



## COBEM-2017-2435

# PROPOSAL OF AN ADVANCED DATA MODEL FOR STEP-NC COMPLIANT ADDITIVE MANUFACTURING

### Efrain Rodriguez

Department of Mechanical and Mechatronics Engineering, University of Brasilia, GIAI (Grupo de Inovação em Automação Industrial), 70910-900, Campus Universitário Darcy Ribeiro, Asa Norte, PO Box: 04386, Brasilia, Brazil  
efrain.rodriguez@aluno.unb.br

### Renan Bonnard

SENAI/SC Innovation Institute for laser manufacturing, manufacturing systems and embedded systems, Florianópolis, Brazil  
renan.bonnard@sc.senai.br

### Alberto Alvares

Department of Mechanical and Mechatronics Engineering, University of Brasilia, GIAI (Grupo de Inovação em Automação Industrial), 70910-900, Campus Universitário Darcy Ribeiro, Asa Norte, PO Box: 04386, Brasilia, Brazil  
alvares@alvarestech.com

**Abstract.** Additive Manufacturing (AM) is upheld as one mega-trend from new industrial landscape - Industry 4.0. Massive benefits are promised by AM for development of the new products including reduced time-to-launch, manufacturing design freedom and supply chain improvements. Nevertheless, serious problems persist on AM digital chain with the use of format old styles for data exchange. The STL (1987) format has been used as the "de facto" standard for data exchange between 3D-design softwares and AM systems. Similarly, numerical controllers of AM systems still use the G-code (ISO 6983/1980) standard. But they have drawbacks that make them incompatible with the idea of a high-level digital chain for AM. ISO 14649, known as STEP-NC, is now trusted as a solution for AM data exchange. This paper explores the STEP-NC standard to support the AM high-level digital chain and highlights the advantages of such a digital chain. An application activity model using the nomenclature IDEF0 and an application reference model in EXPRESS are presented. The concept of AM-layer-feature is introduced for referencing AM features within of the EXPRESS model. Finally, the architecture of a indirect STEP-NC AM platform for implementation of the new model also is presented.

**Keywords:** additive manufacturing, STEP-NC, ISO 14649, direct digital manufacturing, industry 4.0

## 1. INTRODUCTION

The new industrial revolution, called Industry 4.0, is expected to change the industrialized production systems by integrating intelligent manufacturing systems and, information and communication technologies. This movement is encouraging the automation of the process chain through Digitization and Networked Production. It involves Cyber-Physical Systems, Internet of Things (IoT) and Cloud Computing to create the "Smart Factory", with lots of data flowing seamlessly from machine-to-machine and machine-to-human (Yu *et al.*, 2015).

Meanwhile, Additive Manufacturing is considered as one mega-trend from Industry 4.0. A clear addition is the ability to create a physical object directly from the virtual 3D-model data. Moreover, parts with complex geometries that cannot be easily fabricated through machining processes, can now be achieved by using additive processes without needing of multiple setups and waste of material. Initially, AM was destined exclusively for rapid prototyping of products, but thanks to the immense development that it has experimented in terms of speed, quality, materials and machine resources, has been extended to full-functional and whole parts production directly for end-user. Consequently, this fact has changed the way to produce many products in the industry and it has led to AM to gain more space within a important range of applications including aerospace and automotive industry, biomedical engineering, product development, architecture, electronic devices, etc. (Negi *et al.*, 2013).

Despite this enormous progress, there are still drawbacks on digital chain that involve both AM and machining processes, with the lack of a standard format for data exchange. This undesirable destandardization has been for a long time the major issue faced by manufacturer industry (Brunnermeier and Martin, 1999). With the advent of smart factories, manufacturing systems are being forced to migrate to more collaborative and interoperable environments, where large amounts of data are generated, stored, exchanged and used to produce the new products. In this scenario, full integrity

and transparency of data must be provided by appropriate management through standardization. Therefore, an integrated digital chain with a single format containing high-level information of the product is required (Bonnard *et al.*, 2010). In an international effort, the ISO 14649 (ISO 14649-1, 2003) standard, informally known as STEP-NC (STandard for the Exchange of Product model data - Numerical Control), emerges to solve the problems of the digital chain of advanced manufacturing systems. STEP-NC proposes a hierarchical data structure for engineering and manufacturing data exchange. Integration of digital chain based on STEP-NC have been gradually developed so far for machining processes (turning, milling...) (Suh *et al.*, 2003; Rosso *et al.*, 2004; Rauch *et al.*, 2012). In AM, the subject is still in an early stage and has to be challenged with a new STEP-NC AM model and a STEP-NC platform proposition. That is why this work proposes a concept of STEP-NC compliant AM data exchange model aimed at new industrial landscape.

The outline of this paper is: first, to analyze the current situation of the digital chain in AM and identify its weaknesses; second, highlights new possibilities for a integrated and standardized AM digital chain with the STEP-NC. Then, the new STEP-NC compliant AM data model proposition is presented, and finally, the architecture of an indirect STEP-NC AM platform is described.

## 2. CURRENT STATUS OF THE AM PROCESSES

Seen holistically, the AM process can be basically considered as a sequence of four main stages: part design; process planning; fabrication; and, post-processing. The sequential organization of these stages is known as the digital chain or "digital thread" of the AM. The typical digital chain currently used in AM process is illustrated in Fig. 1. In the first stage, the part design is generated as a solid 3D-model through the use of Computer-Aided Design (CAD) software. The CAD model is then passed onto the Computer-Aided Process Planning/Manufacturing (CAPP/CAM) software by using most of the time the Standard Triangulation Language (STL) file format. In the CAPP/CAM software (second stage), the optimal part orientation is selected and the support structure is provided for the part's surfaces that are fully suspended. After the part model is sliced in layers of a defined thickness and additional fabrication parameters such as fill density of each layer, number of perimeters and external infill pattern, may also be specified by the manufacturing engineering. The CAPP/CAM software automatically determines the tool-paths necessary for each layer and a post-processor is responsible for generating optimized instructions (G-code) based on a pre-defined Computerized Numerical Control (CNC) machine. In the third stage, the part is then manufactured through the sequential execution of the instructions contained into machine specific CAM file. Finally, the manufactured part can be tested and validated (fourth stage) before being addressed for end-user.

It is notable that to manufacture a product with an AM system, it is necessary to use many files and many conversions process. Firstly, the STL format has been used as the *de facto* standard for the transfer of 3D-design data for almost all AM systems. However, it is known that the STL format is only an approximation of the exact geometry of the part model represented by discrete triangular elements (Szilvési-Nagy and Mátyási, 2003). Each triangle is defined by twelve floating point numbers corresponding to its unit normal and vertices (direction and order given by the right-hand rule). Already, this introduces geometric gaps since one vertex can be shared for two or more triangles and small rounding errors result in vertices that do not exactly match. Moreover, high-level information such as tolerances, roughness, material, color, etc., are not present in this format. Also, the STL format presents problems such as information redundancy, poor scalability, loss of geometric elements, no defined dimensional units, among others. On the other hand, CNC controllers of AM systems still use the G-code (ISO 6983-1, 1982) standard. The language of ISO 6983 defines alphanumeric commands with information limited mainly to the movement of the axes of the machine, that being unconcerned for process information itself. Already, this mean a waste the capabilities of the CNC systems. In addition, each CNC systems vendor is reluctant to define specific instructions for their controllers. So, it is necessary one post-processor and one expert per machine, which severely limits the flexibility and interoperability of this systems. Besides that, bi-directional data flow and integrated feed-back information from shop-floor are not possibles on this digital chain.

So far, this chain has operated acceptably, but demands for a new industry, including Industry 4.0 concept, require more flexibility, traceability and interoperability for manufacturing systems that are impossible with the current digital chain. Therefore, new possibilities for the standardization and integration of the AM digital chain should be explored.

## 3. NEW POSSIBILITIES FOR A COMPLETE STANDARDIZED AM DIGITAL CHAIN

As outlined above, both STL and G-code are incompatible with the concept of a AM high-level digital chain. This problem is solved by making changes in the current AM digital chain (Bonnard *et al.*, 2010), which means adopting a new standard file format to carry design and manufacturing data in AM systems. Over the years, several research (Kumar and Dutta, 1997; Pratt *et al.*, 2002) evaluated the data requirements in AM processes and concerned about the shortcomings of the STL format for transferring data between CAD softwares and AM systems. In response, alternative file formats have been evaluated in order to overcome such limitations of the STL. Some of the considered formats include RPI (Rensselaer Polytechnic Institute) (Rock and Wozny, 1991), LMI (Layer Manufacturing Interface) (Kai *et al.*, 1997), CLI (Common Layer Interface) (Zeng *et al.*, 2013), STH (Surface Triangles Hinted), CLF (Cubital Facet List) and, recently, the AMF

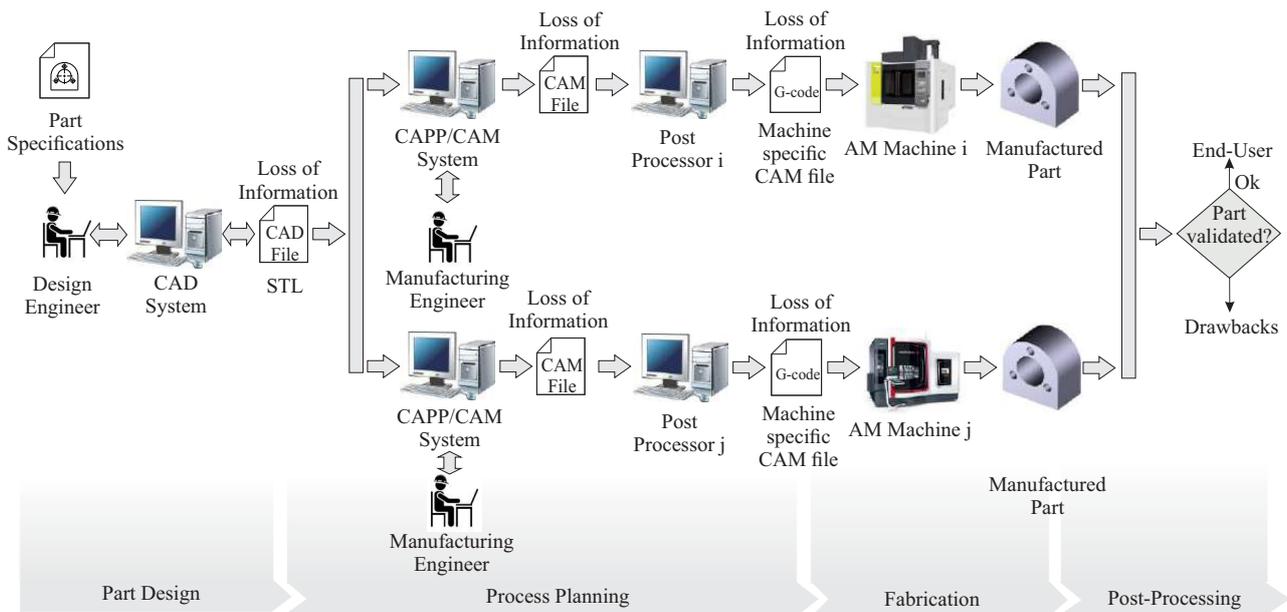


Figure 1. Current situation of the AM digital chain.

(Additive Manufacturing Format) (Nassar and Reutzel, 2013) and 3MF (3D Manufacturing Format) formats, but were not totally suitable to all the data requirements of the industrial AM processes, and much less they allow to transfer manufacturing data up the CNC level.

Since the late 1980s, a unifying effort was started by international community to development a powerful set of standards, all under ISO 10303 (Pratt, 2001)-well known as STEP. The goal of STEP is to provide a common language to describe all aspects technical product data throughout the life-cycle of a product. The neutral nature of this standard make it suitable for transferring data between CAD and CAM programs independently of a particular system. The new STEP compliant NC standard, known as STEP-NC, extends the ISO 10303 STEP models to include manufacturing process and machine tool data. STEP-NC is intended to facilitate the seamless data exchange between CAPP/CAM and CNC systems and provide a high-level object oriented data model for a next generation of intelligent controllers with advanced functions. Nowadays, within of ISO there are two versions of STEP-NC under development: ISO 14649 (ISO 14649-1, 2003)-Application Reference Model (ARM) by ISO TC184/SC4 committee and the other ISO 10303-238 (ISO 10303-238, 2011)-Application Interpreted Model by ISO TC184/SC4 committee. ISO 10303-238 links everything in ARM within an AIM to achieve better integration with other resources of STEP (Xu *et al.*, 2005). Kramer *et al.* (Kramer *et al.*, 2006) demonstrated that both versions of STEP-NC can be implemented successfully. Then, the development of STEP-NC data models has been carried out mainly for machining processes (Suh *et al.*, 2003; Rosso *et al.*, 2004; Rauch *et al.*, 2012).

STEP-NC is now championed as great challenger of the weaknesses of the AM digital thread. New possibilities for support a standardized high-level digital chain of the additive manufacturing systems are given by STEP-NC standard. Figure 2 illustrates the concept of an integrated and standardized STEP-NC compliant AM high-level digital chain, which is support on a single file format for AM data exchange from design to NC controller. Thus, the AM STEP-NC file is therefore enriched with AM high-level data from each CAx system. Potential possibilities can be achieved by adopting this digital chain model. For example, bidirectional data flow between CAD-CAPP-CAM and CNC systems is possible, allowing modifications in product design throughout manufacturing cycle without any information loss. High-level information of product such as geometry, process parameters and workplan are incorporated within an unique AM STEP-NC file thanks to feature concept. The need for post-processors is eliminated and interoperability between AM systems is enabled. This concept of chain also allows to include integrated feed-back information from shop-floor for part inspection task form CAIP/CAI (Computer Aided Inspection Planning/Inspection) system (Jaimes *et al.*, 2017). All information contained in STEP-NC file is stored on a cloud database.

### 3.1 MOTIVATION FOR THE NEW STEP-NC COMPLIANT AM DATA MODEL

With the increase in complexity of the part and digital processes, linking the geometric data and high-level information is becoming more and more important to achieve higher quality products and process efficient. The usage of a standard format for exchanging of data contributes to significantly improves data quality and reduce the time for product development. Carleberg (Carleberg, 1994) was the first to propose the use of a STEP based format for representing of data in AM

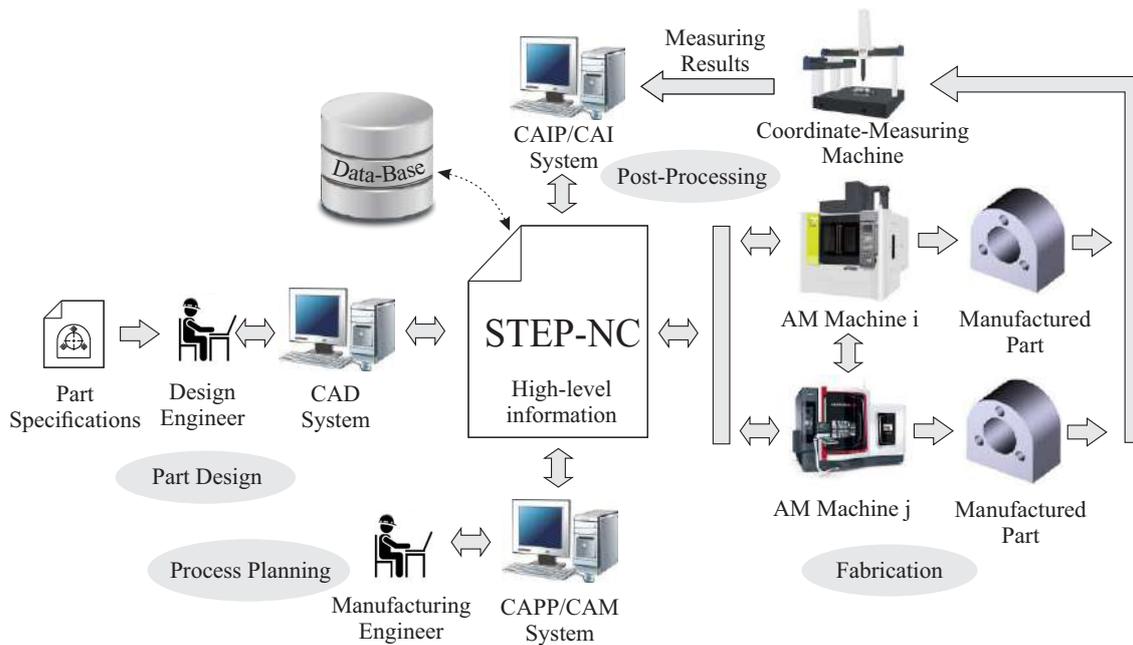


Figure 2. New concept of STEP-NC compliant AM digital chain.

process. Dutta et al. (Dutta *et al.*, 1998) stressed that the STL format puts limitations to integration of geometry data and additional types of information required, and they proposed the utilization of STEP resources to carry additional data such as material specification, process parameters, tolerances and roughness requirements. Others research (Pratt *et al.*, 2002; Danjou and Koehler, 2008; Lipman and McFarlane, 2015) also highlighted the advantages of STEP for connecting part geometry data and high-level information in AM systems. Ryou et al. (Ryou *et al.*, 2006) proposed an information model of AM part design seeking to include the AM process in the ISO 14649 standard. The methodology used by Ryou et al. (Ryou *et al.*, 2006) consist of dividing the part design data in four categories representing entities within a EXPRESS model. The first category refers to detailed geometry design data of the part; the second category contains non-geometry design data of the part such as tolerances, roughness, material... the third category provides information about process history of the AM system; and in the fourth category (optional) contains a data representation of multicolor parts. They also developed a ISO 14649-based preprocessor for implementation of the models contains high-level design information of a test part.

In France, the Professor Hascoët's team (Bonnard *et al.*, 2010) concerned about the need for a global approach with a AM digital chain involving the representation of manufacturing data at the NC controller level. Therefore, they have proposed a methodology to achieve a complete integrated AM digital chain with the use of an unique STEP-NC file format. Such a chain enables a bidirectional exchange of AM high-level data between CAD-CAM-CNC systems and offers potentials opportunities for the development of new advanced and flexible AM systems (Bonnard *et al.*, 2009, 2010). This proposal of the Professor Hascoët's team was done in accordance with the ISO TC 184/SC 1 committee's intention to include the AM processes within ISO 14649 standard. Actually, the Additive Manufacturing has been proposed as Part 17 of ISO 14649 (ISO/AWI 14649-17, 2016), which is a project still under development. This stage creates opportunity for proposition of both new STEP-NC AM data models and for the development of an implementation STEP-NC AM platform to validate the proposed models.

STEP-NC promises huge benefits for the AM digital chain, but at the same time its implementation becomes quite complex. This is an important point, as not only it is enough to highlight the capabilities of STEP-NC, but also to demonstrate that the models can be applied on a real system. Rauch et al. (Rauch *et al.*, 2012) propose a method to gradually overcome such complexity and achieve STEP-NC programming. This method is based on three levels of implementation: 1) *Indirect STEP-NC programming*, where a interpreter is used to translate the STEP-NC program to G-code commands, which are easily understood by existing controllers; 2) *Interpreted STEP-NC programming*, where tool-path generation and operation execution is perform directly form the STEP-NC program; 3) *Adaptive STEP-NC programming*, in which NC controller is able to perform the machining task in a way intelligent and make decisions about the process in real time. This last level is the goal to be achieved for all advanced manufacturing systems. However, STEP-NC programming has only been partially developed for machining processes such as milling, turning and EDM (Xu *et al.*, 2005). Now, AM with STEP-NC is less developed in comparison to machining processes due to the lack of implementation AM STEP-NC programming platforms. To change the situation must start with the development of STEP-NC AM platform prototypes from the first level and go up to match the level of machining systems. Hence,

a research work (Rodriguez *et al.*, 2017a) is underway at LaDPRER (*Laboratorio de Desenvolvimento de Produto e Engenharia Reversa*) laboratory from University of Brasilia, with the objective of developing a new STEP-NC compliant AM data model aimed at implementation on a layer-by-layer based AM open platform. The methodology for new model proposition is well described in next section.

#### 4. STEP-NC COMPLIANT AM DATA MODEL PROPOSITION

##### 4.1 Application Activities Model

An Application Activities Model (AAM) can be built in order to inform about activities to be implemented in the process digital chain. The AAM is formalized in ISO 14649-1 (ISO 14649-1, 2003) and it uses the IDEF0 nomenclature to describe the flow of information between activities in the life-cycle of a product. From this representation model, each activity transforms an input data into an output data through mechanisms and controls. Such a representation results in multi-layer diagrams where an activity may contain sub-activities and in turn each sub-activities can contain others sub-activities. Figure 3 shows the upper level of the IDEF0 representation for a AM digital chain with STEP-NC. This level represents the activity A0 according to the nomenclature IDEF0, which is decomposed in three sub-levels or sub-activities corresponding to the CAD, CAPP/CAM and CNC modules. Each module is explained in detail.

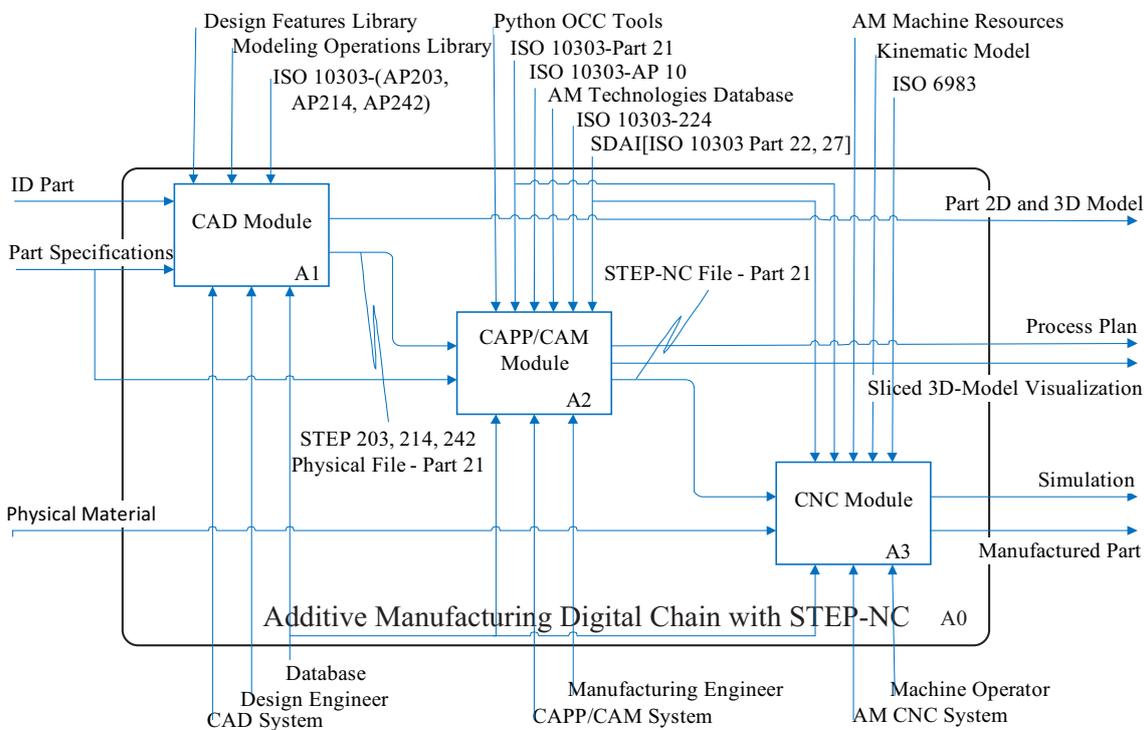


Figure 3. Upper level of IDEF0 representation of the AM digital chain with STEP-NC.

In the CAD module (A1), the part is modeled from a input data with design specifications (geometric and non-geometric informations) by using any commercial modeler software with support for ISO 10303 resources (e.g. *Solidworks, Catia, etc.*). The CAD module's output is a STEP file containing all design data of the part described in some of the Application Protocols (APs) of ISO 10303 intended for description of product design data. The APs of STEP commonly used in the CAD domain are: AP203-configuration controlled 3D designs of mechanical parts and assemblies; AP214-core data for automotive mechanical design processes; and, AP242 managed model-based 3D engineering. The STEP physical file will be as the starting information in the CAPP/CAM module.

Process planning and preparation for production are essential pre-manufacturing tasks in life-cycle of a AM product. These tasks are carried out in the CAPP/CAM module (Activity A2). This module is decomposed in four sub-activities showed in Fig. 4. This module receives the STEP file with the geometrical and topological information of the part being manufactured. In STEP, the part data is represented by design features that include contour representation data such as shells, faces, edge loops and vertices; geometric surface data such as planes, cylinders, cones, toroids and spheres; and, curve geometry data such as lines, circles, B-splines and ellipses. Such design features are recognized in activity A21 by using *PythonOCC* (Paviot, 2014) tools to define the finished geometry of the AM-workpiece. Immediately after, in the activity A22, the workpiece is sliced in layers with a certain thickness. Each layer is treated as a feature of AM (concept to be explained later). The list of layers goes to the next activity (A23) in SVG (Consortium World Wide Web,

1999) format to generate the process plan (workplan). In this activity, the AM-workingsteps are created by associating an addition material operation for each AM-feature. In addition, the type of AM technology used, machine utilities and optimized process parameters are selected from design requirements of the part (such as tolerance, roughness, material, etc.) by using a specialized knowledge-database. Tool-paths are also generated for each layer (AM-feature). Then, in activity A24, the STEP-NC program is automatically generated with the sequence of the AM-workingsteps, referencing ISO 10303-Part 21 and JSDAI (ISO 10303-Part 22, 27). The output of this activity is the physical file STEP-NC in Part 21 with the program of the part to be manufactured.

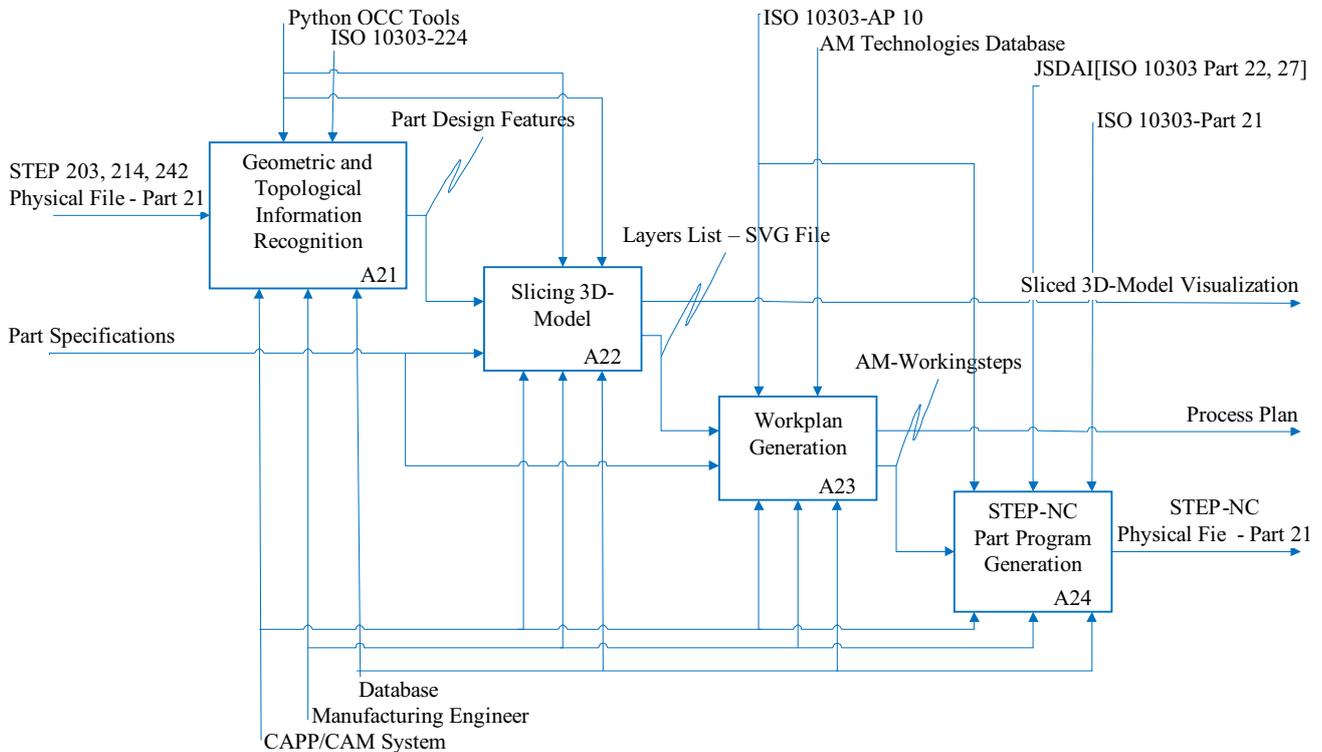


Figure 4. Activity 2: CAPP/CAM module decomposition.

The STEP-NC file passes to the CNC module (Activity A3 - Fig.3) where there is an AM CNC system with indirect control for implementation. The associated information to each AM-workingstep in the STEP-NC file is converted to G-code instructions through an adapter software application. The generated G-code is easily understood by existing controllers in the current AM machines. The interpretation of the G-code commands is done through a firmware embedded into controller, which generates digital signals on the motor-drivers to perform movements in the machine axes. The use of an indirect control allows a quick implementation of the process planning schema generated in CAPP/CAM module. To the end, it is possible to obtain a part manufactured with an AM process, whose planning stage has been carried out based on a STEP-NC model.

So far, the functional architecture of the global system has been described. However, to be able to move to the implementation it is necessary to build an Application Reference Model (ARM) in EXPRESS language, but before a concept of AM-feature is introduced.

#### 4.2 Defining a concept of feature for AM

STEP-NC standard uses the concept of feature-based programming for representing of process plan that incorporates information about manufacturing features, tool and technology description and operations to execute. Within the STEP-NC ARM the part being manufactured (workpiece) is described by manufacturing features that are defined in according to type of process. So, for machining processes have been defined machining-features (such as holes, pockets, slot...) based on manufacturing features of ISO 10303-AP224 (Mechanical product definition for process planning using machining features). But machining-features are not adapted for additive processes and in fact, a concept of feature for AM has not yet been formally established. Therefore, defining the concept of AM feature is an essential step toward the development of a new data model. From the authors' understanding, the AM-feature corresponds to each layer of the sliced 3D-model of the part being manufactured by using planar layer-based additive processes. That is, one AM-feature is with one layer, where each layer is geometrically defined by external and internal contours and the layer-thickness. This concept of AM-layer-feature is illustrated in Fig. 5. Then, the new feature-AM-layer must be modeled within the ARM for AM.

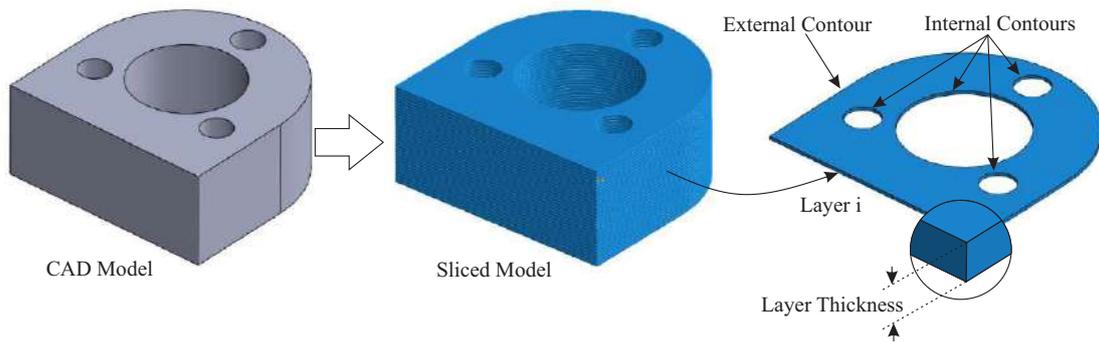


Figure 5. Representation of the concept of AM-layer-feature.

### 4.3 Application Reference Model

The ARM provides an object-oriented data model that uses feature-based programming for representing of the information to be used by NC controller. Such information, including manufacturing feature, technology and tool being used, sequence of operations and process plan, is specified through a data description method that facilitates the implementation. The EXPRESS language is a data description method formalized as Part 11 of STEP, that allows to specify the information of the product in a way consistent, precise and compact using a data model style based on an Entity-Attribute relationship. Thus, in EXPRESS an object is called Entity and the properties of the object are called Attributes. The relationship between entities is given by a degree of kinship (sub-type and super-type). EXPRESS is both computer-interpretable and human readable, and its way of representing of the data can be textual with a lexical semantic or graphic with illustrative diagrams (EXPRESS-G also given in Part 11).

On the left side of Fig. 6 is showed main part of the AM data model representation in EXPRESS-G referenced from the general data schema of ISO 14649-10 (ISO 14649-10, 2004). This model contains data elements that make up an interface between programming software and AM CNC system. An AM Project has associated a main Workplan and a list of executables. In addition, it includes the part geometry description (AM-workpiece). The Workplan contains a list with the sequence of AM-workingstep, where each AM-workingstep has associated one AM-operation that is applied to one AM-feature. In turn, for each operation is defined the AM technology and tool, machine functions and material addition strategy.

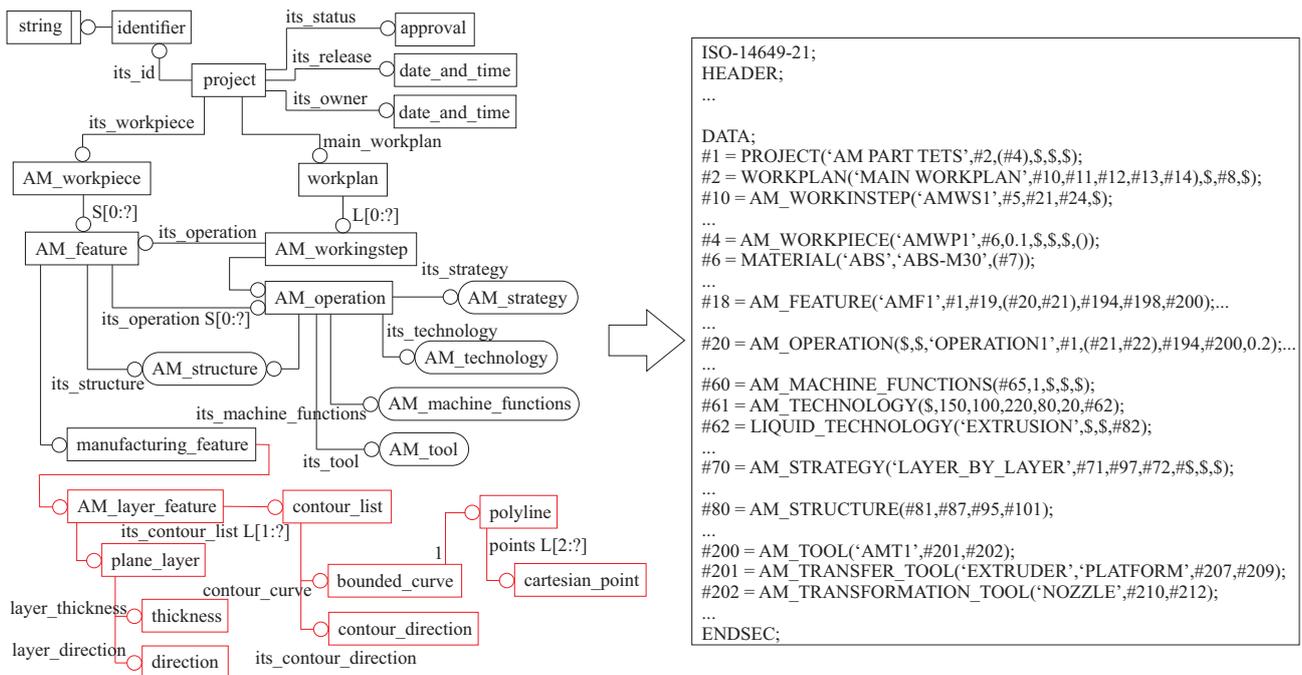


Figure 6. STEP-NC part program generated from AM EXPRESS data model.

The concept of AM-layer-feature has been modeled and introduced in the ARM of AM. In the EXPRESS-G model of Fig. 6, the part highlighted in red corresponds to concept of AM-layer-feature as an entity sub-type of the manufacturing-



on indirect control and a example part has been manufactured in order to validate the AM STEP-NC program generated form EXPRESS model.

In future works, the development of an AM controller that directly interprets the information from STEP-NC program is intended. Likewise, it is intended to extend this approach on hybrid manufacturing platforms (additive with machining) for complemented manufacturing and also, availability of data through MTConnect protocol for AM cloud database.

## 6. REFERENCES

- Bonnard, R., Mognol, P. and Hascoët, J.Y., 2009. "Integration of rapid manufacturing processes in a high-level numerical chain". In *Advanced Research in Virtual and Rapid Prototyping – Proceedings of VRP4*. Leiria, Portugal.
- Bonnard, R., Mognol, P. and Hascoët, J.Y., 2010. "A new digital chain for additive manufacturing processes". *Virtual and Physical Prototyping*, Vol. 5, pp. 75–88. doi:10.1080/17452751003696916.
- Brunnermeier, S.B. and Martin, S.a., 1999. "Interoperability cost analysis of the US automotive supply chain: Final report". *Research Triangle Institute*.
- Carleberg, P., 1994. "Product model driven direct manufacturing". In *The SFF Symposium*. University of Texas, USA.
- Consortium World Wide Web, 1999. "Scalable Vector Graphics - SVG Format".
- Danjou, S. and Koehler, P., 2008. "Bridging the Gap between CAD and Rapid Technologies Exigency of Standardized Data Exchange". *12th European Forum on Rapid Prototyping*.
- Dutta, D., Kumar, V., Pratt, M. and Sriram, R., 1998. "Towards STEP-based data transfer in layered manufacturing". *Proceedings of the tenth international IFIP WG5. 2/5.3 PROLAMAT Conference*, pp. 1–13.
- ISO 10303-238, 2011. "Industrial automation systems and integration - Product data representation and exchange - Part 203: Application protocol: Configuration controlled 3D design of mechanical parts and assemblies."
- ISO 14649-1, 2003. "Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers - Part 1: Overview and fundamental principles."
- ISO 14649-10, 2004. "Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers-Part 10: General process data".
- ISO 6983-1, 1982. "Numerical control of machines - Program format and definition of address words - Part1: Data format for positioning, line motion and contouring control systems."
- ISO/AWI 14649-17, 2016. "Automation systems and integration - Physical device control - Data model for computerized numerical controllers - Part 17: Process data for additive manufacturing processes." Retrieved from <https://www.din.de/en/getting-involved/standards-committees/nwm/projects/wdc-proj:din21:259391588>.
- Jaimes, C.I.R., Alvares, A., Ferreira, J.C.E. and Benavente, J.C., 2017. "Modelo de integração para inspeção em malha fechada aderente a STEP-NC". In *Anais do IX Congresso Brasileiro de Engenharia de Fabricação*. ABCM, Vol. 1. doi:10.26678/ABCM.COBEM2017.COF2017-0290.
- Kai, C.C., Jacob, G.G.K. and Mei, T., 1997. "Interface between CAD and Rapid Prototyping systems. Part 2: LMI - An improved interface". *The International Journal of Advanced Manufacturing Technology*, Vol. 13, pp. 571–576. doi:10.1007/BF01176301.
- Kramer, T.R., Proctor, F., Xu, X. and Michaloski, J.L., 2006. "Run-time interpretation of step-nc: implementation and performance". *International Journal of Computer Integrated Manufacturing*, Vol. 19, No. 6, pp. 495–507. doi:10.1080/09511920600622056.
- Kumar, V. and Dutta, D., 1997. "An assessment of data formats for layered manufacturing". *Advances in Engineering Software*, Vol. 28, pp. 151–164.
- Lipman, R.R. and McFarlane, J.S., 2015. "Exploring Model-Based Engineering Concepts for Additive Manufacturing". *Proceedings of the 26th Solid Freeform Fabrication Symposium*, pp. 385–400.
- Nassar, a.R. and Reutzel, E., 2013. "A proposed digital thread for additive manufacturing". *Solid Freeform Fabrication*, pp. 19–43.
- Negi, S., Dhiman, S. and Sharma, R.K., 2013. "Basics, Applications and Future of Additive Manufacturing Technologies: a Review". *Journal of Manufacturing Technology Research*, Vol. 5, pp. 75–96.
- Paviot, T., 2014. "PythonOCC, 3D CAD/CAE/PLM development framework for the Python programming language". Retrieved from <http://www.pythonocc.org/quick-examples/step-ap203-import/>.
- Pratt, M.J., 2001. "Introduction to ISO 10303-the STEP Standard for Product Data Exchange". *Journal of Computing and Information Science in Engineering*, Vol. 1, p. 102. doi:10.1115/1.1354995.
- Pratt, M.J., Bhatt, A.D., Dutta, D., Lyons, K.W., Patil, L. and Sriram, R.D., 2002. "Progress towards an international standard for data transfer in rapid prototyping and layered manufacturing". *CAD Computer Aided Design*, Vol. 34, pp. 1111–1121. doi:10.1016/S0010-4485(01)00189-0.
- Rauch, M., Laguionie, R., Hascoet, J.Y. and Suh, S.H., 2012. "An advanced STEP-NC controller for intelligent machining processes". *Robotics and Computer-Integrated Manufacturing*, Vol. 28, pp. 375–384. doi:10.1016/j.rcim.2011.11.001.
- Rock, S.J. and Wozny, M.J., 1991. "A Flexible File Format for Solid Freeform Fabrication". *Proceedings Solid Freeform*

*Fabrication Symposium*, pp. 1–12.

- Rodriguez, E., Bonnard, R. and Alvares, A., 2017a. “Propuesta de un nuevo modelo de información para manufactura aditiva basado en STEP-NC”. In *XIII Congresso Ibero-Americano de Engenharia Mecânica - CIBEM*. Lisboa, Vol. 1.
- Rodriguez, E., Jaimes, C.I.R. and Alvares, A., 2017b. “Projeto Mecatrônico de um Robô com Cinemática Paralela Delta Linear para Manufatura Aditiva”. In *Anais do IX Congresso Brasileiro de Engenharia de Fabricação*. ABCM. doi: 10.26678/ABCM.COBEP2017.COF2017-0282.
- Rosso, R.S.U., Newman, S.T. and Rahimifard, S., 2004. “The adoption of STEP-NC for the manufacture of asymmetric rotational components”. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 218, pp. 1639–1644. doi:10.1243/0954405042418554.
- Ryou, M.S., Jee, H.S., Kwon, W.H. and Bang, Y.B., 2006. “Development of a data interface for rapid prototyping in STEP-NC”. *International Journal of Computer Integrated Manufacturing*, Vol. 19, No. 6, pp. 614–626. doi: 10.1080/09511920600623666.
- Suh, S., Lee, B., Chung, D. and Cheon, S., 2003. “Architecture and implementation of a shop-floor programming system for STEP-compliant CNC”. *Computer-Aided Design*, Vol. 35, No. 12, pp. 1069–1083. doi:10.1016/S0010-4485(02)00179-3.
- Szilvsi-Nagy, M. and Mátyási, G., 2003. “Analysis of STL files”. *Mathematical and Computer Modelling*, Vol. 38, pp. 945–960. doi:10.1016/S0895-7177(03)90079-3.
- Xu, X.W., Wang, H., Mao, J., Newman, S.T., Kramer, T.R., Proctor, F.M. and Michaloski, J.L., 2005. “STEP-compliant NC research: The search for intelligent CAD/CAPP/CAM/CNC integration”. *International Journal of Production Research*, Vol. 43, pp. 3703–3743. doi:10.1080/00207540500137530.
- Yu, C., Xu, X. and Lu, Y., 2015. “Computer-Integrated Manufacturing, Cyber-Physical Systems and Cloud Manufacturing - Concepts and relationships”. *Manufacturing Letters*, Vol. 6, pp. 5–9. doi:10.1016/j.mfglet.2015.11.005.
- Zeng, K., Patil, N., Gu, H. and Gong, H., 2013. “Layer by Layer Validation of Geometrical Accuracy in Additive Manufacturing processes”. *Proceedings of Twenty Forth Annual International Solid Freeform Fabrication Symposium An Additive Manufacturing Conference*, pp. 76–87.

## 7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.