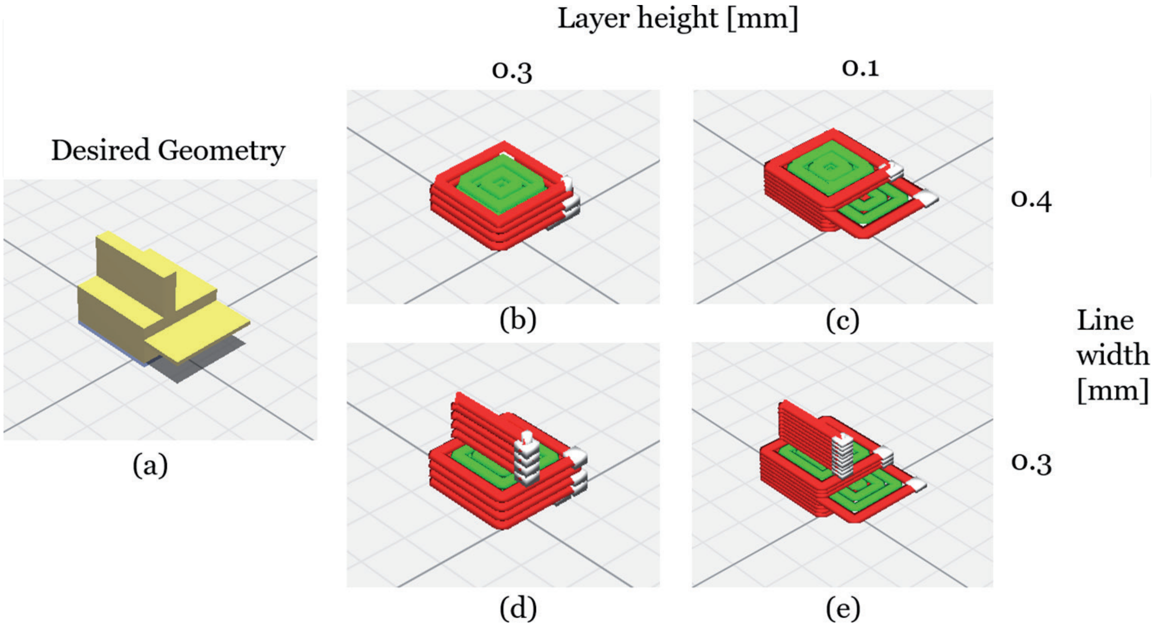

Figure 1.
Variations of parameter settings in slicing process of a complex cuboid object.

user, illustrated in (e). If either layer height or line width is not chosen appropriately, corresponding results will be sliced, as can be seen in (c) and (d), respectively.

3.2 In-process defects

3.2.1 Warping

The occurrence of warping (see **Figure 2**) manifests in an up-curl and a detachment of corners that touch the print bed at the bottom of the part in production due to tension arising from a non-uniform thermal gradient and shrinkage effects in the part. Deposition of additional layers on a corner that has already started to warp can negatively amplify the situation and may lead to an extension of the detached area. In the worst case, the part completely detaches from the bed; at this point, a print job should be canceled to avoid damage to the printer and further material waste. Scholars indeed argue that inclusion of brims or rafts or a reduction of infill percentage can help to avoid warping. As warping is irreversible, its occurrence should trigger a cancelation of the print process.

3.2.2 Detachment

The adhesion of the parts' first layer to the bed is essential for a successful result. If a part detaches from the bed, the print heads' movement will shift the part through its slight connection by the deposition strand. Thus, the material cannot be deposited at the correct location and the process should be stopped. The reason for detachment is an insufficient adhesion between the part and the build plate. Like warping, this defect is practically irreversible and the print process must be stopped.

3.2.3 Shifted layers

The path specified by the G-code must be executed accurately by the machine. Unsuccessful movement execution, for example, caused by missed-out steps of an axis motor, or a detached part creates positional deviations that lead to shifted layers if not compensated for.

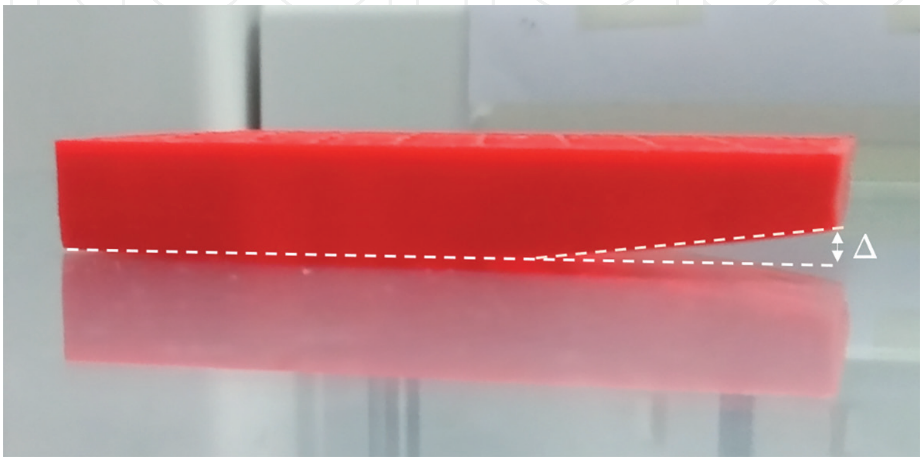

Figure 2.
Warping of a cuboid print model.

3.2.4 Clogging

Over the course of a print, all of the final parts' material must pass through the nozzle. Dust and undesired objects in the raw material can accumulate in the nozzle and lead to obstruction so that no material is deposable. Other causes could be burned residual material inside the nozzle as a result of an excessive extrusion temperature.

3.2.5 Nozzle cake/extruder blob/head flood

If material is continuously fed into the print head but cannot leave through the nozzle, then there is a risk of an occurrence of a head flood. The material sticks to material residuals that have previously been attached to the nozzle. Over time, more and more material accumulates around the nozzle. If the problem is not noticed at an early stage, the printer will likely be damaged severely. Removal of the accumulated material is time-consuming and a downtime eventuates.

3.2.6 Grinding

In FDM printers, a knurled ring drives the filament toward the hot end. If it loses grip on the filament, a small amount of material is removed from the filament's surface. If this happens for some time, then a groove forms in the filament thread, making transportation to the hot end difficult or impossible. Aggressive retraction settings can be the cause.

3.2.7 Overextrusion/underextrusion/missing extrusion

There are multiple causes for a missing extrusion: clogging, nozzle cake, or grinding. A camera, mounted at the nozzle's height, is used by many authors to monitor if the specified extrusion amount is matched.

3.2.8 Overheating

A central concept of extrusion-based 3D printing is the use of heat to extrude the raw filament. Overheating happens when a new layer is deposited on a lower layer, whose temperature has not cooled down to a certain level. Uneven printed parts may occur as a result (see **Figure 3**).

3.2.9 Curling

Another temperature-related defect caused by overheating is curling, which becomes apparent on topmost corners. This is similar to warping, but on the top instead of the bottom.

3.2.10 Pillowing

The exhibition of blisters or undesired holes in the topmost layers is termed pillowing and is caused by overheating. It can be detected the earliest after the last layer has finished and cooled down.

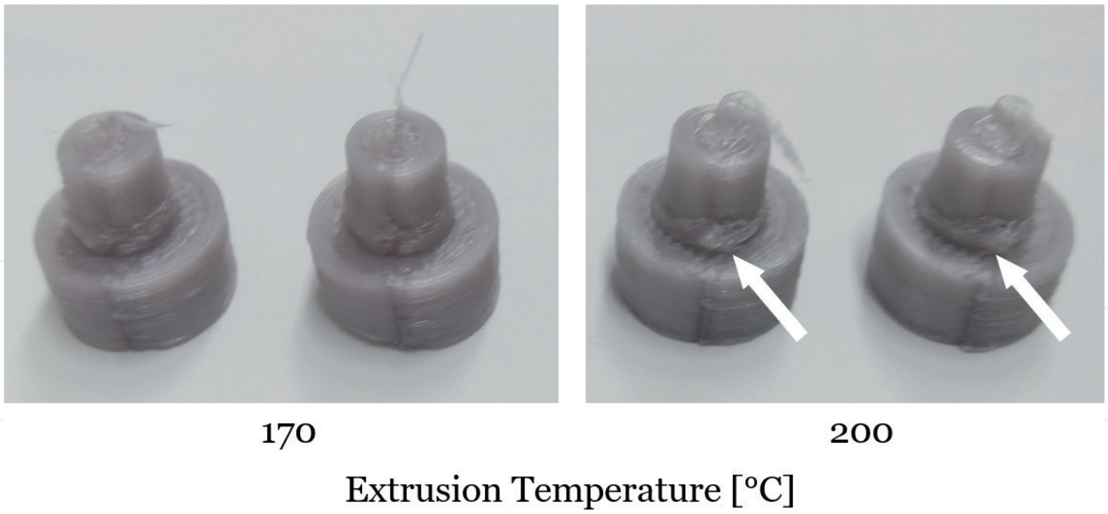

Figure 3.
Effects of overheating on print.

3.2.11 Stringing and oozing

The hot-end provides a continuous stream of liquid material whose flow is influenced by the feeder. As the hot-end consists of metal parts, rapid cooling down below the glass transition temperature of a given material to solidify inside the nozzle is infeasible. Reasons for stringing can be too high extrusion temperature or unapplied retraction settings. Once strings have appeared, there is no way to remove them during the print process. Stringing can be corrected by a post-process heat treatment.

3.3 Post-process defects and quality measures

After a successful production, the quality-related requirements may be assessed.

3.3.1 Blobs and zits

The occurrence of small bulges on the side of a part is termed blobs and zits. The interplay between start/stop position and retraction settings causes this defect. **Figure 4** shows a corresponding example, which demonstrates the development of blobs and zits that appear at the start/stop positions (right), which are marked by white dots on the left figure.

3.3.2 Porosity/voids

Due to the stacked deposition of round material beads, part-internal voids are a natural consequence. Such internal properties may be examined either by a dissection of a parts' region-of-interest or by nondestructive metrology like microcomputer tomography.

3.3.3 Vibrations and ringing

High print speeds induce vibrations that propagate through the printer's frame and cause small deviations in the head position. Hence, patterns according to these deviations appear on the parts' surface.

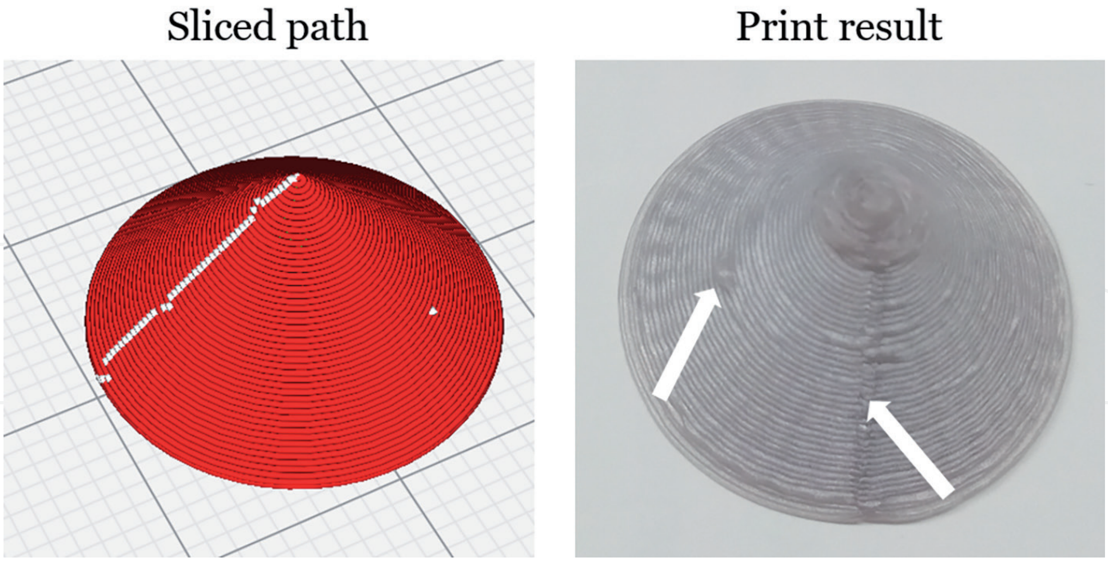

Figure 4.
Blobs and zits on a conical print object.

3.3.4 Dimensional accuracy

Overall shape deviations can be assessed by a separate measurement instrument.

3.3.5 Surface quality

The surface quality is the first aspect of an object that a customer perceives during an inspection of the object. This quality criterion can be checked independently of the actual model.

3.3.6 Mechanical properties

After quality checks of dimensional accuracy and surface quality, mechanical quality checks may be performed. Destructive assessments include tensile, shear, and compressive strengths, while part density can be measured using a scale.

4. Reference framework and quality gate process

The lack of norms and standards often leads to manufacturing processes that are defined from scratch for each individual production run, which provokes plenty of try-and-error operations. Indicative of this are numerous troubleshooting guides that help individuals cope up with problems that occur during the printing process as well as frequently discussed issues in community-based online forums (see for example [21–24]). On the other hand, there are very few references on how to plan quality and prevent easily avoidable defects beforehand. This leads to the overall conclusion that a lot of quality issues can be prevented if a reference process with criteria-based quality gates guides through the manufacturing process to ensure high process and product quality.

A reference process supports process requirements so that the process quality and resultant product quality remain consistent and reproducible at all times. This paper proposes a generic reference process model for additive manufacturing that describes the common sequence of activities for fused deposition modeling. Furthermore, this work suggests a model that contains pre-process, in-process, and post-process steps and starts with the CAD design and ends in machine and product post-processing (see **Figure 5**). The reference process model is based on the standard DIN SPEC 17071:2019–2112 [15] that represents a process chain for additive manufacturing that can be seen in **Figure 6**.

This blueprint of an additive manufacturing process chain is further specified in the reference process model in **Figure 5** and quality gates are added. A quality gate specifies criteria in process steps as well as quality-relevant characteristics and factors that have to be met in order to continue the process flow. It enables to perform corrective and/or preventive action to ensure high quality [25].

The reference process starts with the CAD of the product that is going to be manufactured. After that, the pre-processing steps will ensure the material selection, preparation, loading, and build chamber preparation. Moreover, the build orientation and strategy, as well as the generation of support structures, will be determined. In the manufacturing process itself, the production of the first layer of the build is a crucial part and is a decisive factor for the continuous process. After the build is finished in printing, a cooldown process will harden the material. In post-processing, the build product has to be removed from the build platform and both the machine and the product itself need post-processing. The machine is cleaned-up and restored to the initial state in order to be prepared for following production runs. The support structures are removed from the printed parts and a surface finish is performed where required.

There are nine quality gates in the proposed reference process model that serve in the course of the manufacturing process as points at which a decision is made on the progression to the next process step on the basis of quality criteria clearly defined in advance. Each criterion may be checked to prevent quality issues in the succeeding process steps. **Table 1** gives an overview of all nine quality gates and the respective criteria.

In the following, an example will show how the quality gates may prevent printing issues and may ensure the overall process quality. Therefore, a 3D-printed door hinge was manufactured according to the reference process model, and after each process step the quality gate criteria are reviewed and verified.

The first quality gate is actually positioned before the pre-processing of the additive manufacturing process and verifies the CAD design of the print part (QG 0). First of all, the manufacturability in regard to printer settings and the adherence to design rules can eliminate severe quality issues that may occur during printing' as an example thereto, if the door hinge cannot be assembled after printing because of poorly placed through-hole positions.

In QG 1, storage and material validation should be performed during the material preparation to prevent material-related quality issues. Filament could be damaged because of humidity or temperature-related variations in the storage area and may provoke damage during the printing process. In addition to that, there should be sufficient filament supply for the print that has to be printed as well as a coherent diameter of filament.

After the material was loaded to the feeder of the printer, QG 2 ensures that the orientation of the filament feed is adequate and the nozzle of the printer is unclogged. Moreover, the filament tubes should be empty and the overall filament feed rate is sufficient.

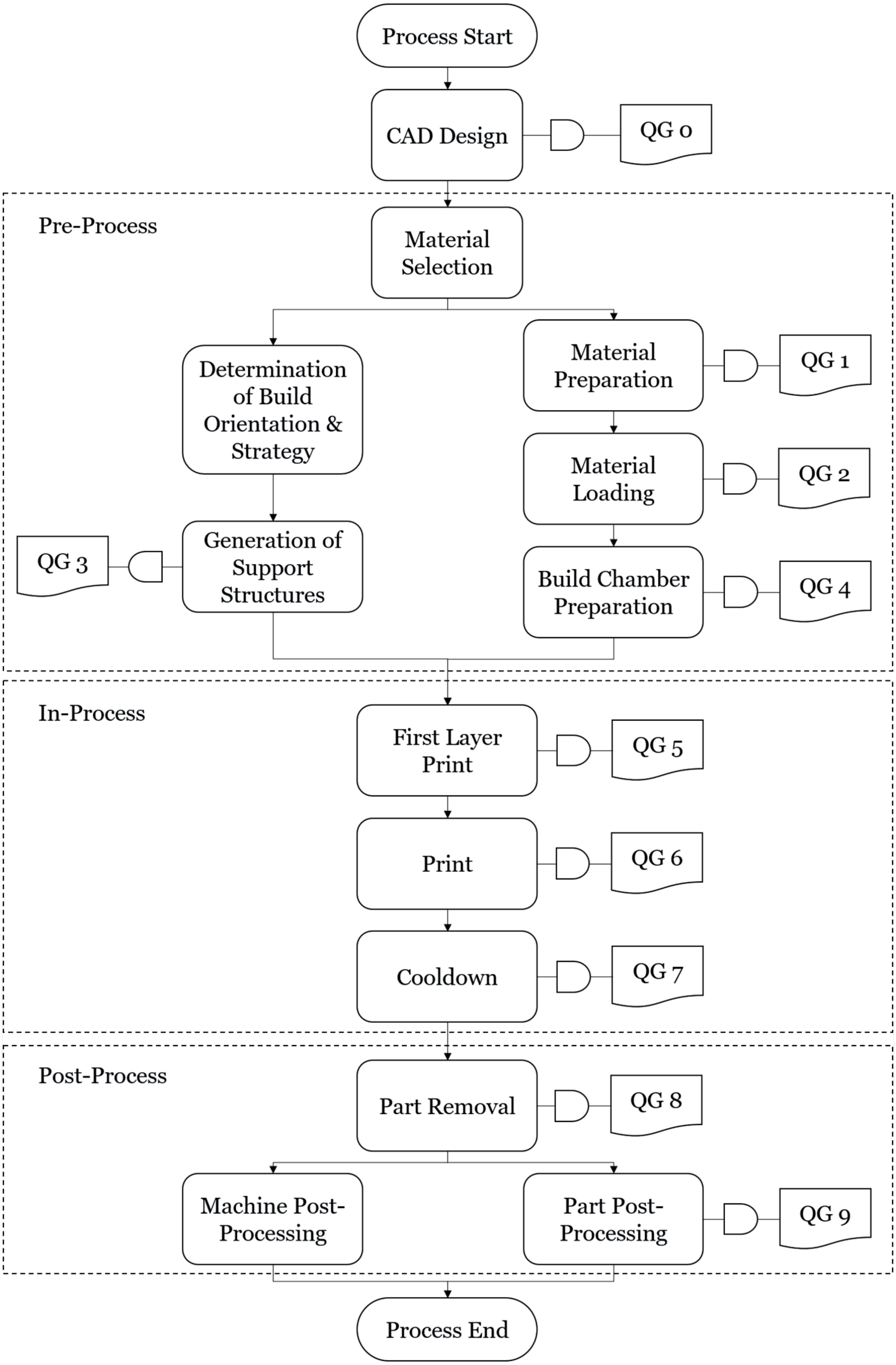

Figure 5.
Reference process for additive manufacturing.

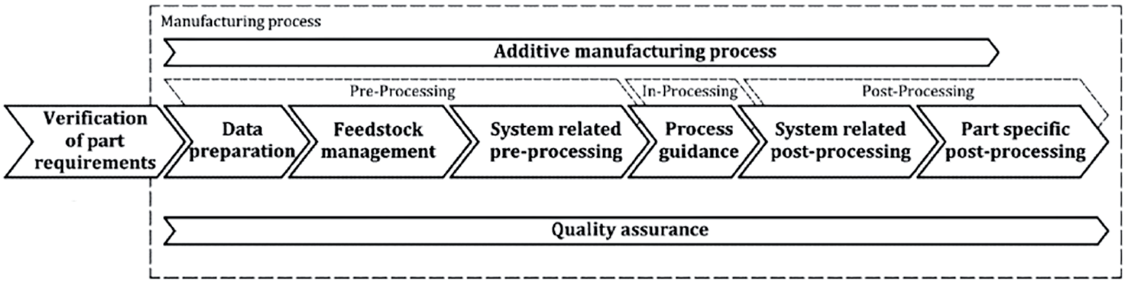

Figure 6.
DIN SPEC 17071 process standard for additive manufacturing [15].

Quality gate	Description	Criteria
QG 0	Verification of requirements and design approval	• Verification of manufacturability • Adherence to design rules • Avoidance of mass accumulation • Verification of process requirements • Verification of product requirements • Customer design approval • Wall thinness according to nozzle size • Solid bottom and support structures
QG 1	Storage and material validation	• Humidity of storage area • Temperature of storage area • No filament tangling • Age of filament according to manufacturers' instruction • Sufficient filament supply according to design • No visual material damages • Coherent diameter of filament
QG 2	Loading quality validation	• Sufficient filament feed rate • Adequate filament feed orientation • Unclogged nozzle • Empty filament tubes
QG 3	Software and file validation	• Error-free STL-files • Correct infill density • No infill overlaps • Error-free slicing process • Updated slicing software • Updated printer firmware

Quality gate	Description	Criteria
QG 4	Build chamber validation	• Free belt movement • Free extrudement wheel • Clean and dry build platform • Adequate build platform temperature • Leveled and flat build platform • Aligned rod • Fixated printer position • Adequate nozzle height from build platform • Adequate retracting settings • Adequate cooling settings • Primed nozzle
QG 5	First layer validation	• Verification of extrusion process • Adherence to build platform • Verification of geometric and dimensional proportions
QG 6	Process monitoring	• Geometric stability of build and filament • Coherent filament flow • Adherence to build platform • Adequate extrusion process • Adequate extrusion temperature • Adequate build platform temperature
QG 7	Cooldown validation	• Geometric stability (no warping or curling) • Verification of layer adhesion • Adequate part temperature • Adequate in-part temperature gradient (to avoid material stress)
QG 8	Visual inspection	• Verification of geometric stability • Verification of nondestructive detachability • Verification of transportability
QG 9	End of line quality validation	• Elimination of porosity/voids • Verification of surface quality • Verification of geometric form • Verification of tolerances • Verification of mechanical, chemical, thermal properties • Verification of density/mass

Table 1.
Quality gates for the reference process model.

QG 3 states that on the other hand, the slicing files, as well as the whole slicing process, should be error-free. Printer firmware and slicing software should load the latest update to prevent failure. The correct infill density and no infill overlap should be checked.

A lot of process failures can be associated with a build chamber that has not been calibrated for error-free printing. QG 4 examines if there is a free belt movement and a free radial movement of the extrudement wheel. Moreover, a leveled and clean build platform that has an adequate temperature can ensure a consistent printing process. The printer should have a fixed position because the printing process may cause vibrations and an unintended re-orientation of the whole system that may, in turn, interrupt the filament feed.

The first layer of printing is a crucial step for the whole printing process. Therefore, QG 5 should verify the extrusion process and the adherence to the build platform. Moreover, a visual inspection of correct geometric and dimensional proportions should be performed.

After the first layer print, the continuous layer-by-layer printing should be in-situ monitored (QG 6). The filament flow and the extrusion process should be closely monitored, as well as the geometric stability of the print. Temperature sensors may observe the extrusion temperature and build platform temperature.

When the printing process is completed, the cooldown process is also a quality-relevant aspect. To prevent warping or curling of the print due to material stress, the temperature should be lowered slowly (QG 7). In addition to that, layer adhesion should be verified.

A visual inspection can be performed as soon as the print is removed in a nondestructive manner from the build platform (QG 8). The geometric stability and the transportability should equally be verified.

Lastly, an end of line quality check should be performed after the post-processing (i.e., surface finish, removal of support structures). Verification of the surface quality as well as the geometric form including all relevant tolerances should also be performed. Finally, the mechanical, chemical, and thermal properties should be checked.

5. Conclusion and further work

The proposed reference process model including the criteria-based quality gates to prevent printing issues serves as a guideline to achieve high process and product quality. Opposed to common troubleshooting that is carried out during the occurrence of printing issues, the presented model herein allows executing corrective or preventive action. The lack of norms and standards in additive manufacturing as well as rudimentary reference processes makes it difficult to meet process and product requirements *per se* and achieve a planned quality level.

This research work has introduced a reference process including pre- and post-process activities with the aim to standardize the printing process of FDM 3D printing. These process steps are sub-divided by quality gates that ensure the fulfillment of requirements to ascertain the prevention of quality issues. There are nine quality gates that have quality descriptions in form of documented requirements that have to be met.

In view of the above, it may be stated that the proposed process model requires some effort for the verification steps in terms of an operational measuring system. Regarding the in-situ monitoring of the printing process, temperature sensors for the extruder system as well as the build platform and a feed rate sensor need to be installed. Additionally, the calibration of the printer settings and the validation of the build chamber is a time-intensive procedure and therefore extends the printing process not inconsiderably. The availability of all required sensors is a valid difficulty.

There are several limitations to the introduced reference process model. First of all, it only addresses manufacturing processes that are based on thermoplastic materials. Powder bed fusion like selective laser melting is not considered in this reference process or in the quality gates. Therefore, this reference process model has to be adjusted accordingly in order to allow for these alternative additive manufacturing processes.

Further research activities have to be performed to achieve a more concise insight into how to prevent quality issues during additive manufacturing processes. First of all, this model needs further verification and validation in order to define the degree at which it can prevent relevant quality issues. Qualitative and quantitative studies may focus on what the overall benefits of this quality gate process are in terms of not aborted production runs or customer-relevant requirements. Moreover, the list of documented requirements in the quality gates is not exhaustive and quality criteria may be composed through further research to generate a complete reference model.

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