



## A Product-Process Model for Decision-Aid Perspective in Additive Manufacturing Field

Farouk Belkadi<sup>1</sup> , Emilio M. Sanfilippo<sup>1</sup> , Alain Bernard<sup>1</sup>  and Laura M. Vidal<sup>1</sup> 

<sup>1</sup>Ecole Centrale de Nantes, Laboratory of Digital Sciences of Nantes, ECN-LS2N-UMR 6004, France  
[farouk.belkadi@ls2n.fr](mailto:farouk.belkadi@ls2n.fr)

Corresponding author: Farouk Belkadi, [farouk.belkadi@ls2n.fr](mailto:farouk.belkadi@ls2n.fr)

**Abstract.** Additive manufacturing is a data and knowledge intensive process in which experts need to consider multiple co-relations between disparate parameters in order to perform fabrication processes that achieve pre-defined goals in an efficient way. In real industrial situations, engineers and operators set fabrication parameters based on their experience and initial knowledge. It is a process which is not only time-consuming, especially when multiple products are to be fabricated at the same time, but it is also prone to errors, since dependencies between the parameters have to be manually checked. The purpose of the paper is to lay down the core concepts towards the development of a Computer Aided system to assist practitioners in complex decision-making procedures related to AM fabrication goals. With this ultimate purpose at stake, we present in the paper a modeling framework based on both UML class diagrams and BPMN process models by which AM processes can be represented in tandem with the entities they manipulate.

**Keywords:** Knowledge representation, additive manufacturing, product model, process model, decision aid.

**DOI:** <https://doi.org/10.14733/cadaps.2020.1278-1293>

### 1 INTRODUCTION

Additive Manufacturing (AM) processes and technologies are substantially revolutionizing the current product development strategies, from the manner in which products are designed to their production and distribution (see, e.g. [14] , [17] , [35] [36] , [37] ). The changes in current industrial practices concern also the organizational processes supporting the whole AM digital chain [21] , [43] . Additionally, the full exploitation of AM potentialities calls for research efforts at the intersection between various domains including at least material engineering, mathematics, physics, and disparate subfields of computer science like knowledge engineering and data science [42] . The latter are particularly needed to analyze and reason over AM knowledge and data.

In order to get full control over the huge quantity of data and knowledge manipulated during AM processes, information systems like Product Lifecycle Management (PLM) systems specifically tuned to AM requirements and coupled with knowledge-based facilities are needed [4] , [43] . These systems are required to allow users to trace data and reuse them for future projects.

Notoriously, AM technologies are moving fast from the prototyping phase to the fabrication of final, end-products [12] ,[36] . Especially in domains like aerospace and biomedical industry, this means that AM data have to be continuously controlled to gain full control over processes and support the high quality of the fabricated products. Additionally, information systems for AM need to support experts' decision making procedures over multiple and co-related parameters [21] , [22] ,[43] . Lessons learned from past projects may provide useful support to configure the execution of new processes.

As a first step towards an information system for AM, heterogeneous experts' knowledge needs to be represented and structured in an integrated manner. Data and process models are helpful to understand how various AM activities and objects are connected to reach the desired objectives. The purpose is to declare which information concerning, for instance, products, manufacturing devices, processes, or organizations the information system needs to manage.

To tackle this first step, the paper presents a conceptual modeling framework to represent AM knowledge about, e.g., processes, machines, materials, and parameters in an integrated way. The core contribution of the paper consists in multiple and inter-related conceptual models which can serve as backbone for structuring knowledge-based repositories to support application in the AM domain. The ultimate ambition is to develop a knowledge-based decision aid system to assist experts in the optimal configuration and management of AM processes.

This paper is structured as follows. The next section lays down the research problem addressed in the paper and the approach proposed to tackle it. Section 3 reviews the state of art about conceptual modelling in additive manufacturing, while stressing the strengths and limits of current approaches. Section 4 introduces various models constituting the conceptual framework. Section 5 describes some instance models as a simple academic example to validate that the conceptual model covers various situations of the studied system. The validation criteria are that all aspects identified in a real world are covered by the models of chapter 5. The last section concludes the paper by summarizing our contribution and addressing the need for future work.

## 2 RESEARCH PROBLEM AND METHODOLOGY

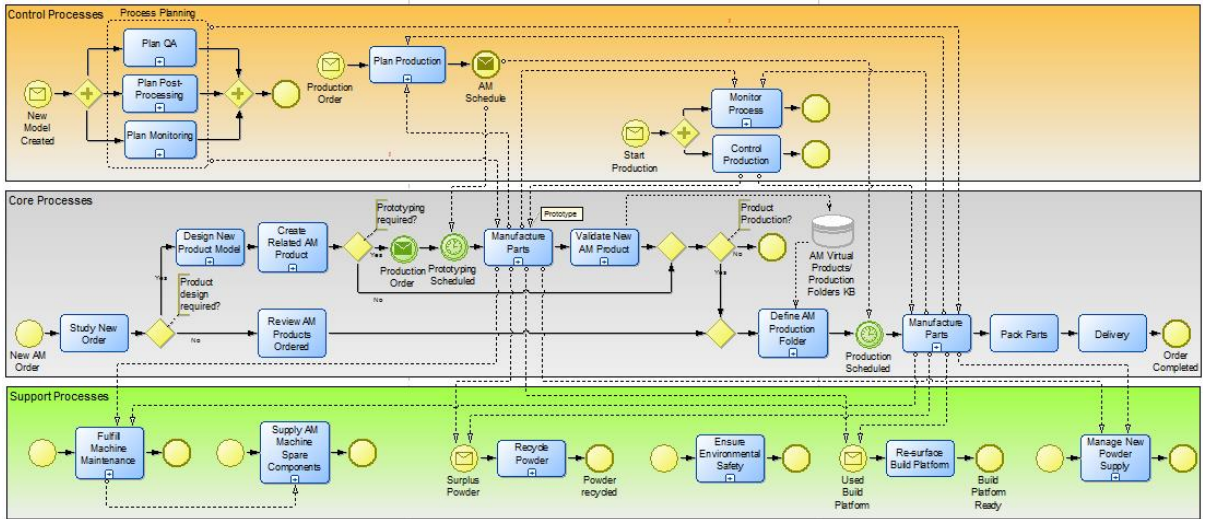
Differently from subtractive manufacturing processes, additive manufacturing processes fabricate products by joining materials usually layer upon layer [12] . This allows for more flexibility in the creation of a broad range of customized shapes and complex geometries [37] . High potential to spur innovation is therefore possible with minimum of material, energy and waste [17] .

The planning, scheduling, and execution of additive manufacturing processes require the representation of multiple and heterogeneous aspects of experts' knowledge, as well as a careful analysis of the dependencies holding between different parameters [3] ,[11] ,[16] ,[36] . According to Gibson and colleagues [12] for example, the power of the laser used during powder bed fusion processes has a relevant impact on the quality of the fabricated layers. Co-relations between parameters need to be clearly identified, represented, and monitored during manufacturing to gain full control over processes.

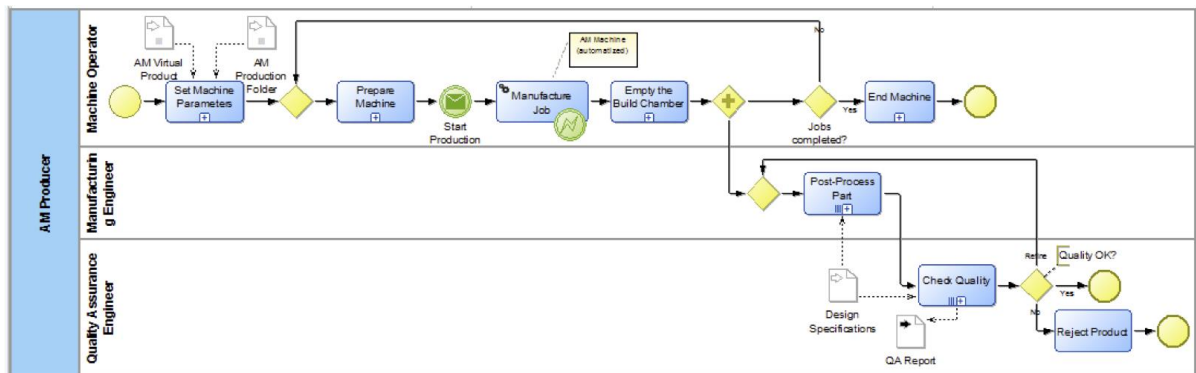
To have a clearer picture of the whole additive manufacturing value chain in terms of operations to be realized, input materials to be transformed by the operation, resources involved, and manufacturing parameters, as well as to handle the dependencies between multiple parameters, we propose hereby an approach grounded on conceptual modeling techniques [28] . The driving idea is that, in order to manage the whole AM value chain, there is the need to analyze their input and output data, assist experts within decision making procedures, and monitor derivation of performance indicators from their nominal values. To do so, a representation of experts' knowledge is above all required. The knowledge base is seen as a container to store the past experiences. Face to a new AM project, the knowledge based combined to suitable decision aid engines will help decider to choose the best solution based on similarity with past projects.

In more practical terms, this means that models representing the core entities and relations involved in AM processes, or process plans are needed. For instance, the process model in Figure 1

is specified with the Business Process Model and Notation (BPMN) language [26], which is one of the most used modeling languages for process modeling [40]. Recall that a BPMN diagram mainly consists of activities (rectangular boxes) and events (circles) related to each other by arrows indicating the temporal flow of the depicted process. Gateways (diamonds) indicate alternative workflow executions based on the occurrence of certain conditions. The reader can refer to [26] for a technical insight on BPMN.



**Figure 1:** BPMN model about the general additive manufacturing value (from [4]).



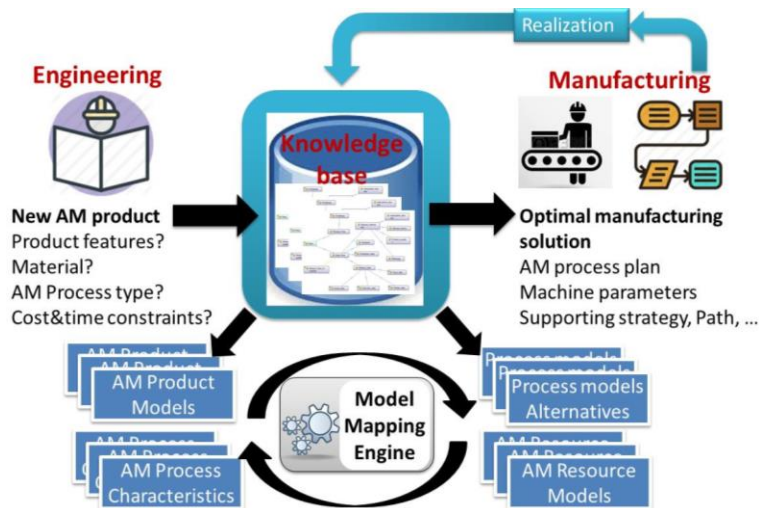
**Figure 2:** BPMN model for Manufacture Job (from [4]).

The model provides a general view on core fabrication processes along with control and support processes. BPMN language provides useful notations to describe variety of complex processes behind the AM value chain. For example, looking at the activity "StudyNewOrder" (as part of the Core Process), a gateway condition is used to split the process execution in alternative paths depending on whether the condition expressed by the gateway ("Is) Product design required?") is satisfied. Second, once a process model is defined, it can be used to support the specification of the parameters for each activity in the process, as well as of the physical entities that each activity requires (as input, mechanism, or control) or produces (as output). For example, the BPMN diagram in Figure 2 shows the expanded view of "ManufactureParts" represented within the Core

Process of the diagram in Figure 1. The activity “ManufactureJob” is the core element of this process model, because it represents the (complex) activity leading to the fabrication of the desired product. Hence, during process planning stages, it is fundamental for experts to define precisely which entities this activity requires and manipulates.

Despite a process modeling language like BPMN is useful to get a clear picture of process elements and their flow, BPMN models need to be supplemented with other types of models to realize an overall view over both processes and their participants. Indeed, since BPMN is focused on process modeling, it cannot be used to explicitly represent the static view, e.g., that a certain energy source satisfying a specific power parameter is required for the desired task [1]. Hence, we rely on Unified Modeling Language (UML) class diagrams [27] to specify categories of data or physical objects manipulated in AM processes.

The proposed conceptual modelling framework can provide various benefits. In addition to the contribution towards the definition of reference models for AM, complementary to other initiatives (such the process model proposed by the U.S. NIST [8]), conceptual models can be used to represent and capitalize industrial best practices within and across organizations. This can be particularly helpful to assist novice workers in learning from experts and finding solutions to their operational problems. It is also a good manner to formalize operational procedures that make collaborative work more homogeneous. Additionally, traceability of the AM process in terms of actions, decisions, results, and justifications is a direct consequence of the modeling framework that could help the optimization of the whole value. E.g., by defining and structuring the characteristics of AM products, experts can trace data for quality checking by comparing the as-specified and as-produced products’ characteristics with reference to common models. These models can be also helpful to ensure semantic interoperability between software applications used for AM purposes through the mapping of their respective data models. Another important perspective of the modelling framework is, as previously said, to support a knowledge-based decision aid system that allows various stakeholders to capitalize their knowledge and reuse it in future projects.



**Figure 3:** Knowledge reuse perspective within the conceptual modeling framework.

Figure 3 gives an overview of the proposed solution for such a decision-making system, which is meant to be specifically applied in the context of metal-based additive manufacturing with powder bed fusion technologies. The key functionality is to help engineers to set up the optimal configuration of manufacturing parameters for fabricating new products. As said above, indeed, in order to execute efficiently an AM process, experts need to consider the co-relations between various parameters and the manner in which the parameters affect the item(s) to be produced.

The basic idea we put forward is that by describing a product model in terms of key characteristics [43], it is possible to match such characteristics to machine parameters for manufacturing. These matches, once enriched with rules and further operational constraints, can be then used to aid experts' in decision making. Assuming that the information system already support traceability of previously performed AM processes. Then, given a new product model, by identifying its key characteristics like geometric features or constituting material, and by indicating the AM process type for fabrication, the system will search for similar cases stored in the knowledge repository, and extract potential parameters as knowledge fragments to be reused. Once the product is realized, all the data related to its production are stored in the knowledge repository as an instance of existing case or a new case, if it is completely new, to be reused for future projects.

It should be clear that in order to use the information system in the way just described, it must be fed with experts' knowledge, which allow the system to interpret and classify data coming from disparate sources in a homogeneous manner. In the next section, the state of art about conceptual modeling for additive manufacturing purposes is revised.

### 3 LITERATURE SURVEY

The development of AM technologies goes along with the design of various approaches to handle digital data in tight connection with experts' knowledge. Because of the relatively recent application of conceptual modeling approaches and knowledge-based technologies in the AM domain, only few models are available in comparison with other engineering domains like machining, assembly, or inspection (see, e.g., [19], [34], [38]).

The U.S. National Institute of Standards and Technology (NIST) presented various process models for AM encoded in the IDEF0 (Integrated Definition for Functional Modeling – the 0th level) language [8], [18]. The ultimate purpose is to have a clear understanding of data flows during the planning and execution of AM processes. For instance, according to the authors, an activity of tessellate product model takes as input a *geometric product model*, and delivers as output a *tessellated model* representing the desired product geometry with three-dimensional triangulated surfaces. Hence, the idea is that when a tessellate product model activity is planned or executed, the process model can be used to support experts in specifying the inputs and outcomes that the process is requested to manipulate. The work done at NIST is one of the first studies aimed at the formal representation of AM processes from a conceptual modeling perspective. A similar approach on the use of IDEF0 models for decision aid in AM is presented in [21]. However, IDEF0 does not allow for the explicit representation of temporal constraints, e.g., the fact that some activities run in parallel, nor the organizational dimension of processes, e.g., that a person with a certain role is responsible for executing a process. These observations motivated the work of Belkadi and colleagues [4], where models for different tasks related to additive manufacturing are represented by using BPMN (see Figure 1 and Figure 2 in the previous section).

Dinar and Rosen [6] present a model in the Web Ontology Language (OWL) [39] specifically targeted to the representation of features in products created by additive manufacturing processes. The model makes implicit assumptions concerning the semantics of the represented classes, hence the modeling choices behind its design remain unclear to third parties. For example, the authors distinguish between Process Type and Additive Manufacturing Event. This distinction is not explained, so that it is hard to understand how to reuse and, possibly, extend the proposed model. Eddy et al. [7] present the so called Semantic Additive Manufacturing Process Planning (SAMPro) ontology, which – as the name suggests – is specifically targeted to process planning for additive manufacturing. Differently from the work presented in [6], SAMPro covers the classification of AM processes as provided by the American Society for Testing and Materials (ASTM), see [11]. From a modeling perspective, it is not clear how the proposed ontology distinguishes between some of its classes. For example, SAMPro ontology includes the classes "ProcessOutput" and "Part". It remains however unclear what are the conditions that an individual entity must satisfy to be classified by one or the other class; hence it is hard to understand how these classes can be reused and adapted for our purposes.

In different publications, researchers at NIST [29] ,[41] explore the application of in OWL or UML formalisms to the representation of knowledge related to powder bed fusion processes. In [41] , the authors propose ontology model based on five main classes, namely, "PowderMaterial", "AMPartComponent", "AMProcessPlanningParameter", "Qualification", and "AMProcessComponent". The ontology is affected by different modeling drawbacks. For instance, the classification of processes blurs the distinction between taxonomical "is-a" and parthood "part-of" relations (Recall that according to the standard semantic of the "is-a" relation, when a class "c1" is-a "c2", i.e., "c1" is subsumed by "c2", then all instances of "c1" are instances of "c2" [33] ). The ontology therefore does not provide a robust model for further reuse. The situation is no better in the work recently presented in [21] ; the model introduced in the paper blurs, indeed, basic conceptual modeling distinctions. For example, the same relation is used to define is-a links between classes but also to model the link between a class and its attributes such as names or dimensions, whereas it is clear that different relationships have to be used [33] .

From the above analysis, it emerges that – although relevant work has been already done to support modeling tasks related to the representation of additive manufacturing knowledge – further work is required to increase the robustness and (semantic) transparency of AM-based conceptual models.

#### 4 CONCEPTUAL MODELS FOR ADDITIVE MANUFACTURING

This section introduces various UML class diagram models for representing the core entities involved in additive manufacturing process. In particular, recall that the application domain of our research is powder-based AM. The construction of the models is based on two main sources: literature survey and analysis of industrial practices from the SOFIA project. The models are based on existing works like the Core Product Model (CPM) [9] and the MOKA model, which are hereby adapted and further extended to meet modeling requirements emerging from the AM domain. Recall that UML class diagrams can be automatically converted into OWL models [10] .

The model in Figure 4 introduces a basic taxonomy of physical objects. As it can be seen from the model, physical objects can be made of some material "AmountOfMatter". The "PhysicalObject" class is extended into the disjoint classes Artefact and Person. Following [9] ,[30] , "Artefact" class refers to physical objects that are intentionally designed and created. This class is extended into the Device, Layer, "AMProduct", and "AMFeature".

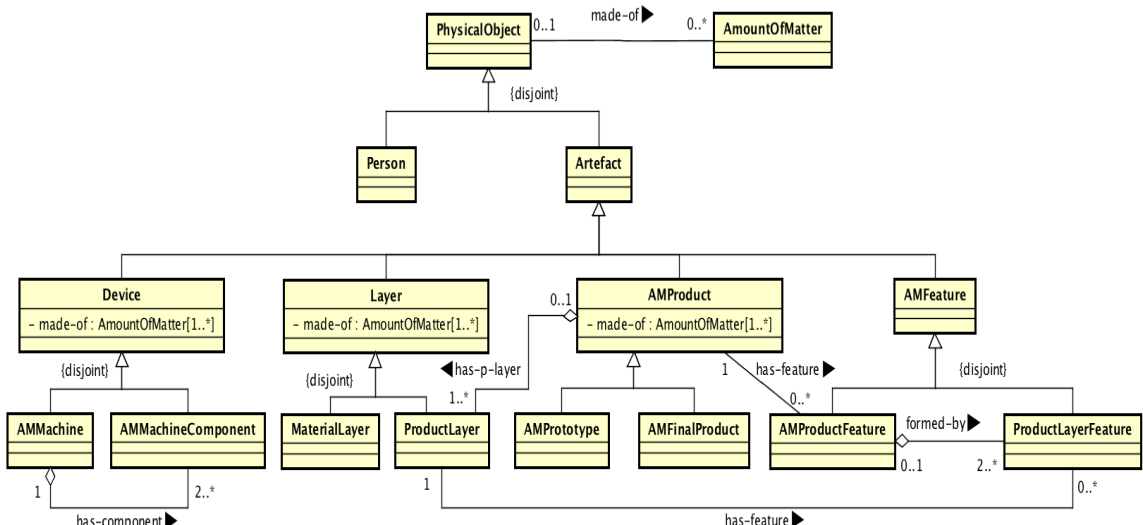


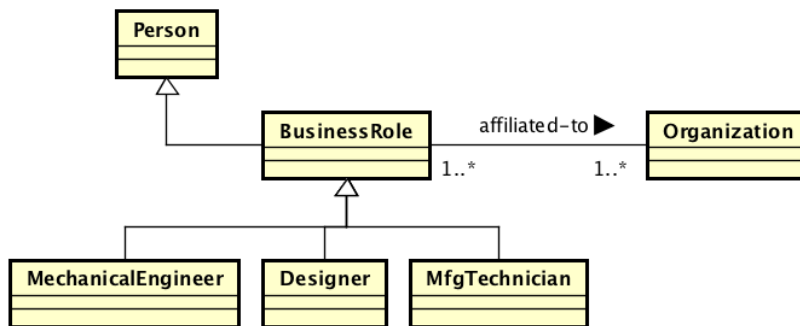
Figure 4: Model for physical objects.

Device is a general class subsuming physical objects that in virtue of their capabilities can be used in manufacturing processes, e.g., to fabricate the desired products. Examples are additive manufacturing machines "AMMachine" and their components "AMMachineComponent".

Layer and its subclasses "MaterialLayer" and "ProductLayer", as the names suggest, refer to layers of material that are used/constructed along an AM process. The distinction between the latter two classes lies in the fact that only a portion of the layer that is placed in the building platform of the employed machine is commonly processed to create the final product. The remaining part may have the function of supporting well product positioning. E.g., during powder bed fusion processes, only a portion of the layer is usually sintered (or melted). In this sense, we call material layer the layer that is placed on the building platform of the machine that is used, whereas the portion of the material layer that is sintered is the product layer.

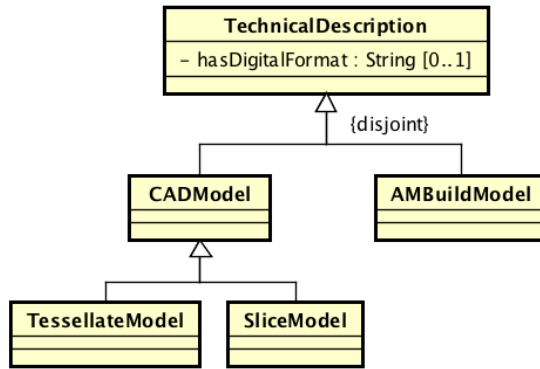
The "AMProduct" class refers to the product fabricated in additive manufacturing processes. In the taxonomy we distinguish prototypes from final products, where – differently from the former – the latter are end-use products that satisfy design and customers' requirements. Concerning the representation of additive manufacturing features "AMFeature", we distinguish – from a high-level perspective – between product "AMProductFeature" and product layer features "ProductLayerFeature". The idea is to explicitly distinguish between, e.g., a "hole" feature in a product layer, and a "hole" feature in a (final) product resulting from the composition of the holes in the layers forming the product. More specific feature classes for the representation of, e.g., slots, pockets, bumps, etc. can be easily added in the model by extending the taxonomy. The next section presents a non-exhaustive example since Recall that the literature lacks an exhaustive classification of features [31].

The model in Figure 5 introduces some basic classes for the representation of business roles, that are, the roles that persons may play within organizations. As we saw in Section 2, it can be relevant, especially during process planning procedures, to specify the role of the person responsible for a certain task. It should be clear that "BusinessRole" can be extended in various classes, whereas we show here only some examples.



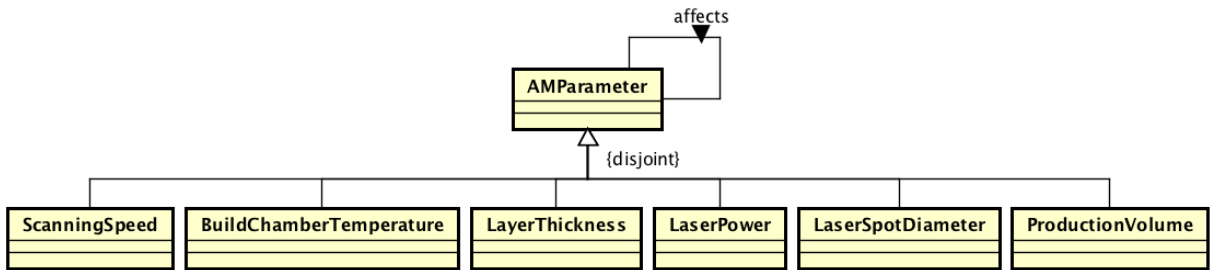
**Figure 5:** Model for business roles.

The most general class "TechnicalDescription" is shown in Figure 6 and refers to digital or paper-made documents that are produced during or are used for engineering tasks. Examples are product models developed by means of Computer Aided Design (CAD) systems ("CADModel" class) or AM build models ("AMBuildModel" class), the latter being plans for additive manufacturing. As the label suggests, the relation "hasDigitalFormat" can be used to specify the computer format, when present, of a description. Examples of CAD formats for additive manufacturing are Stereo lithography (STL) or Additive Manufacturing File Format (AMF) [11].

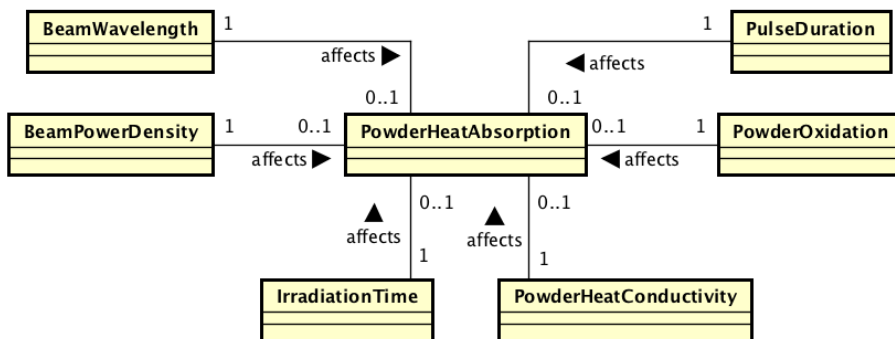


**Figure 6:** Model for technical descriptions.

From the literature about additive manufacturing (see, e.g., [11] ,[14] ,[16] ,[36] ,[43] ), the representation of parameters (“AMParameter” class) is fundamental to specify attributes relevant for fabrication. There is not an exhaustive classification of parameters; Figure 7 shows some recurrent examples (see also next section). Note that the relation affects holding between instances of “AMParameter” is used to model the fact that parameters may influence each other. An example is showed in Figure 8; the figure is based on [41] and captures the fact that powder heat absorption is affected by beam wavelength, beam power density, pulse duration, powder oxidation, irradiation time, and powder heat conductivity.



**Figure 7:** Model showing some additive manufacturing parameters.



**Figure 8:** Example of dependencies between parameters.

Figure 9 shows the classification of additive manufacturing processes (“AMProcess” class) according to the American Society for Testing and Materials (ASTM) (see [12] ). As it can be seen from the taxonomy, “AMProcess” is specialized in seven main classes, namely, “MaterialJetting”,



"BinderJetting", "DirectedEnergyDeposition", "MaterialExtrusion", "VatPhotopolymerisation", "SheetLamination", and "PowderBedFusion". Each class can be further extended to cover specific AM process classes. E.g., the figure shows the specialization of "PowderBedFusion" into "DirectMetalLaserSintering", "ElectronBeamMelting", "SelectiveHeatSintering", and "SelectiveLaserSintering".

Besides the taxonomy, the representation of AM processes requires to take into account other processes that are fundamental for their execution. For example, as will see in the next section, a powder bed fusion process is commonly formed by processes such as powder spread and sintering. Following the classification of processes in [2] ,[5] and the ASTM definition of additive manufacturing processes, the "AMProcess" class is subsumed by a more general taxonomy for manufacturing processes ("MfgProcess" class) that distinguishes between mass conserving processes (e.g., bending or forming), mass reducing processes (e.g., turning, milling, drilling), and joining processes, among which additive manufacturing processes (see Figure 10). At a more general level, the taxonomy includes other process classes, among which "MonitoringProcess" and "TransportationProcess". It should be clear that the taxonomy is incomplete and further classes can be easily added, e.g., based on [2] , depending on more specific application requirements.

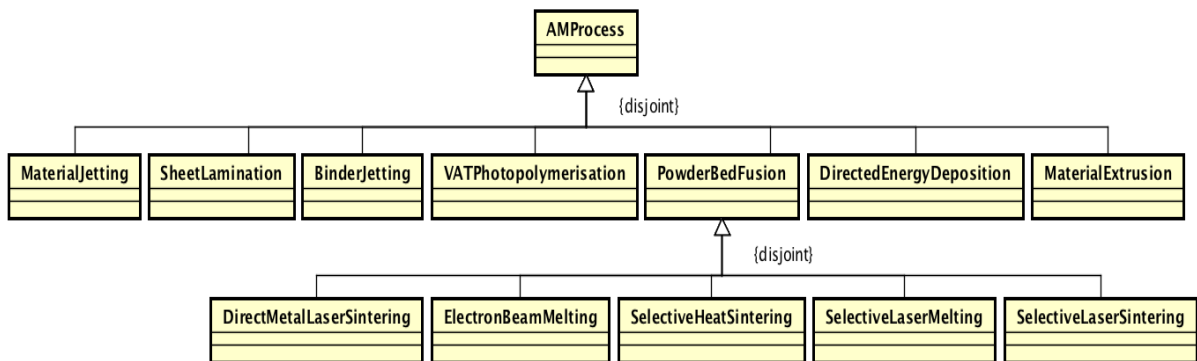


Figure 9: Taxonomy of additive manufacturing processes according to the ASTM standard.

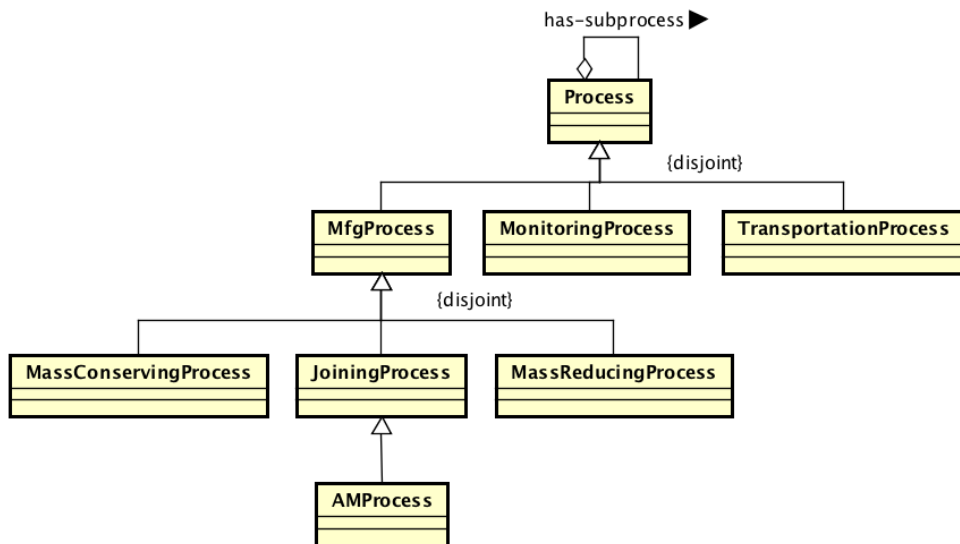
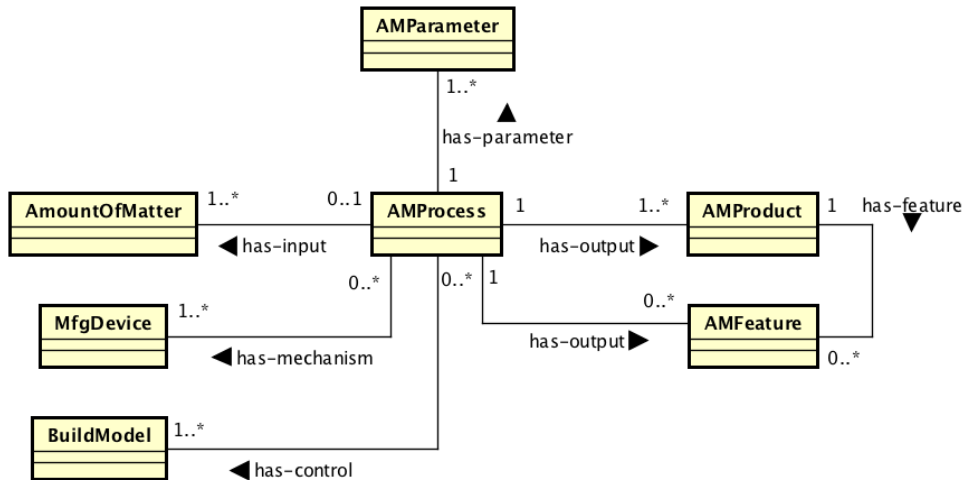


Figure 10: Model for process representation.

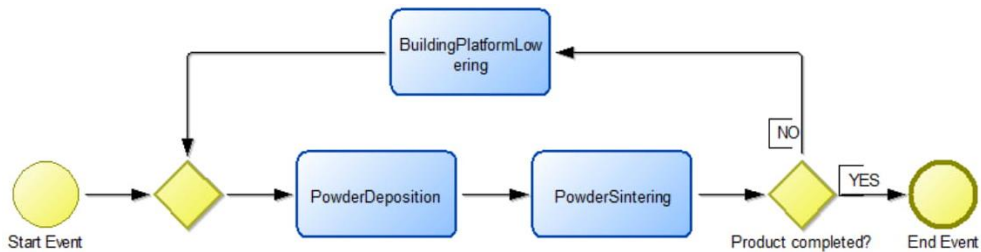
In addition, Figure 11 shows the integration of “AMProcess” class with other classes related to participants (inputs, outputs, controls, and mechanisms) and parameters. The specification of the former is based on both the IDEF standard and the work presented in [32] . Accordingly, the relationship has-input is used for physical entities that (passively) undergo additive manufacturing processes, differently from has-mechanism which binds a process to its (active) devices, e.g., machines and tools; has-control is used to relate processes to build models; has-output models the entities resulting from the process, namely, products or features.



**Figure 11:** Integrated representation of AM process with other classes.

**5 MODELING APPLICATION EXAMPLES**

This section introduces an example where the models presented in the previous section are extended, when needed, and instantiated to a specific modeling case. In particular, we show the use of UML models in tandem with a BPMN diagram to provide a modeling view on powder bed fusion processes that integrates knowledge on both the process at stake and its participants. UML instance diagram help verification and validation of conceptual models through their application in simple but realistic use cases. The class diagram is verified if it is able to cover all important information in the studied case.



**Figure 12:** BPMN model for the basic activities of powder bed fusion processes.

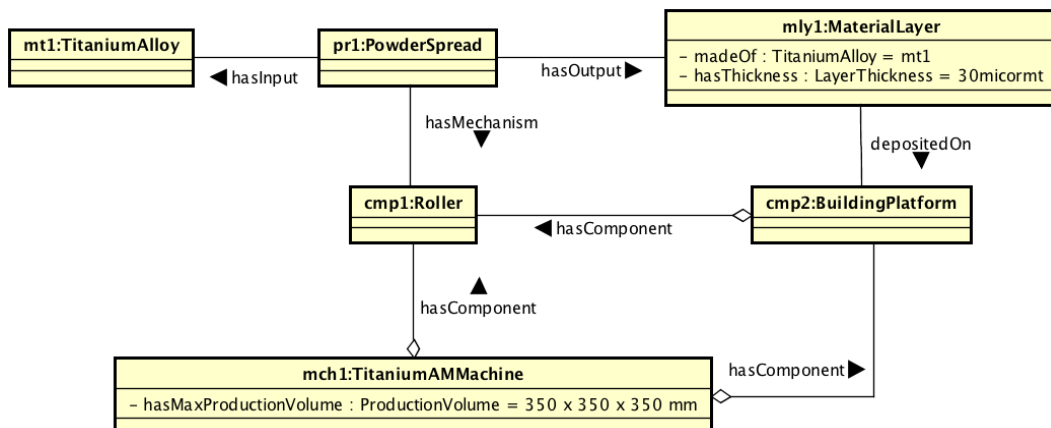
Following [4] ,[12] , By looking back at Figure 2 presented in Section 2, the diagram in Figure 12 provides the inner view of the activity labeled “ManufactureJob”. This figure shows the basic activities to be executed to fabricate a product in powder bed fusion processes. Accordingly, the overall process consists of three activities: “PowderDeposition”, “PowderSintering”, and “BuildingPlatformLowering”. The first one has the purpose of spreading out the metal powder on

the build platform of the machine to be used, hence to create a material layer. The second one sinters the metal and creates the first product layer of the product that is built during the overall process. Finally, the third activity lowers the building platform of the machine, allowing the creation of a new layer. Note that according to the process model, the execution of "BuildingPlatformLowering" is subjected to the condition "(Is) product completed?", which is graphically expressed by the second BPMN gateway. This means that the activity is executed only if the creation of a new product layer is required. If this is not the case (i.e., gateway exit condition returns "yes"), the overall process ends. As we saw throughout Section 2, BPMN diagrams allow for a straightforward representation of processes flows, although they cannot deal with the specification of processes' participants, to which we now turn by relying on the use of UML models. Therefore, for each activity in the BPMN model, the purpose is to characterize the entities that take part in its execution(s).

Examples of application of conceptual models presented in Section 4 are described in Figure 13, Figure 14, and Figure 15 respectively. Following the UML language, each rectangular box in such diagrams represents the instance of a class. For example, "mch1:TitaniumAMMachine" refers to the individual "mch1" instantiating the class "TitaniumAMMachine", which is a subclass of "AMMachine" with the capability of processing titanium powders. Note that we intentionally avoid referring to machines available on the market, although the models can be easily customized to cover them in application contexts.

Accordingly, Figure 13 shows some of the entities that are required during the occurrence of the individual "PowderSpread" (process) named "pr1", where "PowderSpread" extends the class "TransportationProcess" showed in Figure 10. In particular, "pr1" instance has:

- As input the amount of matter "mt1" instantiating the class "TitaniumAlloy", which is a new subclass of the "AmountOfMatter" class showed in Figure 4;
- As output the material layer mly1 that is deposited on the individual cmp2, where the latter instantiates "BuildingPlatform" and is amongst the components of the machine "mch1". the "hasThickness" relation used to specify the thickness of the "mly1:MaterialLayer" provides values in micrometers;
- As mechanism the roller cmp1, which is component of both "mch1" and "cmp2". We assume that if a physical object o1 is component of another physical object o2, and o1 is the mechanism of a process p, then "o2" is the mechanism of p, too. Looking at the figure, this means that "pr1" has both "mch1" and "cmp2" as mechanisms in addition to "cmp1". Also, the class Roller is a new subclass of Device. Since both "cmp1" and "cmp2" are related to an instance of "AMMachine" via the "hasComponent" relationship, we assume them to be classified as instances of "AMComponent".



**Figure 13:** Instance pr1 of PowderSpread.

Figure 14 shows the instance "pr2" of "PowderSintering" such that it has:

- As input the material layer "mly1", which from Figure 13 we know resulting from "pr1";
- As output the product layer "ply2" and the hole feature "hl1", such that "hl1" is the feature of "ply2". The class "HoleFeature" is subsumed by the class "AMFeature" showed in Figure 1 and since "hl1" relates to "ply2", it instantiates "ProductLayerFeature";
- As mechanism "cmp3", which instantiates "FiberLaser" (a new subclass of "Device" class) and is component of the machine "mch1". As for the previous figure, we assume that cmp3 is classified as an "AMMachineComponent", since it is related to "mch1" via the "has-component" relation.

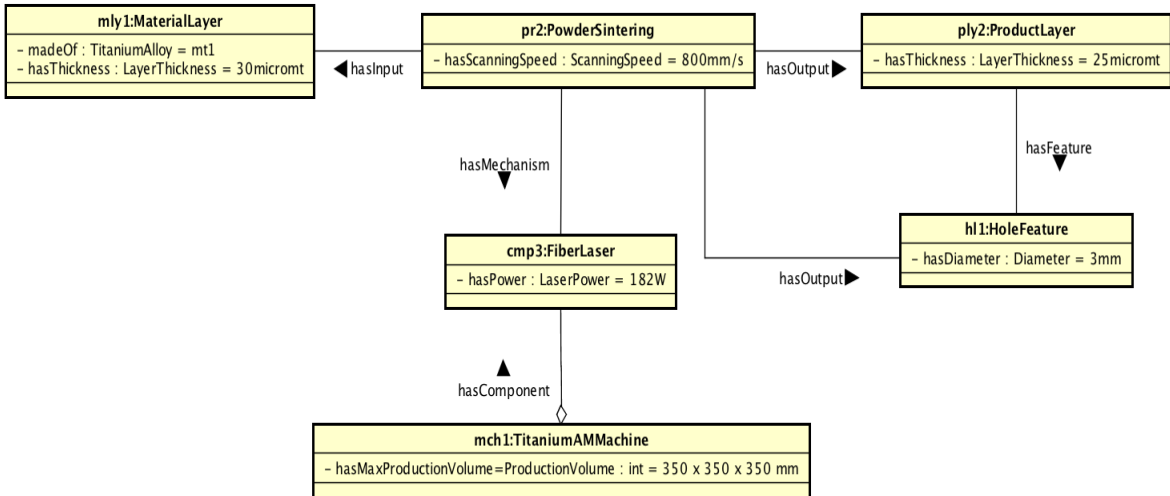


Figure 14: Instance pr2 of PowderSintering.

Finally, Figure 15 shows the instance "pr3" of "BuildingPlatformLowering" that has:

- As output the building platform "cmp2" (but with a new spatial position);
- As mechanism the lowering mechanism "cmp4", which is component of both "cmp2" and (by transitivity of "hasComponent") of "mch1". Similarly to previous cases, "LoweringMechanism" extends the class Device.

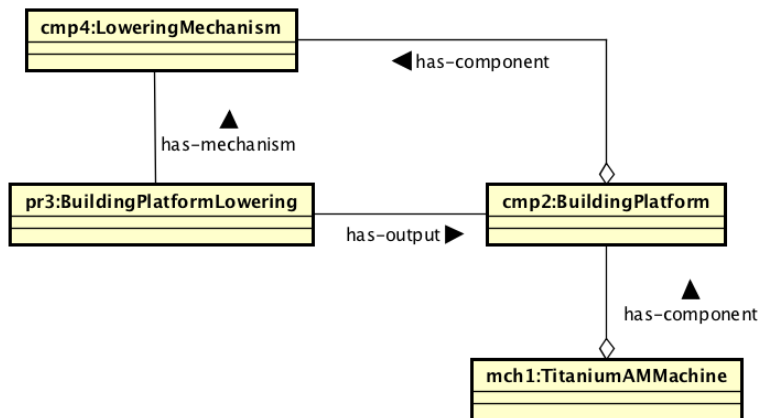


Figure 15: Instance pr3 of BuildingPlatformLowering.

Some clarifications are due. First, the models in Figure 13, Figure 14, and Figure 15 can be easily specified in more details to match specific application requirements. E.g., one can explicitly model the laser power parameter for the process "pr2:PowderSintering" and connect it to other parameters via the relationship affects in order to model dependencies between multiple parameters. Also, one can explicitly add information concerning the organization in which the processes are performed. Second, since the UML diagrams above represent individual entities, they refer to the participants in a single execution of the process model in Figure 12. In fact, according to the BPMN diagram, during a specific execution, if after the activity "PowderSintering" the final gateway condition returns "no", then the process model executes once again. In order to abstract from single instances, the three figures can be refactored at the class level. It should be however clear that UML instance models can be useful to represent specific data that need to be exchanged or traced.

## 6 CONCLUSION AND FUTURE WORK

This paper presents a first version of the conceptual modeling framework for additive manufacturing knowledge representation. The purpose was to lay down the basic entities that need to be taken into account when managing additive manufacturing processes data. This conceptual framework will be used as a background of a decision aid framework that aims to manage the whole AM value chain. As said throughout the paper, we rely on both BPMN and UML class diagrams, the first one to represent processes, the second one to deal with the specification of processes' participants and their attributes.

As said in Section 2, the models represent the bases to handle knowledge and data in an information system which is tuned to additive manufacturing requirements to assist data management and knowledge-based decision making. The proposed models are therefore meant to support various tasks. First, the management of additive manufacturing data based on experts' knowledge. A preliminary academic example is showed in Section 5, where UML models were used to specify the entities required and manipulated during the execution of a powder bed fusion process along with some parameters. Second, to facilitate the traceability of data across the additive manufacturing processes. For example, by modeling the dependencies between various parameters, experts can better control the process and being aware of how a certain parameter may affect other parameters. Third, to foster data sharing across software applications and experts communities. It is a well-known problem that one of the main bottlenecks for the interoperability of applications is the use of disparate conceptual models whose semantic is not aligned. From this perspective, the models presented can be used as common references across various applications to facilitate data exchange procedures in a smooth manner. Last but not least, the models represent the general knowledge upon which specific rules can be defined to support decision making systems, e.g., to set the optimal values for the parameters of a certain process.

Further work has to be addressed to foster the usability of the proposed approach. In particular, by collaborating with academic experts and industrial partners, we will further refine the models presented in the paper in order to match more specific requirements emerging from the practice of planning and scheduling additive manufacturing processes, especially concerning powder bed fusion processes. Additionally, robust case studies will be carried out to test the models against both experts' knowledge and application settings. We also foresee the use of formal logic to finalize the models in order to better capture domain knowledge and allow computer systems automatically reason over knowledge and data. Finally, as part of an ongoing research project, a decision-making system will be developed on the grounds of what said in section 2. Clearly, the development of the system requires a careful analysis of specific application requirements in order to specify the rules and functionalities needed for the required tasks.

## ACKNOWLEDGMENTS

The presented results were conducted within the French National project "SOFIA" (SOLutions pour la Fabrication Industrielle Additive métallique). This project has received support from the French

Public Investment Bank (Bpifrance) and the French National Centre for Scientific Research (CNRS). The authors would like to thank all industrial and academic partners for their involvement in this research.

Farouk Belkadi, <https://orcid.org/0000-0003-2783-4147>

Emilio M. Sanfilippo, <https://orcid.org/0000-0003-2511-2853>

Alain Bernard, <https://orcid.org/0000-0002-7037-2980>

Laura M. Vidal, <https://orcid.org/0000-0002-0057-9978>

## REFERENCES

- [1] Adamo, G.; Borgo, S.; Di Francescomarino, C.; Ghidini, C.; Guarino, N.; Sanfilippo, E. M.: Business processes and their participants: an ontological perspective, *Advances in Artificial Intelligence*, Springer, 2017, 215-228. <https://doi.org/10.1007/978-3-319-70169-1>
- [2] Alting, L.: *Manufacturing Engineering Processes*, Marcel Dekker, 1982.
- [3] Bandyopadhyay, A.; Traxel, K. D.: Invited review article: Metal-additive manufacturing— modeling strategies for application-optimized designs, *Additive Manufacturing*, 4, 2018, 758-774. <https://doi.org/10.1016/j.addma.2018.06.024>
- [4] Belkadi, F.; Vidal, L. M.; Bernard, A.; Pei, E.; Sanfilippo, E. M.: Towards a unified additive manufacturing product-process model for digital chain management purpose, *Procedia CIRP*, 70, 2018, 428-433. <https://doi.org/10.1016/j.procir.2018.03.146>
- [5] Colledani, M.; Terkaj, W.; Tolio, T.; Tomasella, M.: Development of a conceptual reference framework to manage manufacturing knowledge related to products, processes and production systems, *Methods And Tools For Effective Knowledge Life-Cycle-Management*, Springer, 2008, 259-284. <https://doi.org/10.1007/978-3-540-78431-9>
- [6] Dinar, M.; Rosen, D. W.: A design for additive manufacturing ontology, *Journal of Computing and Information Science in Engineering*, 17(2), 2017, 9p. <https://doi.org/10.1115/1.4035787>
- [7] Eddy, D.; Krishnamurty, S.; Grosse, I.; Perham, M.; Wileden, J.; Ameri, F.: Knowledge management with an intelligent tool for additive manufacturing, *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers, ASME, Boston, Massachusetts, USA, August 2-5, 2015.
- [8] Feng, S. C.; Witherell, P.; Ameta, G.; Kim, D. B.: Activity model for homogenization of data sets in laser-based powder bed fusion, *Rapid Prototyping Journal*, 23(1), 2017, 137-148. <https://doi.org/10.1108/RPJ-11-2015-0160>
- [9] Fennes, S. J.; Foufou, S.; Bock, C.; Sriram, R. D.: CPM2: a core model for product data, *Journal of Computing and Information Science in Engineering*, 8(1), 2008, 6p. <https://doi.org/10.1115/1.2830842>
- [10] Gasevic, D.; Djuric, D.; Devedzic, V.; Damjanovi, V.: Converting UML to OWL ontologies. *13<sup>th</sup> International World Wide Web Conference on Alternate*, ACM, New York, USA, May 19-21, 2004, 488-489. <https://doi.org/10.1145/1013367.1013539>
- [11] Ghose, S.; Babu, S.; Nai, K.; Hooper, P. A.; Jeffers, J. R.: The influence of laser parameters, scanning strategies and material on the fatigue strength of a stochastic porous structure, *Additive Manufacturing*, 22, 2018, 290-301. <https://doi.org/10.1016/j.addma.2018.05.024>
- [12] Gibson, I.; Rosen, D.; Stucker, B.: *Additive Manufacturing Technologies – 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*, Springer, 2015, 498p. <https://doi.org/10.1007/978-1-4939-2113-3>
- [13] Grosse, I. R.; Milton-Benoit, J. M.; Wileden, J. C.: Ontologies for supporting engineering analysis models, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 19(1), 2005, 1-18. <https://doi.org/10.1017/S0890060405050018>

- [14] Gu, D. D.; Meiners, W., Wissenbach, K., Poprawe, R.: Laser additive manufacturing of metallic components: materials, processes and mechanisms, *International Materials Reviews*, 57(3), 2012, 133-164. <https://doi.org/10.1179/1743280411Y.0000000014>
- [15] Hamdi, M.; Aifaoui, N.; Louhichi, B.; Benamara, A.: Idealization of cad model for a simulation by a finite element method, *European Journal of Computational Mechanics*, 19(4), 2010, 419-439. <https://doi.org/10.3166/Ejcm.19.419-439>
- [16] Heeling, T.; Cloots, M.; Wegener, K.: Melt pool simulation for the evaluation of process parameters in selective laser melting, *Additive Manufacturing*, 14, 2017, 116-125. <https://doi.org/10.1016/J.Addma.2017.02.003>
- [17] Huang, S. H.; Liu, P.; Mokasdar, A.; Hou, L.: Additive manufacturing and its societal impact: a literature review, *International Journal of Advanced Manufacturing Technology*, 67(5-8), 2013, 1191-1203.
- [18] IDEF Method Website: <http://www.edef.com/> Last Accessed April 2019.
- [19] Imran, M.; Young, B.: The application of common logic based formal ontologies to assembly knowledge sharing, *Journal of Intelligent Manufacturing*, 26(1), 2015, 139-158.
- [20] Li, C.; McMahan, C.; Newnes, L.; Liu, Y.: Ontology-based annotation in PLM systems, 7<sup>th</sup> IFIP International Conference on Product Lifecycle Management, BIBA University of Bremen, 12th-14th July 2010.
- [21] Liang, J. S.: An ontology-oriented knowledge methodology for process planning in additive layer manufacturing, *Robotics and Computer-Integrated Manufacturing*, 53, 2018, 28-44. <https://doi.org/10.1016/J.Rcim.2018.03.003>
- [22] Mani, M.; Witherell, P.; Jee, H.: Design rules for additive manufacturing: a categorization, ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers. Cleveland, Ohio, USA, August 6-9, 2017, 10p. <https://doi.org/10.1115/DETC2017-68446>
- [23] Stokes M.: *Managing Engineering Knowledge: MOKA Methodology for Knowledge Based Engineering Applications*, Bury St Edmunds, 2001, 310p.
- [24] Perry, N.; Ammar-Khodja, S.: A knowledge engineering method for new product development, *Journal of Decision Systems*, 19(1), 2010, 117-133. <https://doi.org/10.3166/jds.19.117-133>
- [25] Nowak, P.; Rose, B.; Saint-Marc, L.; Callot, M.; Eynard, B.; Gzara, L.; Lombard, M.: Towards a design process model enabling the integration of product, process and organization, 5<sup>th</sup> International Conference on Integrated Design And Manufacturing in Mechanical Engineering, IDMME'04, University Of Bath, UK, 2004.
- [26] Object Management Group, *Business Process Modeling and Notation Specification, Version 2.0*, January 2001, available at <https://www.omg.org/spec/BPMN/2.0/About-BPMN/> Last Accessed April 2019.
- [27] Object Management Group, *Unified Modeling Language Specification, Version 2.5.1*, Decemb. 2017, Available at <https://www.omg.org/spec/UML/About-UML/> Last Access April 2019.
- [28] Olivé, A.: *Conceptual Modeling of Information Systems*, Springer Berlin, 2007.
- [29] Roh, B. M.; Kumara, S. R.; Simpson, T. W.; Michaleris, P.; Witherell, P.; Assouroko, I.: Ontology-based laser and thermal metamodels for metal-based additive manufacturing, International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, ASME, 2016, V01AT02A043-V01AT02A043. <https://doi.org/10.1115/DETC2016-60233>
- [30] Sanfilippo, E. M.: Towards an ontological formalization of technical product for design and manufacturing, international workshop formal ontologies meet industries, *Lecture Notes in Business Information Processing*, Springer, 225, 2015, 75-87.
- [31] Sanfilippo, E. M.; Borgo, S.: What are features? an ontology-based review of the literature, *Computer-Aided Design*, 80, 2016, 9-18. <https://doi.org/10.1016/J.Cad.2016.07.001>
- [32] Sanfilippo, E.M.; Benavent, S.; Borgo, S.; Guarino, N.; Troquard, N.; Romero, F.; Rosado, P.; Solano, L.; Belkadi, F.; Bernard, A.: Modeling manufacturing resources: an ontological approach, 15<sup>th</sup> IFIP Product Lifecycle Management Conference, Italy, 01-04 July 2018.

- [33] Smith, B.; Ceusters W.; Klagges, B.; Köhler, J.; Kumar, A.; Lomax, J.; Mungali, C.; Nechaus, Rector, A.; Rosse, C.: Relations in biomedical ontologies, *Genome Biology*, 6(5), R46, 2005.
- [34] Solano, L.; Romero, F.; Rosado, P.: An ontology for integrated machining and inspection process planning focusing on resource capabilities, *International Journal of Computer Integrated Manufacturing*, 29(1), 2016, 1-15. <https://doi.org/10.1080/0951192X.2014.1003149>
- [35] Sossou, G.; Demoly, F.; Montavon, G.; Gomes, S.: An additive manufacturing oriented design approach to mechanical assemblies, *Journal of Computational Design and Engineering*, 5(1), 2018, 3-18. <https://doi.org/10.1016/j.jcde.2017.11.005>
- [36] Thompson, M. K.; Moroni, G.; Vaneker, T.; Fadel, G.; Campbell, R. I.; Gibson, I.; Bernard, A.; Schulz, J.; Graf, P.; Ahuja, B.; Martina, F.: Design for additive manufacturing: trends, opportunities, considerations, and constraints, *CIRP Annals*, 65(2), 2016, 737-760. <https://doi.org/10.1016/j.cirp.2016.05.004>
- [37] Tofail, S. A.; Koumoulos, E. P.; Bandyopadhyay, A.; Bose, S.; O'Donoghue, L.; Charitidis, C.: Additive manufacturing: scientific and technological challenges, market uptake and opportunities, *Materials Today*, 22(1), 2018, 22-37. <https://doi.org/10.1016/j.mattod.2017.07.001>
- [38] Usman, Z.; Young, R. I. M.; Chungoora, N.; Palmer, C.; Case, K.; Harding, J. A.: Towards a formal manufacturing reference ontology, *International Journal of Production Research*, 51(22), 2013, 6553-6572. <https://doi.org/10.1080/00207543.2013.801570>
- [39] W3C <https://www.w3.org/TR/2012/REC-Owl2-Overview-20121211/> last access April 2019.
- [40] Weske, M.: Business process management architectures, *Business Process Management*, Springer, Berlin, Heidelberg, 2012, 333-371.
- [41] Witherell, P.; Feng, S.; Simpson, T. W.; Saint John, D. B.; Michaleris, P.; Liu, Z. K.; Chen, L.-Q.; Martukanitz, R.: Toward meta-models for composable and reusable additive manufacturing process models, *Journal of Manufacturing Science and Engineering*, 136(6), 2014, 061025. <https://doi.org/10.1115/1.4028533>
- [42] Witherell, P.; Lu, Y.; Jones, A.: Additive manufacturing: a trans-disciplinary experience, *Transdisciplinary Perspectives on Complex Systems*, Springer, 2017, 145-175.
- [43] Zhang, Y.; Bernard, A.: AM feature and knowledge-based process planning for additive manufacturing in multiple parts production context. 25<sup>th</sup> Annual International Solid Freeform Fabrication Symposium, Austin, Texas, August 4-6, 2014.