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Towards an Unified Additive Manufacturing Product-Process Model for Digital Chain Management Purpose

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Abstract

Additive Manufacturing (AM) is a real example of emerging technologies that can influence the whole product development process. During the AM process, large amounts of data are created, modified stored and retrieved. The management of large amounts of data, as well as the complexity of the relationships between stakeholders are amongst the major challenges. Design activities should be well-integrated with the production process to ensure the consistency of the whole AM value chain, which begins from the conception to the production and post-treatment of the product. This paper discusses the main characteristics of the AM process. The Business Process Modelling Notation (BMPN) is used to describe the entire AM value chain and the connection between design and manufacturing processes. This is a preliminary step towards the definition of complete model dedicated to the representation of AM related knowledge. Semantic interoperability and the monitoring of the whole digital chain involved in the AM value chain are the most important applications of the proposed modeling framework.

Keywords: Type your keywords here, separated by semicolons ;

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1. Introduction

The American Society for Testing and Materials (ASTM) describes Additive Manufacturing (AM) as a “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Other synonyms include additive fabrication, additive processes, additive techniques, layer manufacturing, additive layer manufacturing, and freeform fabrication.” [1] AM allows a broad range of customized shapes and complex geometries to be easily and quickly produced [2].

Compared with traditional manufacturing techniques, AM has the potential to spur innovation, reduce downstream processes, minimize material and energy use, and reduce waste [3]. As a result, certain manufactured parts can have a lower cost and can be produced in a more sustainable way. However, the use of AM technologies requires important changes in current industrial practices at both technical and organizational levels.

To support this transition, process modelling is helpful to understand the whole value chain behind the AM processes. Descriptive process models allow representing and identifying the basic entities that are needed for and manipulated during AM processes’ executions. Additionally, they support the specification of collaborative workflows between involved stakeholders.

This paper presents some preliminary results towards the definition of a more general modeling framework to handle data and knowledge in AM projects. In particular, we introduce process models to support the identification of both AM data and knowledge constraints needed to manage the additive manufacturing digital chain.

The paper is structured as follows: in the next section, we introduce some of the core characteristics of AM technology. Section 3 presents the process models. The conclusion summarizes our contribution and addresses the need for further work.

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2. Research Background

2.1. Key Pillars of AM

Although AM techniques have progressed over the last decade [4][5][6], many challenges remain to be addressed. A core challenge is the variety of technologies and materials that are involved, as well as the dependencies between various processing parameters.

From a technological standpoint, four main enablers have been identified as the most important factors for improving the robustness of AM approaches and their application to the industry [7][8]. These include geometry design for AM; material design for AM; manufacturing tools; process development; computational tools and related graphical interfaces. However, technology is not the only factor. Research is necessary to investigate the operational and informational aspects of AM with respect to experts' knowledge. Therefore, four additional pillars are identified: standardization and certification; interoperability and integration; traceability of data and digital chain, knowledge reuse for decision making assistance.

Improving the quality of fabricated products requires an understanding of the process performance drivers. The first step is to identify the diverse interaction between design activities, material specification, manufacturing processes, and evaluating the quality of the parts. It is in this context that the techniques of process and data modelling become valuable to manage, share and integrate available knowledge linked to AM processes. This is also necessary to connect the technologies employed, and the actors involved in the process. Additionally, data and process models can be used to enhance decision-making processes and to aid the overall efficiency and innovation.

2.2. Existing Models for AM

Process modeling enables a better understanding and the improvement of the behavior of a given system [9]. There are many business process modeling languages and methods, e.g., Event-driven Process Chains [10], Business Process Modeling Notation (BPMN) [11], UML Activity Diagrams [12], Role Activity Diagrams [13], IDEF0 and IDEF3 [14]. Among them, BPMN offers a rich semantic to represent various operational situations [15].

The conceptual modeling of AM processes as part of the digital solution process is still maturing [16]. Kim et al. [17] defined various types of data along the AM digital chain. They started to identify systems-level requirements for the development of integrated information system for metal-based AM, and explored which factors had to be taken into account when addressing interoperability between the digital formats used throughout the development of an AM part.

Lu, Choi and Witherell [18] worked towards the definition of an overarching information model for AM product and process data management. They classify information into the product, process, and resource domains. Additionally, they defined the scope of the considered schema and investigated the information requirements based on an AM-driven IDEF0 process diagram. Other IDEF0 diagrams for AM have been proposed across the literature [19][20]. As an extension of the existing works, the purpose is to contribute to the definition of a general modeling approach for AM.

3. Proposition of AM Process Model

Based on rigorous analysis of literature survey and interviews with industrial partners of the SOFIA project, a synthesis work is achieved to identify the main invariants of the AM process. The detailed sub-processes and activities are still specific to every company and it is difficult to integrate as a standard framework.

3.1. AM Activities Classification

Based on the type of contribution that every process is expected to bring to the whole AM chain, three main types of processes can be identified, namely, Core Processes, Support Processes, and Control Processes. The distinction between core and support processes was discussed by Porter [21]. The first category meant to generate products or services elements while the second, is required to ensure the functioning of core processes. Further classifications have divided support processes to include those that contribute indirectly to the final results, and control activities that manage, plan, or monitor different aspects integrated into the whole process. Based on these considerations, Fig. 1 presents a UML class diagram that classifies the three types of processes, which we define as follow:

- Core Process: includes all the activities that contribute to the development of a product with AM technologies from receiving a new order to the delivery of the finished parts;
- Support Process: includes all the sub-processes that are required by the core process, such as maintenance, supply chain, and safety management;
- Control Process: includes all the sub-processes which are required to plan, monitor, control, manage, and operationally coordinate all the other processes.

3.2. Generic AM Process Models

The chosen modelling language to create process models for AM is BPMN. The first step in the development of the models was to acquire the basic information about AM processes, in order to fully understand their functionalities. Based on the above classification, all the acquired data regarding AM processes such as activities, roles, inputs, outputs, and other pre-conditions were used to create the BPMN model shown in Fig. 2 The first level descriptor organizes the main BPMN architecture and it can be expanded for more detailed descriptions. For the second step, the main processes were divided into further sub-processes to add more information to the model. The description of the process was built until the definition of the elementary activities could not be reduced further.

The use of BPMN allows the inclusion of gateway elements to divide workflows. This makes it possible to represent all alternative execution scenarios that might occur in AM project. BPMN allows the representation of alternative workflow paths that can be introduced in the “nominal” process. As shown in Fig. 2, the process starts when an order to manufacture an AM part is received. At this point, the first sub process identified is the study of the order. Depending on the requirement, a design stage may or may not be required. For orders requiring a design stage, the next sub-process to take place is the design of the related AM product model (see Fig. 3). Once the model is ready, a related AM product to be manufactured is created (see Fig. 4). At this point of the design stage, prototyping and validation sub-process can also take place. On the other hand, if the design stage is not required, the order is then reviewed. If a virtual product in the form of a CAD file is provided by the client, they are analyzed and validated. The products to be manufactured are stored in an existing knowledge base to make it available for future steps. Whether there has been a design stage or not, a new production folder is created and once the folder is completed, the production of the parts takes place followed by their packing and delivery. Fig. 5 describes the main steps of the manufacturing sub-process. The critical task is the setting of the machine parameters and the preparation for new jobs. The execution of the job commences once the manufacturing order is sent. After finishing a manufacturing operation, the machine is cleaned and available for the next order. Quality assurance, post-processing, and monitoring plans are usually undertaken at the early stage of the design of the part and their outputs are included in the virtual product definition. A production plan assigns the resources that are required to manufacture the parts, and process and production monitoring plans control both process respectively. Six support and six control activities are identified in AM process:

- Machine maintenance to ensure that the manufacturing line is in an operational state;
- Spare part supply to ensure that the inventory is checked and that the parts are available when needed. If required, orders for spare parts are placed with the supplier;
- Recycling of unused material such as powder is undertaken after manufacturing operation to ensure that this material can be used again in future jobs;
- Environmental safety checks are undertaken to ensure that materials and by-products are safely disposed, such as support structures, cleaning fluids, and other consumables.
- Resurfacing is carried out once the parts are extracted from the build platform. Any possible remnants are completely removed usually through grinding or milling;
- Powder supply management is performed periodically to inspect and update the powder stock based on the level of consumption so that the print jobs and subsequent activities are not affected.
- Quality assurance plans define all testing and validation activities to ensure that the required quality of the AM part is achieved according to the customer’s requirement and job specifications;
- Post-Processing plans define all activities needed to obtain the desired quality of the part. It covers all aspects of the axillary materials that are needed, and the use of machines such as tumblers or polishing machines, etc.
- Monitoring plans define all necessary guidelines and procedures, sometimes in a check list, to ensure that the production processes are correctly conducted;
- Production plans ensure that necessary resources are properly assigned, jobs are scheduled and the budget and the tasks durations are well-defined.
- Process monitoring uses data being collected from machine sensors in order to assess the progress of the manufacturing and correct some of its parameters in case of failures;
- Production monitoring requires the manufacturing space to be supervised and that manufacturing tasks are allocated appropriately according to the production plans.

To ensure the consistency of the whole AM process until the delivery of a correct AM part, the quality assurance, post-processing and monitoring plans are elaborated in the early stages of the design of the part and their outputs are included in the virtual product definition.

4. Conclusions

In this paper, we outlined the generic activities that take place in a typical AM process, the stakeholders that participate in each activity, their roles, and how data flow during its execution. Using BPMN as modeling language, we represent explicitly processes’ workflows. This allows individuating explicitly the basic building blocks of a process, and the temporal order in which they are meant to occur. This highlights the variety of aspects to consider and the complexity to integrate them in a common model.

Process modelling is the first step towards a more robust framework to handle AM data. Process models help to identify the physical and digital resources involved in each activity. They describe the materials and information that are needed in AM application scenarios. The analysis of exchanged information is necessary to define the interoperability between the used software applications to support the digital continuity through an integrated framework. The proposed BPMN models offer a different approach to map AM processes and to offer an expanded view of the system’s performance, by taking into account all support and control activities. The presented process models are part of a larger modeling framework that provides a detailed description of AM concepts, and relations with other elements, thus representing products, processes, resources, and organizational aspects. This model is helpful to increase the maturity and stability of AM technology and therefore deserve particular attention during planning and execution.

For future work, the presented process models will be taken as starting references for the development of a formal knowledge base, grounded on ontology engineering methods and technologies, to handle AM data and knowledge in an integrated manner. Several exploitation areas can be expected such as training and communication in the form of formal procedures for new users and new customers; value chain analysis and monitoring to identify critical processes and to seek improvement; capitalizing expert knowledge for future reuse in similar situations so that to help the actors in their daily situations like process definition, machine parameters’ configuration or failure diagnostic and repairing; traceability for decision making and quality management based on the storage of relevant decisions in each development steps and related performance indicators; and semantic interoperability between organizational processes and between data models of the involved software tools.

Particularly, the intention is to use the final models as a support to create a digital framework in charge of the management of information flows around a given AM machine. Even if it is agreed that the processes of the companies are specific to each one, the ambition is to provide the Machine producer by conceptual guidelines that can help designing the AM solution as generic as possible to deal with large variety of customers.

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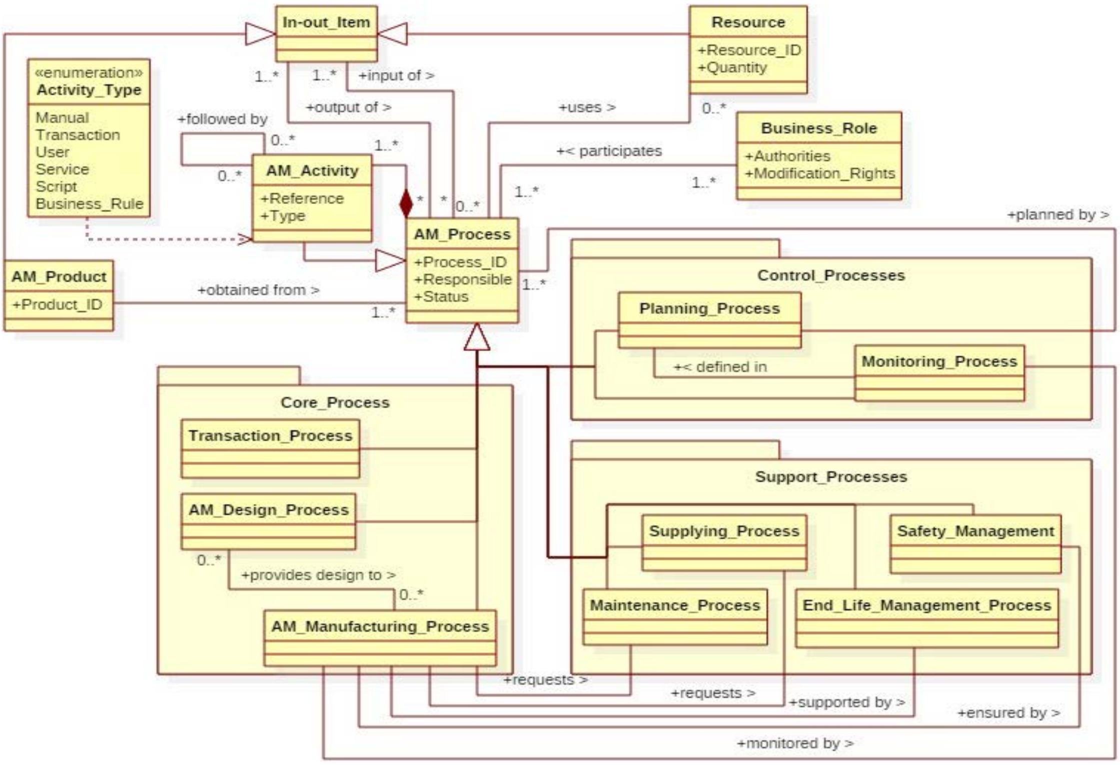

Fig. 1. Classification of processes

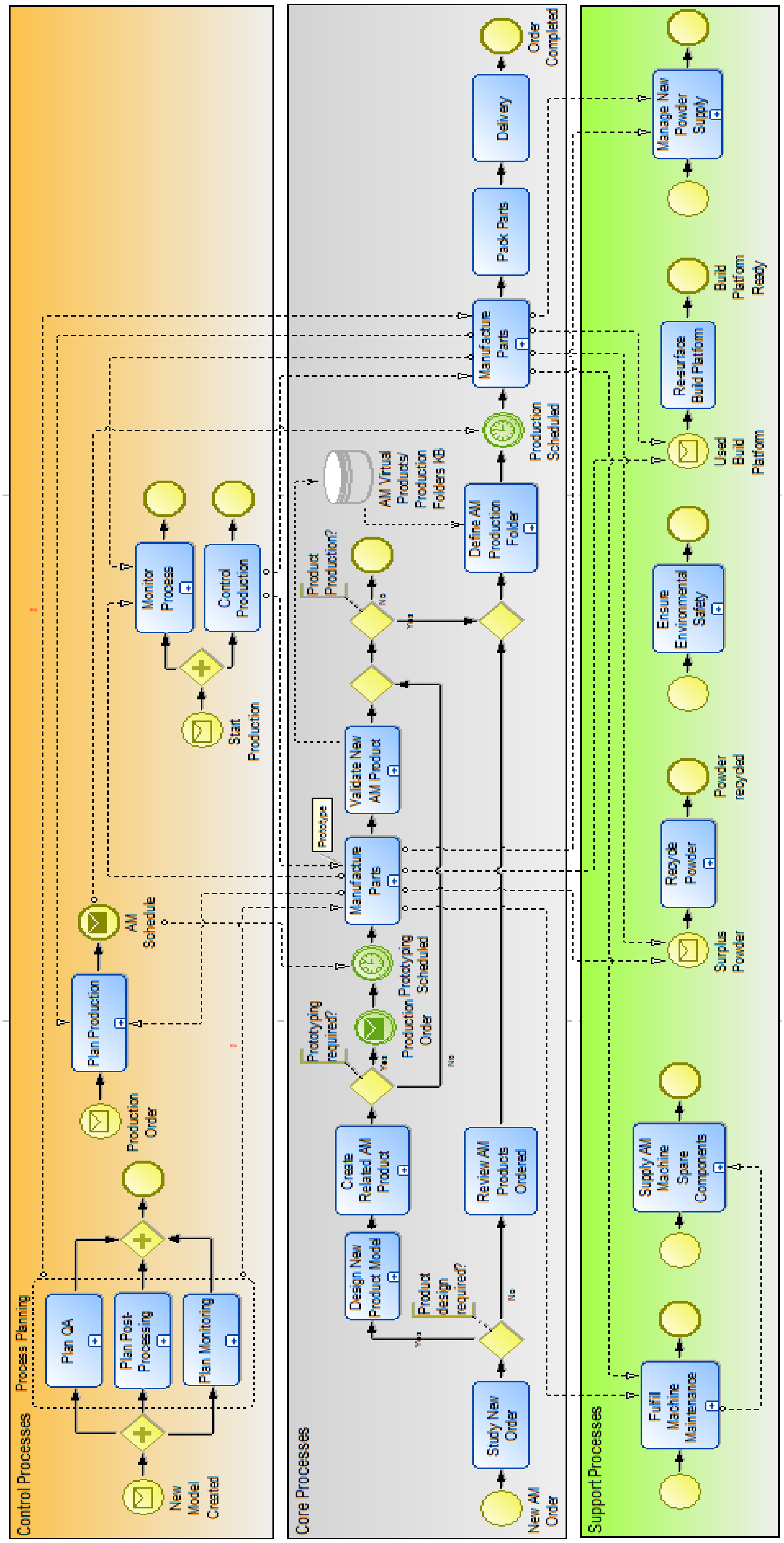

Fig. 2. The AM Process Model

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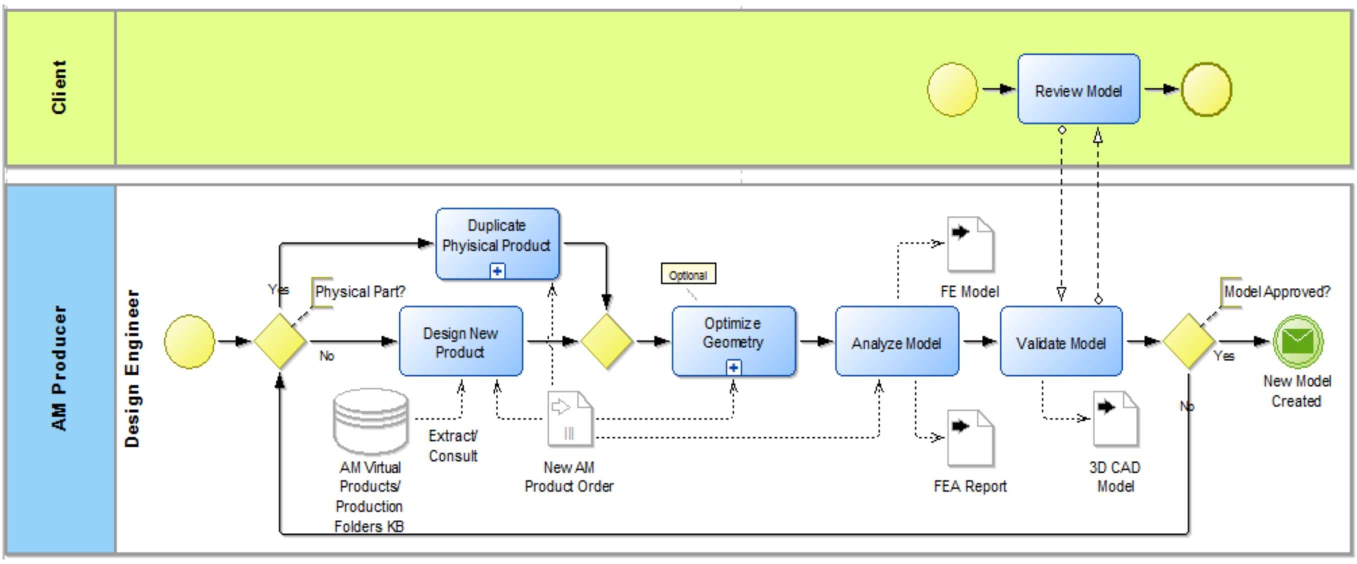

Fig. 3. Designing a New Product

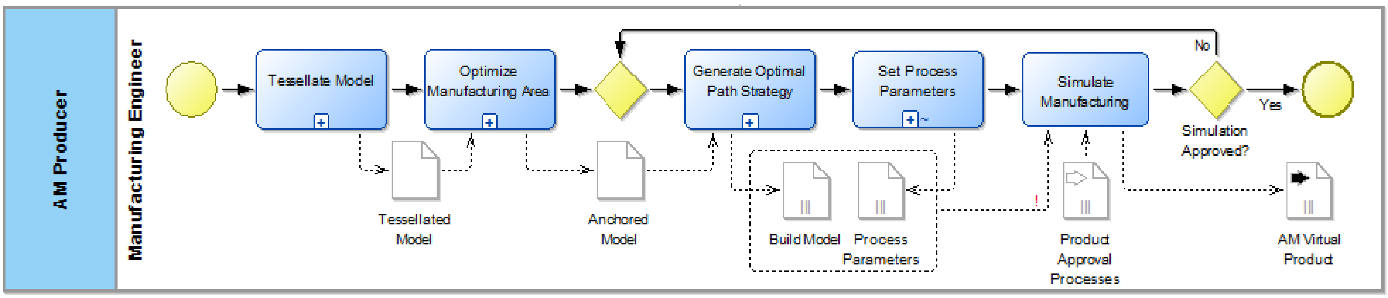

Fig. 4. Creating an AM Product

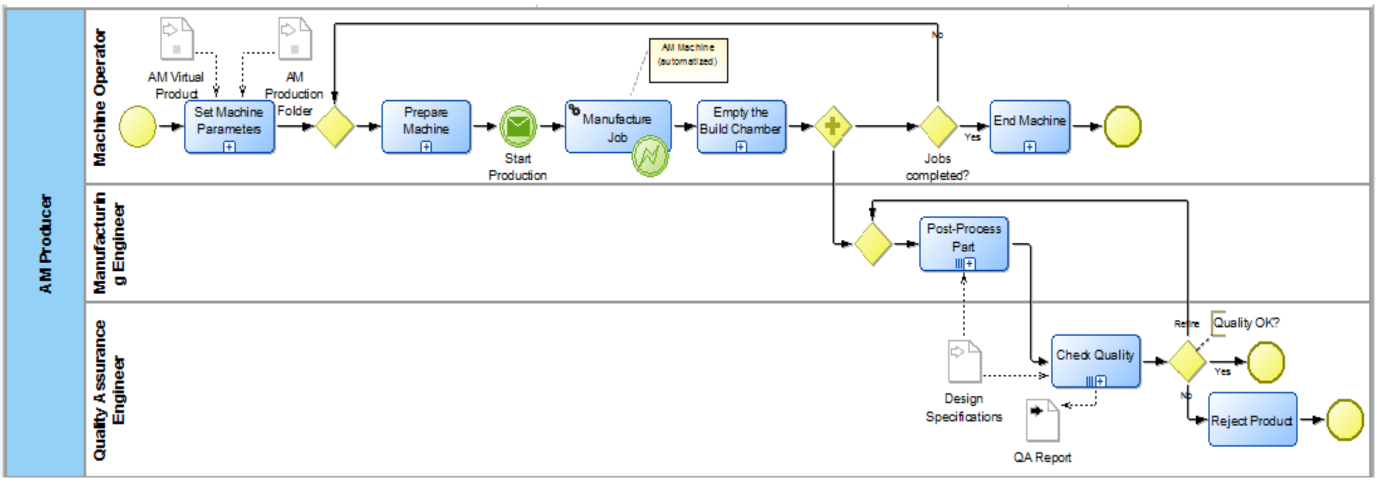

Fig. 5. Production of AM Parts