Title:
Towards a Conceptual Modeling Framework for Additive Manufacturing Knowledge Representation

Authors:
Farouk Belkadi, firstname.lastname@ls2n.fr,
Emilio M. Sanfilippo, firstname.lastname@ls2n.fr,
Alain Bernard, firstname.lastname@ls2n.fr,
Laura Martinez Vidal, firstname.lastname@ls2n.fr,
[1]Ecole Centrale de Nantes, Laboratory of Digital Sciences of Nantes, ECN–LS2N–UMR 6004, France

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Introduction:
Additive manufacturing technologies are evolving as key-technologies for customized, highly efficient and flexible production systems that have a great potential still to be fully realized. In nowadays industry, AM process provides many advantages comparing to conventional one. Concretely, AM process consists of the successive addition of material layers until the desired final part is achieved.

Nevertheless, before AM can be successfully applied to industrial use, there is much need for improvement yet. To do so, an initial step is the creation and the understanding of the complete cartography of operational and structural elements involved in this value chain behind this process.

Indeed, during the AM process, large amounts of data and knowledge are created, modified, and stored. The incredibly big quantity of these data and knowledge, in addition to the variety and complexity of resources involved (i.e. AM parts, design methodologies, machine parameters, materials, etc.) make their management a major challenge.

A critical task for data and knowledge management is their conceptual representation, which can be realized by formal models and ontologies. Several modeling languages are already proposed by the standardization organisms in order to support the modelling of different situations within a unified manner (i.e. BPMN, UML, etc.). This paper is part of a research work that introduces two AM complete models: a BMPN process model and a UML data meta-model for AM. The scope of this paper is limited to the static view with UML class diagrams. In a first part, AM technology is introduced and described. The complexity associated to the different AM processes is exposed and the main problematic related to this field is discussed. In a second part, the different modeling techniques and existing AM models are reviewed. Finally, the AM process model and the AM data meta-model are proposed and described.

AM Process Characteristics – A review:
Additive manufacturing is a new concept of production in which the material (plastic or metal) is deposited layer by layer in a controlled way. It has been defined by the American Society for Testing and Materials (ASTM) as [1]: “A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.”

With such a technique, a broad range of customized shapes and complex geometries are produced quickly and without difficulty according to the needs of each sector.

Compared with traditional manufacturing techniques, additive manufacturing has the potential to spur innovation, reduce intermediate processes, minimize material, energy, and waste [6]. As a result, the manufactured parts have a lower cost and are produced in a more sustainable way.

While additive manufacturing now existed for 30 years, it experienced the most significant progress in the last decade. Currently, the main trend of AM technology has evolved to the direct fabrication of functional end-use products, and it has been progressively applied to manufacture parts in small or medium quantities. This remarkable growth has come about as a result of recent developments in a variety of different technology sectors [4]:

- Improvement of the processing power, graphics and controlling capabilities of the available computers, their integration as central components of AM systems and the development of complex networking platforms.
- Improvements in the way CAD data is shown, treated and stored in means of realism, functionality, engineering content, speed, accuracy and complexity.
- Improvement of other associated technologies such as lasers, printing technologies, materials, …

The range of possibilities which the development of these technologies has introduced to the AM domain has motivated, in turn, the increase of the interest of enterprises and researchers in the fields of materials, processes, software, equipment, and integration [5]. In 2010, the ASTM formulated a set of standards that classify the range of additive manufacturing processes into 7 categories [1] based on the type of materials used, the deposition technique, and the way the material is fused or solidified. This research work focuses on the "powder bed fusion (PBF)" technology [2], in which a heating source such as a laser or an electron beam is used to selectively melt layers of material powder. Within the PBF category of AM processes, the most widespread techniques are metal laser sintering (DMLS), electron beam melting (EBM), selective laser melting (SLM) and selective laser sintering (SLS).

A PBF process starts with the spreading of a layer of powder over the build platform using either a roller or a blade. Then, the energy source fuses the first layer of the part. When the first layer is done, the build platform is lowered and another layer of powder is added on top of it, being subsequently fused by the energy source. Following these basic steps, further layers are added and fused on top of the previous ones until the entire part is manufactured. The loose powder remaining in the part is removed during post processing.

Although several different AM technologies exist, all AM processes have a common base in terms of general principles of part building. It is possible to identify eight key steps in the generic process of CAD to part [4]:

- A CAD solid modeling software is used to obtain a 3D solid or surface representation that fully describes the external geometry of the part to be manufactured.
- The 3D CAD model is converted to a STL file, which is subsequently sliced.
- The STL file is introduced into the AM machine and some parameters are defined.
- The AM machine settings (build parameters) are defined.
- The part is built inside the AM machine by an automated process. The parts are removed from the AM machine.
- Additional cleaning, machining and treatment (post-processing) is applied to the parts before they are ready for use.
- Quality control and verification to validate the conformity of the resulted part with the requirements. Additional treatment activities can be performed to repair the problems.
- The parts are ready to be used. Assembly and packaging might be required.

To support the transition between these generic steps, process modelling is the way to describe the sequencing of all activities as well as the resources involved and the flows exchanged along the whole value AM chain. Data modelling describes the organization of all the above items in a unified format to allow the clarification of all relationships between concepts. In the following, UML (Unified Modeling Language) class diagrams are used to provide a static description of AM processes and related resources. In the extended version, an ontology-based model is proposed to clarify the operational and systemic view of the AM value chain.

<u>AM Process Description:</u>
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 [3]. 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.

For instance, The AM CORE PROCESS diagram (Fig. 1) is a representation of the main additive manufacturing process. A core process describes all activities strongly impacting the value chain of the AM development project and has direct contribution to the final AM product result. In this figure, three types of core processes are identified: the transaction process, the design process and the manufacturing process. All of them contribute to obtaining the product while taking into account the different constraints given by a set of specifications.

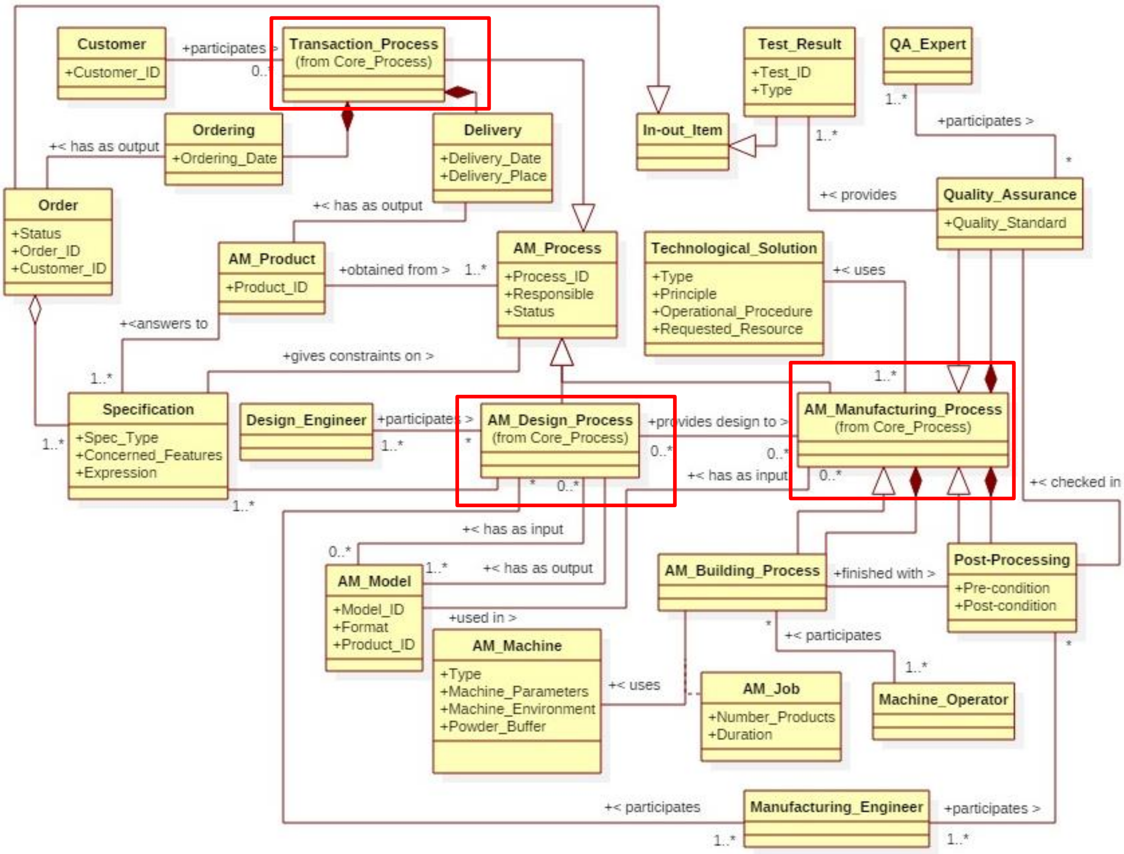

Fig. 1: AM CORE PROCESS (UML Class Diagram).

The transaction process is constituted of two steps: ordering, which has as an output an order; and delivering, which has as an output a manufactured product. The product is designed in a design process with the participation of the design engineer and manufacturing engineer roles. One or more models might be used as input to have a ready-to-manufacture model as an output.

Three types of process are identified as manufacturing processes and are steps of the manufacturing process itself: a building process, which uses an additive manufacturing machine to fulfill one or more additive manufacturing jobs with the participation of the machine operator role; the post-processing of the parts with the participation of the manufacturing engineer role; and the quality assurance, which provides test results with the participation of the quality assurance expert role.

Similarly, the different support processes are represented in the AM SUPPORT PROCESSES diagram. The "Support process" includes all activities without real added value for the final product yet necessary to achieve the core processes. The safety management process is focused on the supervision of the manufacturing room and the administration of the safety equipment with the participation of the safety manager role. The end life management process is focused on the re-surfacing of the used build platforms, with the participation of the machine operator role; and the recycling of the used powder in the sieving system, with the contribution of the powder manager role. The powder manager role is also required in the supplying process in addition to the maintenance expert role and the supplier role. In this process, the machine components and powder are re-stocked when required. Finally, the maintenance process ensures the correct performance of the equipment by reviewing the state of the machines and renewing the machine components when required, with the participation of the machine supplier role and/or the maintenance expert role.

<u>AM Product Description:</u>

In parallel to the process view, the AM product model is described by UML class diagram (Fig. 2). It gives a global overview of the AM product characteristics, which answers to a set of specifications and is represented in a set of models. Product models are not a new paradigm; several models are proposed in the literature to describe mechanical models and the product lifecycle information [7].

Different types of models are identified: the 3D CAD model, which represents the geometry of the product; the tessellated model; the anchored model, which includes one or more tessellated models, the support models and the setting items related to the manufacturing area of the machine's build chamber; the build model, which adds the slices and tracks to the anchored model; and the final element model.

Two different types of products are represented: the prototype and the final manufactured product. The proper relations between the product and the different entities related to it, such as the material, features, function, geometry and behavior, are also included.

Two different types of behaviors are distinguished: the as-designed behavior, described by the final element analysis model elaborated in the design stage and summarized in the finite element analysis report; and the as-produced behavior, obtained from the different tests applied to the produced product in the quality assurance process in the manufacturing stage.

<u>Conclusion:</u>

In this paper some preliminary results towards the definition of a more general modeling framework are presented. The aim is to handle data and knowledge in AM projects. In particular, we introduce UML knowledge models to support the characterization of AM process and product, as well as constraints needed to manage the additive manufacturing digital chain. A more complete modeling framework is under development to represent AM knowledge with the ambition to serve as backbone structures for a knowledge-based information system for application in the AM domain.

Additional models are already developed as part of the global modeling framework for AM. This framework includes also the operational view with BPMN. The ultimate ambition is to use the framework as a support for a future knowledge-based decision aid system to assist experts in the optimal configuration and monitoring of daily AM processes.

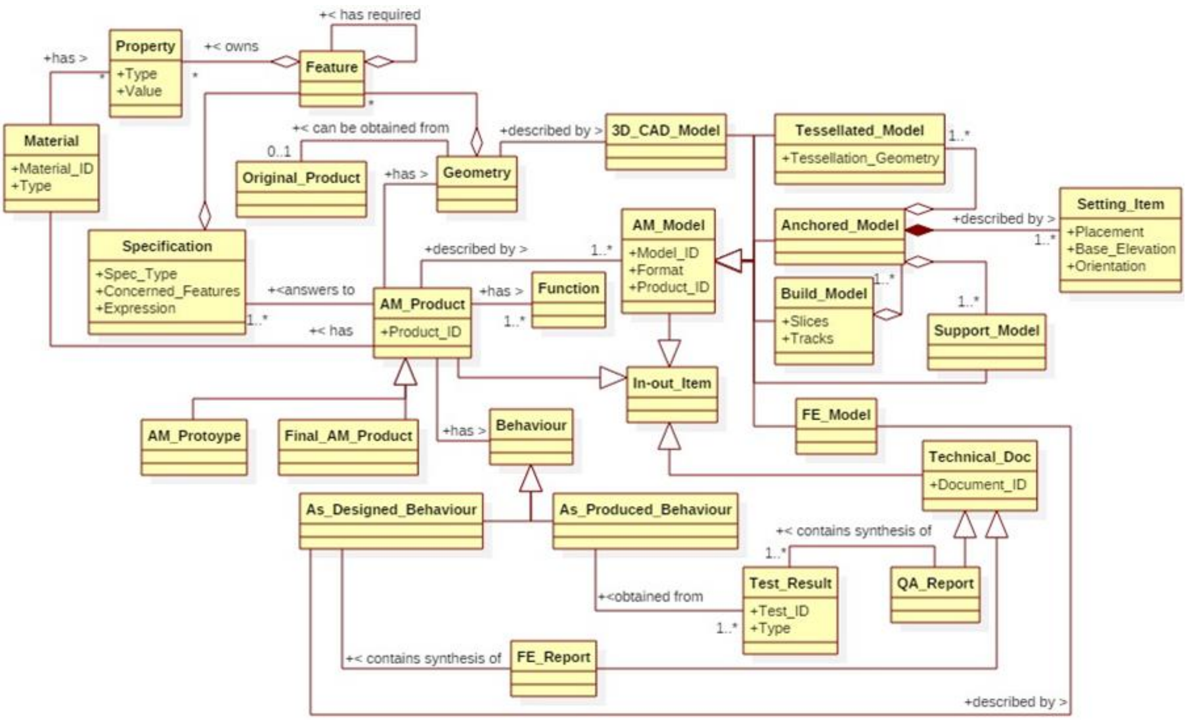

Fig. 2: AM Product model (UML Class Diagram).

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