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CLOSED-LOOP INTEGRATION MODEL FOR DIMENSIONAL AND GEOMETRIC INSPECTION OF PRISMATIC PARTS BASED ON THE STEP-NC STANDARD

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Abstract. *Manufacturing systems require significant changes in the way information is handled to meet the challenges of the fourth industrial revolution. To achieve this great step, it is necessary to integrate the physical resources involved in the manufacturing processes with the available digital technologies in order to obtain a greater control of the production in all the phases of the life cycle of a product. STEP, the Standard for the Exchange of Product Model Data, provides a structured architecture for data management that makes it possible to meet the current information demands. This paper presents a closed-loop model for the implementation of an integrated CAD/CAPP/CAIP/CAM/CAI (Computer-Aided Design, Process Planning, Inspection Planning, Manufacturing and Inspection) system based on the STEP-NC standard. The model allows the inspection results to be fed back into the process. In this model, the application protocols ISO 10303-238 and ISO 10303-219 are used to integrate the manufacturing and inspection data. The data structure, information flow and required functional activities are exposed in detail using AAM (Application Activity Model) and ARM (Application Reference Model) models created in IDEF0 and EXPRESS. The integration model presented in this paper leads to a computational implementation that integrates the functions to execute dimensional and geometric inspection in closed-loop in the STEP-NC Modeler system. The presented model defines the path for the computational implementation of the closed-loop inspection system based on the analysis of the inspection performed by a coordinate measuring machine. The results obtained are presented in the end of the paper, as well as new approaches that are derived from the research.*

Keywords: *Advanced Manufacturing, Computer-Aided Inspection (CAI), Computer-Aided Inspection Planning (CAIP), Industry 4.0, STEP-NC.*

1. INTRODUCTION

Industry constantly requires the manufacture of complex parts with increasingly demanding requirements. Numerous advances and changes in manufacturing processes have made it possible to promote progress in different areas such as aeronautics, robotics and automotive, but there are issues that stand in the way of integration with current digital technologies. In the perspective of the fourth industrial revolution, the productive processes require important changes in data management and processing of information generated during the manufacturing process. The goal is to interconnect available digital technologies with physical resources associated with manufacturing processes (Lee *et al.*, 2015). With the integration of systems, machines and people, greater control of production is achieved in each of the phases that make up the life cycle of a product. Manufacturing needs complete integration of CAD/CAPP/CAIP/CAM/CAI (Computer-Aided

Design, Process Planning, Inspection Planning, Manufacturing and Inspection) systems to operate in an interoperable environment regardless of the technology that each system uses (Zhao *et al.*, 2008). Data shared between systems require interpretation, analysis, and processing to generate information that can support decision-making, implement decentralized control, virtualize processes, and automate manufacturing (Paris *et al.*, 2017).

Increases in demands for accuracy and precision in the manufacture of parts have made measurement tasks a vitally important process within the manufacturing chain. The use of CMMs (Coordinate Measuring Machines) as computer-aided inspection tools provides the characteristics necessary to close the manufacturing loop with feedback from the measurement data (Xu, 2009). The efficient use of CMMs depends on the information provided by the Computer-Aided Inspection Planning (CAIP) system, which is responsible for generating the measurement execution plan (Zhao *et al.*, 2011b). The data acquired in CAI, translated into information, allows for making corrections, but the integration of inspection within the closed manufacturing loop still faces major problems in sharing the results among different systems. The information generated in the inspection process, used efficiently, can leverage new challenges and promote increasingly sustainable environments (Mahmoud *et al.*, 2016).

The STEP standard, referred to as ISO 10303, provides an architecture for data management, which makes it easy to adapt manufacturing processes to new requirements. This integration is mainly possible by the structure with which STEP describes the information of a product throughout its life cycle (Hu *et al.*, 2016). The STEP standard seeks to establish itself as an essential tool in the integration of industrial processes, providing support for different implementation methods and developments that seek to access, transfer and store product data (Newman *et al.*, 2008).

The geometric and dimensional inspection model is proposed to obtain an architecture of data and information integration within closed-loop manufacturing, in order to define a suitable structure for sharing data between CAD/CAPP/CAIP/CAI systems, to create measurement strategies based on the extraction of features, and to propose an expert system for correcting errors based on the inspection results. With the proposed architecture it is sought to meet the information flow needs for an advanced manufacturing environment compatible with digital technologies and compliant with the industry 4.0 concept (Xu* *et al.*, 2005; Lasi *et al.*, 2014).

The paper presents both relevant information found in the literature and results obtained in the construction of the proposed model. The paper begins with the presentation of the literature review related to the current challenges of advanced manufacturing within the industry 4.0 context. The following describes the exchange of data through the STEP-NC standardized structure to share information within a closed manufacturing mesh. The paper ends with the presentation of the proposed model to integrate prismatic parts inspection results and the implementation methodology.

2. ADVANCED MANUFACTURING WITHIN THE INDUSTRY 4.0 PERSPECTIVE

The manufacturing industry in seeking to deliver the best results include advanced technologies to improve product quality, reduce resources and meet the demands of users. Parts with higher levels of complexity need technologies to gather information from design processes, process planning, manufacturing and measurement. The concept of intelligent manufacturing is related to the fourth industrial revolution known as industry 4.0 where different digital technologies converge to harness the data and generate information to promote the evolution, optimization and interoperability of the processes (Lee *et al.*, 2015; Danjou *et al.*, 2017).

It is clear that manufacturing systems are not ready to manage information and need both smart tools and data structures that facilitate integration. The most relevant issues to be solved with the literature review are: to find the data model that meets the current demands for information exchange, architecture for implementation and appropriate method of inspection for integration with manufacturing. The following is a summary of the literature surveyed to answer these questions.

(Danjou *et al.*, 2017) carried out a study of the application context of STEP-NC standard as a solution for the integration and interoperability problem of processes. A model was proposed for the creation of a closed-loop manufacturing based on an ontoSTEP-NC model and product data representation and exchange: PLM systems for CAD/CAM. (Zhao *et al.*, 2011a) provided the basics of dimensional measurement, inspection planning, analysis and reporting of quality data, metrology and interoperability issues. They presented information modeling methods with language such as UML (Unified Modeling Language), IDEF1X (Integration Definition for Information Modeling), EXPRESS, XML (Extensible Markup Language). The activities to generate focused product definition information with aspects of dimensional metrology were discussed. (Li, 2013) showed research developed with standards for product information. An implementation methodology ws presented for integrating product information into a standardized data model, emphasizing the importance of using EXPRESS and SDAI (ISO 10303-22 Standard Data Acces Interface) for computational implementations. The contribution of the research is a computational tool based on STEP. (Zhao *et al.*, 2011a) contextualized the integration of inspection tasks in a closed-loop with machining operations, presenting data structures based on ISO 14649-16. That paper also shows the exchange of inspection process information using DMIS (Dimensional Measuring Interface Standard) and the exchange of measurement results with DML (Dimensional Markup Language). (Xu* *et al.*, 2005) detailed the reasons that allowed the emergence of the STEP standard for information exchange. They presented different researches on the integration and exchange of data in manufacturing systems using the ISO 10303 standard. (Brecher *et al.*, 2006) presented the data stream based on the standards STEP and STEP-NC for the integration of measurement in machining sequences. They showed an overview of part 16 and its relationship to other standards such as AP219 to integrate inspection results into the manufacturing chain. (Peak *et al.*, 2004) described technologies such as XML and UML to assist the integration and interoperability of systems that make part of the life cycle of a product, having a data structure based on the STEP standard. STEP implementation methods by means of EXPRESS and p21 provide standardization, but combined with other more widely-used languages, facilitate integration with Internet-based solutions. (Alvares, 2005) presented a methodology for CAD/CAPP/CAM integration for manufacturing cylindrical parts with collaborative, interoperable and intelligent web functions. The systems are integrated by means of the concept of features. (Bhandarkar and Nagi, 2000) used feature representation capabilities to obtain geometry and topology information from a part using the AP224 application protocol. The primary goal of that research was to develop a system using STEP definitions for extracting features to convert design information to manufacturing data.

3. USING STEP-NC FOR DATA EXCHANGE

A manufacturing and inspection integration model compatible with the industry 4.0 approach based on a standardized and neutral data structure requires supporting advanced connectivity, intelligent tools, and connection to database information. In this perspective, the manufacturing processes need changes in data processing of their systems. With a better use of available digital technologies and the physical resources associated with each process, it is possible to reach greater production control in each of the phases that make up the life cycle of a part.

In the process of integrating the information obtained in a manufacturing and inspection process, it is necessary to think beyond using the information to improve the manufacturing process of a part, to process the data to generate knowledge that allows learning from the operating conditions and the measurement results. At this point this research is focused on the need to find a method to structure the data that satisfies the new requirements of industry 4.0, seeking to guarantee interoperability and integration of information regardless of the technology involved in each phase of the part's life cycle.

In the search for an integration method it is necessary to propose an architecture for the flow of data between the systems involved in the manufacture of the part. Figure 1 shows the proposed digital chain to integrate inspection and manufacturing. The chain contains the CAD/CAPP/CAIP/CAM/CNC/CAI systems and the resources that support manufacturing and inspection of the part fully integrable with digital technologies. The inspection process has great relevance within the digital chain because it affects directly the decisions that allow to improve the quality of the part and the improvement of the process (Zhao *et al.*, 2011b).

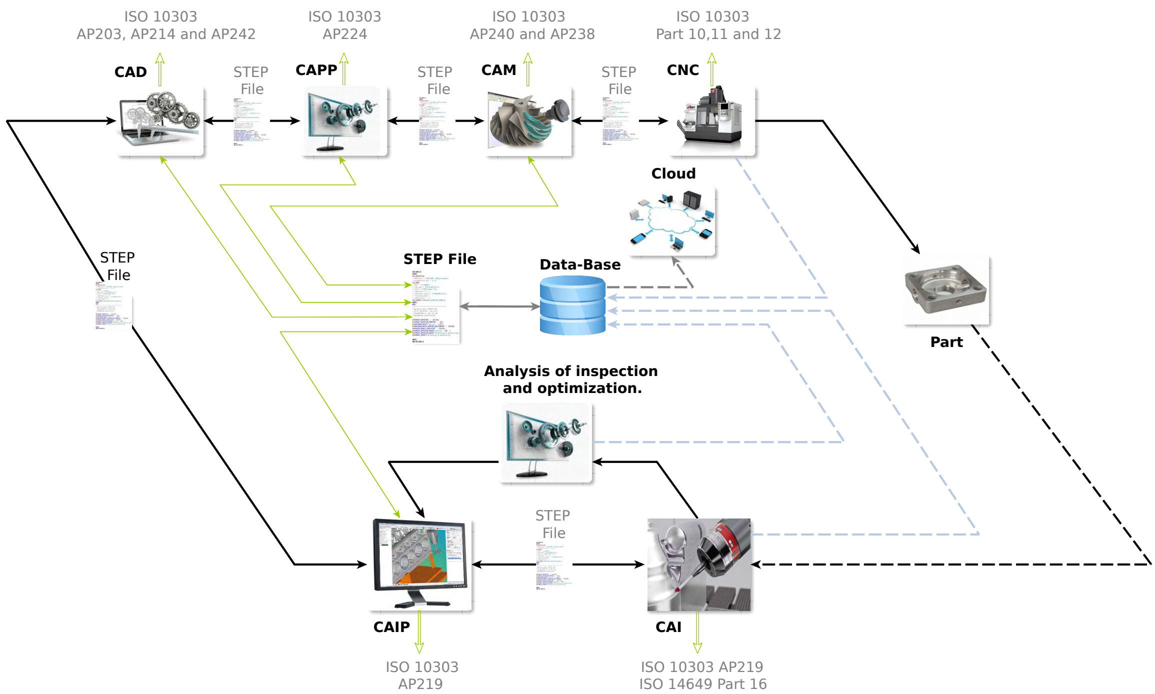

Figure 1. Closed-loop manufacturing and inspection architecture and STEP-NC compliant

The information flow in the closed loop system presented in Figure 1 supports the functional activities of design, process planning, process control, machining, inspection and knowledge management. The output data in each functional activity are standardized in a neutral format, allowing to integrate new information generated in the process.

The ISO 10303 standard provides a representation of product information and provides the necessary settings for exchanging, storing, transferring, and accessing information of a product by means of different technologies (Kern *et al.*, 1997). One goal of STEP is to provide data formatting that can be used by different software and systems that are related to the product lifecycle. Data to be exchanged are of a different nature and need definitions to convey product specifications, tolerances, maintenance information, result analyzes, process diagrams, material specifications, etc. STEP is composed of many parts which describe each branch of the process and represent a specialized subset in an application of the standard.

The choice of the STEP standard as a method of integration and interoperability is guaranteed by its data structure based on the open architecture philosophy. The figure 1 shows the data flow schema and the mechanisms that STEP makes available to support each system.

The basic information that supports the architecture is obtained from a CAD model. The data provided by CAD systems, finite element analyzes and other design systems are shared in the architecture and retain the original data in each exchange. The information generated in the CAD system is structured within the STEP standard by means of the application protocols ISO 10303-203:1994 (AP203), ISO 10303-214:2010 (AP214) or ISO10303-242:2014 (AP242). The AP203 is a standard application protocol for data exchange designed to represent product information such as geometry and data topology of mechanical parts. Subsequently, the AP214 extended version of the AP203 was defined, which includes additional information such as GD&Ts. The ISO 10303-242:2014 was developed to merge the AP203 and AP214 data structures, allowing to transmit the data of a product with the specifications of dimensional and geometric tolerances. AP242 provides the mechanism for defining and communicating tolerances in the engineer context that describes geometry, nominal and permissible variations, indicating the degree of accuracy and precision to be controlled in a part (Venu and Komma, 2017; Bhandarkar and Nagi, 2000).

CAPP/CAM integration represents the process planning tasks at a macro level made through the ISO 10303-240:2005 (AP240) (Process plans for machined products) standard. The protocol provides the necessary definitions to represent the activities of process planning, sequencing of activities, configurations, materials, properties, process requirements, data for manufacturing or assembly of parts and representation of shapes with features and tolerances. STEP through AP224 provides high-level information associated with part machining (Zhao *et al.*, 2011b).

The future of complete integration of CAM/CNC systems still depends on the type of control built into the equipment. Adapters are available as a solution for using STEP files in equipment compliant with the ISO 6983 standard. The ISO 10303-238:2004 (AP238) standard provides a framework for computer numerical controllers to define feature-based manufacturing instructions. The control based on the STEP-NC standard allows to provide interoperability to the machining process by establishing bidirectional communication of the CAD/CAM/CNC systems, where data of operation and condition of the machine tool are fed back. Some intelligent and autonomous tasks such as feature recognition, generation of tool paths, tool selection, operation parameter setting, monitoring, self-diagnosis, storage and feedback are possible to implement based on the definitions given by the AP238.

Inspection verifies the design specifications on the manufactured product to inform the differences and, by means of analysis, establish the respective corrections. Computer-Aided Inspection Planning (CAIP) generates the plan for performing measurements, taking CAD model structured information that contains the nominal product geometries and constraints. The model developed in the CAD system specifies the nominal values, variations, limits, tolerances and constraints in the geometry of a part. Plans generated with CAIP systems are generally developed for coordinate measuring machine (CMM) to perform geometric and dimensional tolerance control (Zhao *et al.*, 2011a; Brecher *et al.*, 2006). The STEP-based closed loop inspection integration requires working with the features. STEP uses the definitions of ISO 14649 part 16 due to its data structure focused on operational aspects, to include the measurement results directly in the neutral file without needing conversion. STEP-NC provides a feature-based environment for exchanging data, defining tolerances, and sharing measurement results in a neutral format for CAD, CAPP and CAM, while retaining part information until a new design redefinition. AP219 was created for dimensional inspection data exchange with a greater focus on inspection operation planning and to specify in a neutral format the GD&Ts of a product.

4. CONSTRUCTION OF THE IMPLEMENTATION MODEL

The STEP standard is extensive in information, which makes it difficult to develop implementations for specific applications. In the literature review it shows a common path that runs through each layer of the ISO 10303 (Application, Logic and Physical) architecture. Figure 2 shows the methodology used for the development of the application of dimensional and geometric inspection (Riaño *et al.*, 2017a). The methodology comprises nine core activities covering all three layers of the STEP architecture and results in the AAM, ARM and AIM models mentioned below.

4.1 The specification of AAM and ARM models

The AAM model describes the functional activities associated with the closed-loop inspection and manufacturing application context. The construction of the AAM model is developed using IDEF0 (Integration DEFinition language 0) which provides the tools to define the information flow and the hierarchy of the activities used in the model. The AAM

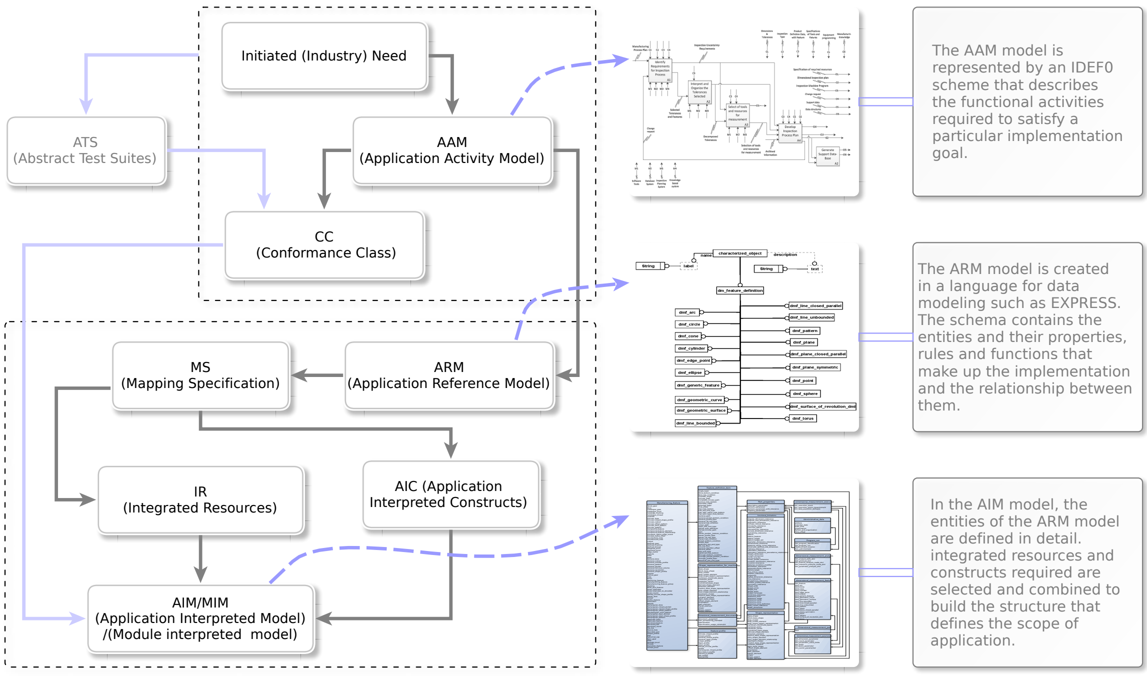

Figure 2. Methodology for developing applications compliant with the STEP standard

model of integration CAD/CAPP/CAIP/CAM/CAI is presented in Figure 3. The functional activities contemplated in the internal level of A0 can be noticed. The model consists of seven functional blocks to define the closed-loop integration model for dimensional and geometric inspection of prismatic parts. The entries subject to change in each system are located to the left of each block. The mechanisms used to transform the inputs are indicated at the bottom of each block (M1-M14). The control means located at the top of each functional block (C1-C18) represent the rules, procedures and restrictions used to correctly generate the outputs of each functional block. The outputs are the objectives of each functional activity are located on the right side of each block.

The AAM model presented in Figure 3 was obtained using the integrated resources of the STEP standard applied specifically in manufacturing and inspection tasks described through the application protocols AP219 and AP238 (STEP-NC). The interpretation of the integrated resources allows to develop the AIM model. The AIM model relates information requirements and integrated resources with the objective of performing dimensional and geometric inspection of prismatic parts.

Figure 3 shows the functional activities that define CAIP/CAI systems within the closed-loop manufacturing. The main objective of the proposed measurement model is to analyze and report the results of dimensional and geometric inspection, creating a connection between systems based on ISO 22093 (DMIS 4.0) and standard models of manufacturing information supported by ISO 10303 such as application protocols AP224, AP238. The STEP standard uses the ISO 10303-219:2007 application protocol to map DMIS and Metrology Interoperabilty Project (MIP) information into interchangeable entities in the same standard.

Figure 4 shows the internal level of the A3 functional activity that represents the CAIP (Computer-Aided Inspection Planning) process. The model contains the functional blocks responsible for identifying the inspection requirements, interpreting and organizing the tolerances to be measured, selecting the tools and resources to perform the measurement and generating specifications for the inspection plan. The diagram shows the relationship between each CAIP functional activity and the data flow it shares within the manufacturing loop. The functional block generates information associated with geometric and dimensional tolerances, uncertainty values for the measurement, classification of tolerances and association with features, equipment programming and plane for dimensional inspection execution.

Figure 5 shows the internal level of functional block A31 (Identify Requirements for Inspection Process). The schema at this level contains the activities related to the reconstruction of the product model by means of its manufacturing features and the association with the tolerances to be inspected. The functional block outputs a list of features and tolerances selected for inspection and the uncertainty requirements associated with each one.

4.2 Dimensional measurement feature

The STEP standard specifies the units of functionality (UoF) for the definition of mechanical products that support the exchange of data associated with dimensional inspection. This part of ISO 10303 specifies the following Units of

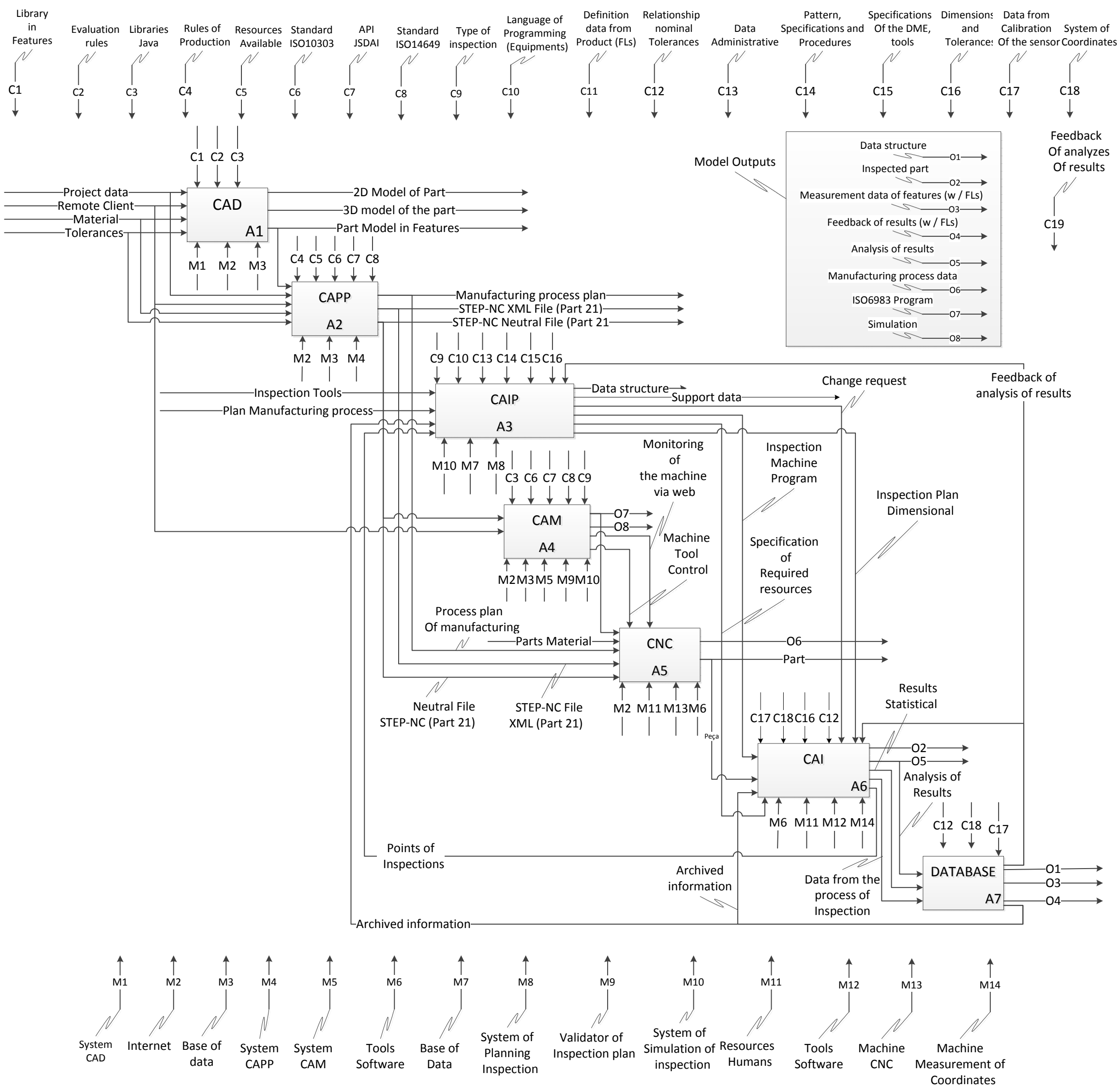

Figure 3. The AAM model of integration CAD/CAPP/CAIP/CAM/CAI
Fonte:Riaño *et al.* (2017b)

Functionality (ISO, 2007):

- Administrative_data.
- Dimensional_measurement_analysis.
- Dimensional_measurement_documentation.
- Dimensional_measurement_execution.
- Dimensional_measurement_feature.
- Dimensional_measurement_part.
- Dimensional_measurement_parameters.
- Feature_definition_item.
- Feature_profile.
- Manufacturing_feature.
- Functional_limitations.

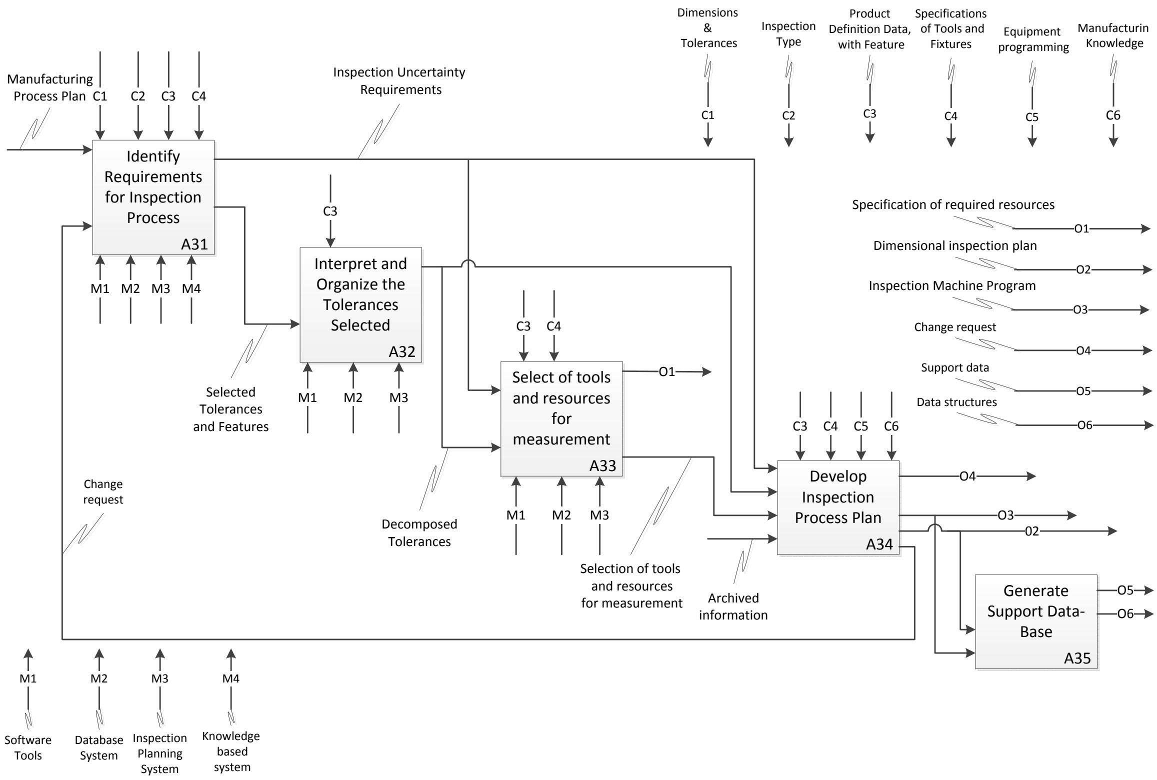

Figure 4. The internal level of the A3 functional activity that represents the Computer-Aided Inspection Planning

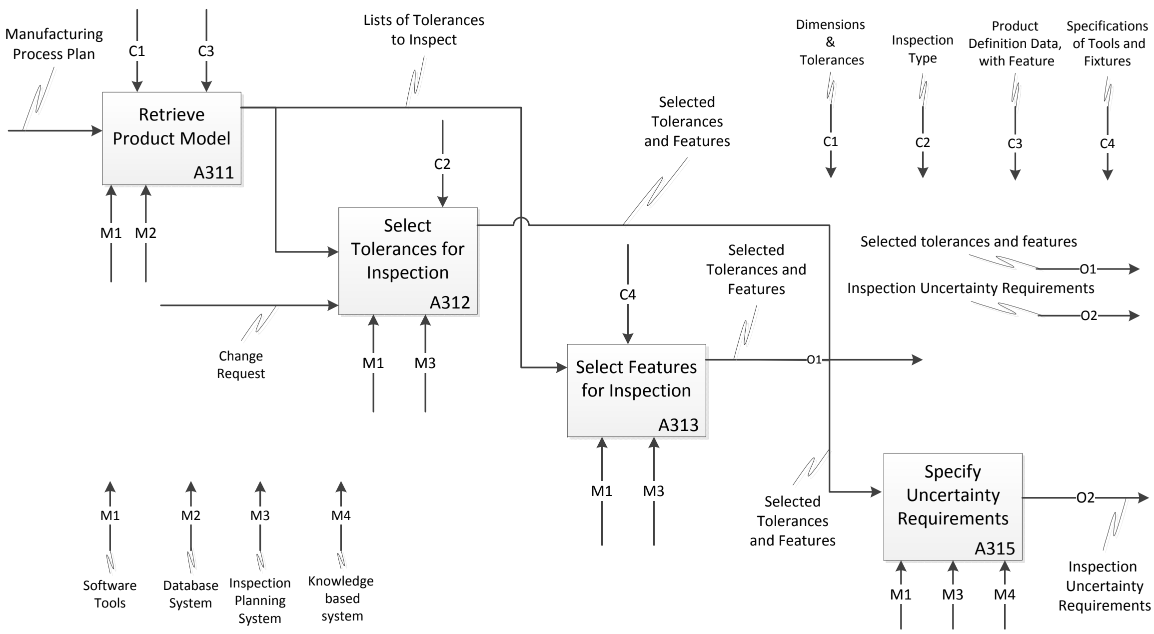

Figure 5. The internal level of functional block A31 (Identify Requirements for Inspection Process)

- Part_properties.
- Program_run.
- Shape_representation_for_machining.

Figure 6 shows the high level relationship between each unit of functionality. The UoF support the planning, administration, execution, inspection information recording activities. With the definitions of the ARM models of these units of functionality, it is possible to implement tasks such as classification by features, identification of dimensional tolerances, specification of references within the measurement process and others defined within the AAM model presented in Figure 4.

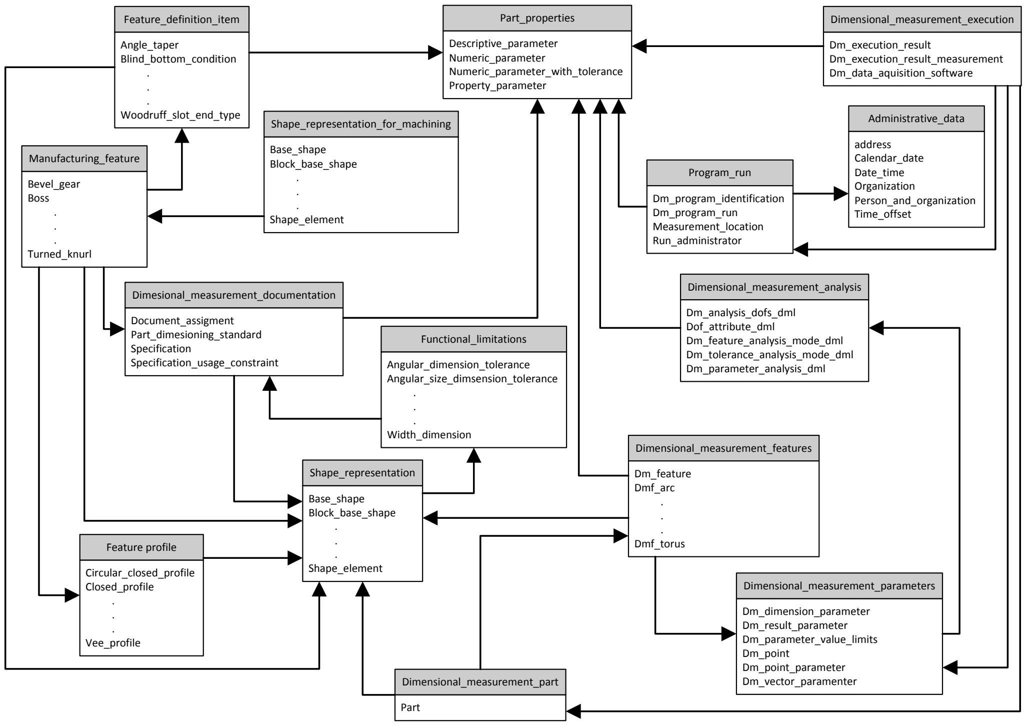

Figure 6. High level relationship of functional units for dimensional inspection information exchange

The functional unit called *Dimensional_measurement_feature* contains a series of mappable entities within the STEP standard that provide information associated with feature-based dimensional measurement. The *inspection_feature_relationship* entity contained within this UoF defines the relationship between parameters obtained with measurement results and design parameters, in addition to creating the relationship between measurement feature and manufacturing features. The *DM_feature* entity can be defined as one of the basic geometric shapes defined in this UoF (e.g. *dmf_arc*, *dmf_cylinder*, etc). Figure 7 presents the EXPRESS-G schema of the definitions included in *Dimensional_measurement_feature*.

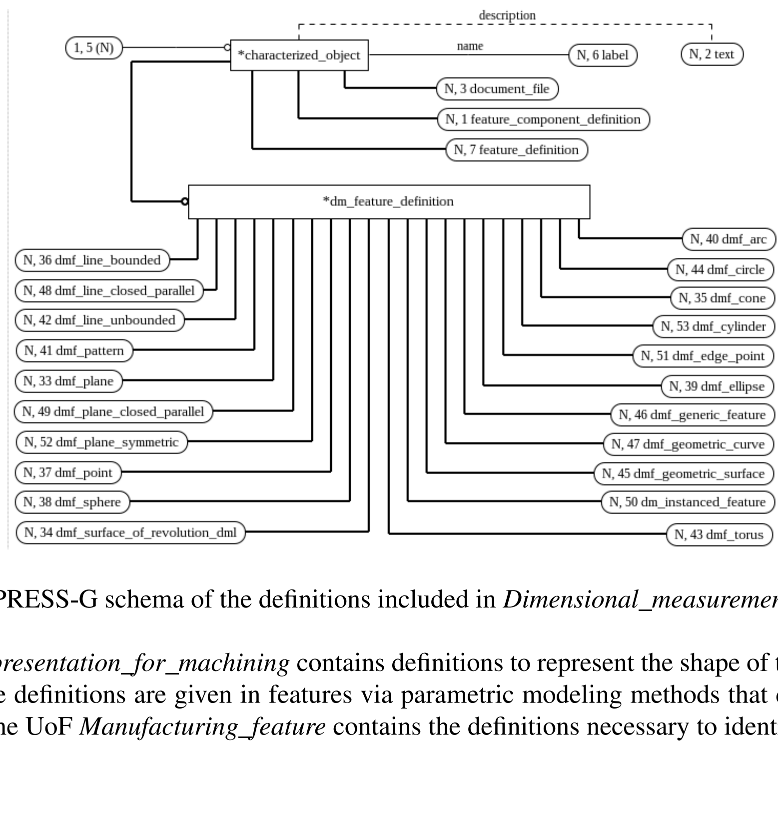

Figure 7. EXPRESS-G schema of the definitions included in *Dimensional_measurement_feature* UoF

The UoF *Shape_representation_for_machining* contains definitions to represent the shape of the part within the CAIP and CAI system. These definitions are given in features via parametric modeling methods that define the geometry and topology of the part. The UoF *Manufacturing_feature* contains the definitions necessary to identify shapes that represent the volume of material to be removed by machining. Figure 8 presents the EXPRESS-G schema of the definitions included in *Manufacturing_feature*.

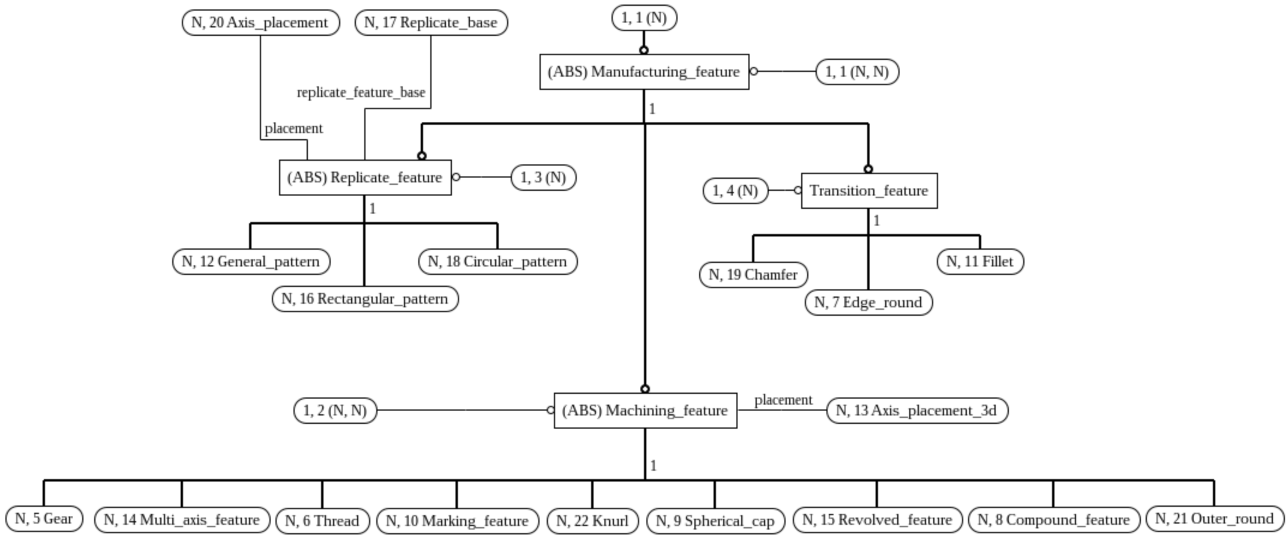

Figure 8. EXPRESS-G schema of the definitions included in *Manufacturing_feature* UoF

After the creation of the ARM models with the entities required to implement the proposed AAM model presented in Figure 3, the following procedure is to create an output file containing the definitions of each entity. Application Programming Interface as JSDAI is used both for reading, writing and runtime manipulation of object oriented data defined in EXPRESS as in the export for Dictionary data in p21 format and creation of an ISO 10303-21 file that contain the meta data according to *SDAI_DICTIONARY_DATA*. The procedure described in this paper leads to the creation of a library used in the model inspection closed-loop prismatic parts. The development of this library as an object-oriented data is used as a data structure within the functional activities defined in the AAM model. This library enables the use of definitions to develop computational implementation in any programming environment. The Dynamic Library Link contains modules, functions and data in executable code that is loaded on demand in the programming environment and is able to interact with other libraries. Using the Application Programming Interface as JSDAI allowed the creation of The Dynamic Library Link with the ARM model definitions extracted from an EXPRESS based data model. This library enables computational implementation under object-oriented programming environments of entities that support the information obtained in dimensional and geometric inspection.

5. CONCLUSIONS

This article describes the methodology to implement dimensional and geometric inspection results within a manufacturing close-loop. In the AAM and ARM models, the relationship between manufacturing features and inspection features was defined to enable the integration and exchange of information between CAD/CAPP/CAIP/CAM/CNC/CAI systems. The final result obtained from this integration model is a detailed description within the AAM and ARM models of the data flow necessary to process information in the CAIP and CAI systems.

The relationship between each of the UoF supporting the inspection tasks was described generally. By implementing the UoF it is possible to extract information such as geometry, dimensions, tolerances and establish the functional limitations to perform the inspection. UoF also provide definitions needed to select inspection features, analyze, share and store measurement results. The entities and definitions used in the UoF are modeled in express language and exported to a dynamic library that enables programming in any object-oriented programming language.

The main contribution of this research is the possibility of feeding back the information obtained in the CAIP and CAI systems, creating a closed-loop with the manufacturing processes that enables the correction of errors, leading to a higher quality in the manufacture of a part. Interoperability is a barrier to be overcome in the inspection systems, which is why it is very important to conceive a STEP-compliant model that already contains a standardized data structure for manufacturing processes.

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