THE INFORMATION SYSTEMS AND MANUFACTURING PROCESSES INTEGRATION: SURVEY AND FUTURE TRENDS

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Abstract. *Today, enterprises have information technology that could fulfil their requirements in each operational phase and with external partners, e.g., suppliers. In fact, in industrial environment, many applications are available to support operating their Product Life Cycle stages. However, organizations typically acquire them aiming to solve focused needs, without an overall view of the global enterprise's system integration.*
Therefore, problems arise when data exchange assumes crucial role in enterprise efficiency, and when coordination between several independent teams is the key factor to stay competitive in growing global market. This new kind of integrating "paradigm" is already under deployment by the research community and it is defined as Product Life Cycle Management (PLM). PLM has recently been recognized as a strategic approach in support of collaborative creation, management, dissemination, and use of product assets.
Nevertheless, the advent of networked production environments has conducted to increase the number of heterogeneous systems that a manufacturer has to manage. Those needs have resulted in major semantic accuracy difficulties when exchanging and integrating information, even when standards guidelines are followed. A standard representation of the semantics associated with the product and processes, has been identified by the research community as a key to solve the problem. Ontologies provide a shared and common understanding of a domain that can be communicated between partners (which are two companies for example) and application systems. Therefore, they may play a major role in supporting information exchange processes in various areas, especially in manufacturing processes.
This paper proposes a framework that integrates the available standard technology for product and process modelling, to render the manufacturing process and management interoperable at data and semantic level, envisaging a next generation of agile manufacturing networked organizations.

Keywords: *Product Life Cycle, interoperability, STEP, meta-modeling, ontology*

1. Introduction

Artifact models (as a conceptualization of a product or process) were the traditional method of scientific disciplines to study and represent diverse engineering subjects [Pahl, 1996, Pugh, 1997]. In fact, a model representing properties and behavior similar to reality is an important tool e.g. for dimensioning structures, analyzing behavior of systems or to prevent defective systems. This model, adjusted to a modern industrial context, involving computational frameworks developed to assist product design and manufacture, has became digital, entailing an electronic representation of the product [Drejer, 2003]. Recent customers' exigencies increase, both in terms of quality and delivery times of final goods, compelled the addition of complexity and refinement to such computational product model. This makes possible features replicating reality, such as functional simulation or photorealistic pictures, becoming possible to visualize a product much earlier before its physical production [Ulrich, 2000].

Besides this scenario, business's ability to digitally connect and interact with local and remote opportunities for partnership is a key factor to enterprise prosperity. Companies in many sectors are, increasingly, willing to adopt electronic technical and business data interchange in order to make more efficient partnerships in the advent of electronic commerce challenges [Jones, 1992, Kreith, 1999].

Particularly in this field, the recent ISO 10303 STEP set of standards enables product data exchange, using a neutral format, where product data includes geometric representation, together with technical and manufacturing specifications [ISO10303, 2003]. Although such successful effort enabled integration capabilities of data between different applications or computational resources, intrinsic differences between geometric and technical data become unveiled. It is needed to deliver supplementary information to shape requisites to make the message understoodable and to perform an acceptable communication of specifications [Anderl, 1998]. A successful communication between production agents requires suitable knowledge exchange complementarily of geometric and technical data.

Hence, computational product modeling was recognized as a high knowledge intensive task. Specific knowledge is required to enhance modeling and simulation tasks, as well as background knowledge from multiple disciplines such as mathematics or physics, among others. Additionally, most of Product Life Cycle knowledge (e.g. design or manufacture related) is tacit, hard to express, and thus hard to transfer through a common support. The knowledge has often heuristic nature, which complicates its implementation directly into computer systems.

Neelamkavil and Kernahan (2003) stated that engineers express and document two types of design knowledge: product and process. The product knowledge focuses on the model of the artifact (physical or virtual) and encompasses factors such as for example design parameters, structure or geometry. The process knowledge focuses on process' factors and variables that will affect the models to be emloyed to simulate and predict the process outcome, related to manufacture, logistic or other phases of the supply chain.

As graphically sketched in Figure 1, today's final physical products or production processes may be viewed both as a combination of material, or intended shape modification, and a larger quantity of information. In each case different information is required: in the product's side the specifications list that product must fulfill is mandatory – as complete as possible, and in the process's side the relevant pieces of information corresponding to instantiations of variables and conditions to be applied to the working piece are needed [Silva, *et al*, 2002].

Both sets of product and process information are shared by modeling activities, dealing with virtual entities, sometimes rather different than real material condition or technological issues. The following section illustrates that the final physical product results quite often from an intricate mix of information sets relative to product and process, both presenting several incompatible constraints that the final solution must consider and merge.

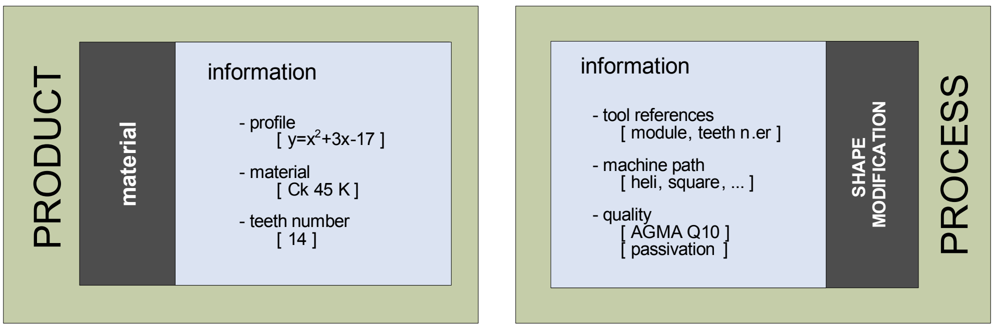

Figure 1 – Schema of information substrate adjacent to nowadays product or processes data representation.

1.1. Product and process data inter-dependency

Despite the information package generated by the design team through instantiation of the product model, the subsequent manufacture processes usually determine the product feasibility and final physical characteristics.

Frequently, the manufacturing processes are responsible for final product shape. In addition, the manufacturing costs quite often impose solutions respecting simultaneously stated geometric constraints and manufacture process selection, and the design and manufacture departments must review acknowledged constraints, in order to achieve a final product consistent with a quality/cost compromise.

Figure 2 graphically presents two examples where final product geometry includes information from two origins: design and manufacture teams, respectively contributing with geometric ant technical constraints.

Therefore, the initial geometric product definition is the beginning of an iterative process, where, in most cases, process restrictions like those for manufacturing, impose new specification details and even re-design [Silva *et al*, 2003]. The instantiation of the initial design knowledge of the intended product generates the product model, but necessarily process knowledge will somehow refine the final physical product during its materialization.

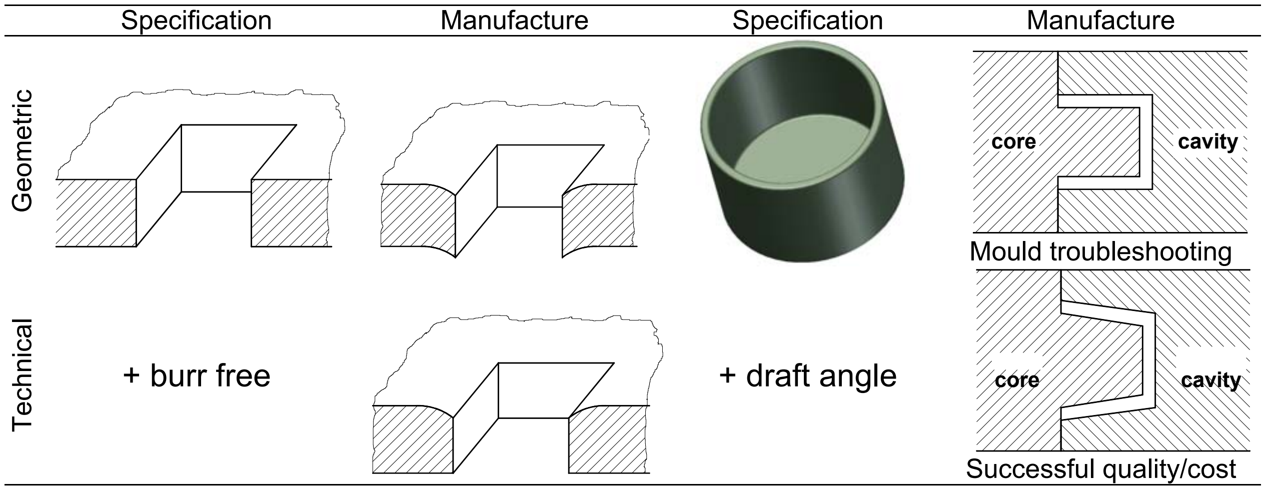

Figure 2 – Influence of different information origin in final product shape (after Silva *et al*, 2003).

2. Managing PLC knowledge: a mechanical scenario

The management of product and process knowledge through the entire product life cycle has recently being the focus of academic and industrial communities. Lack of integration and interoperability issues were identified as main computational barriers to flawless communication and knowledge integration through production chain [Silva *et al*, 2004]. Tracking the path of information and data relative to a typical mechanical element, this section highlights several obstacles to data integration and suitable information and knowledge convey.

In mechanical field, one of the classical physical compatibility problems regards to gear interconnection. When considering the employ of a standard spur gear, despite the mechanical terminology stated, the shape meant and the nominal variables are exactly defined, and should be quantified. In fact, the tooth profile and dimensions were studied and defined, e.g. as pictured in Figure 3, though not preventing unsolved interoperability issues yet remaining at the computational level. Hence, when handling with gear data within computational resources, the integration process should be driven by standard parameters and efficiently made available to the entire range of stages of Product Life Cycle, from early design to subsequent life cycle phases.

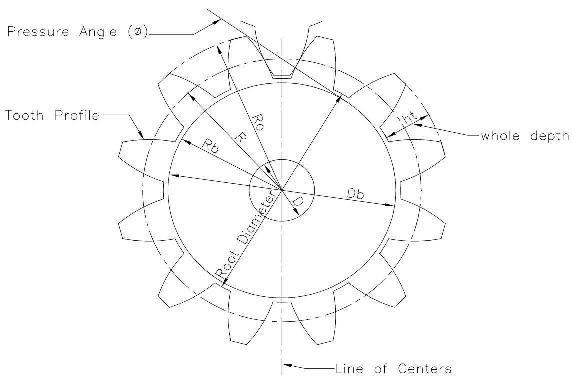

Figure 3 – Main standard variables defining a spur gear surface.

Additionally, different data models are allowed to be developed by different CAD applications, consenting existence of dissimilar data models, with unlike variables, relationships or properties definition. Therefore, difficulties could be expectable when sharing or exchanging data where the same original concept will be shared with unequal data structures and entities.

The adoption of different ISO 10303 normative parts encouraged the discipline of the development of such data model, bringing the needed data integration. However, without a systematic method to dynamically integrate the specific modular models with each other along the PLC stages (e.g., the tooth shape), an universal interoperable PLC can not be achieved [Jardim-Gonçalves, 2002a, Jardim-Gonçalves, 2002b].

This way, the development of a [gear] model supported by an ontology, may provide supplementary semantics for the interconnection of the many views and modules that constitutes the overall product model. PLib [Pierra, 2003] defines a standard methodology suitable for that representation, and a symbiosis between STEP and PLib standards seems to be adequate for this aim [Silva *et al*, 2004].

2.1. Design knowledge

Commonly, design teams include gear shapes in components, when planning interconnections or moving parts in mechanisms or solving similar problems. As illustrated in Figure 4, available design computational applications provide a quite accurate product model of any desired component.

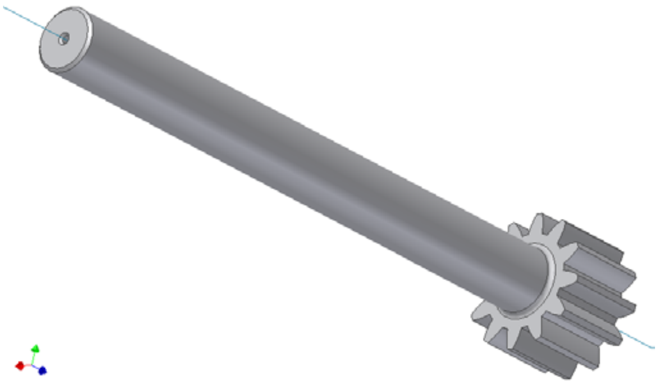

Figure 4 –Designed mechanical component employing a spur gear.

Several knowledge representation and data standards may become the basis for the development of a unified product model of components, which, representing the scope of activity of such applications, will enable knowledge and data handling along the PLC. Using this approach, each application should provide a description at a meta-level, from the point of view of its data structure. Hence, the labeling in a standardized way is nowadays complemented with a refined product data model, often assumed to constitute sufficient data (and information) to subsequent teams involved in the component production chain.

The standard terminology used in a spur gear data model (or meta-model) exchange, using STEP files, limites so far the inaccuracy of shared data, regardless the convey of design intent of the envisaged component recently enhanced due to ISO 10303 Part 108 standard development. Therefore, the computational integration attained through STEP technology is already undertaken in multiple industries, with proven benefits, but a lack of semantic of data and meta-data still prevents flawless computer interaction and suitable knowledge exchange.

When checking for adequate catalogue components to fit designed features, design teams and computational aiding tools face another aspect of integration issues. Exemplified in Figure 5, the taxonomy of gear's properties of Supplier A differ from a Supplier B. Here, the variable's definitions are different for the same gear property addressed, i.e., both properties *teeth_nr* or *number*, respectively in taxonomy of Supplier A and Supplier B, specify exactly the same. Other similar occurrences can be identified within this same example. Another example may be illustrated when checking for a component fitting the gear shaft: a different variable for the same property is found *d* as an internal diameter of ball bearing properties in Figure 6 and *D* as the internal diameter of gear / diameter of the shaft in Figure 3.

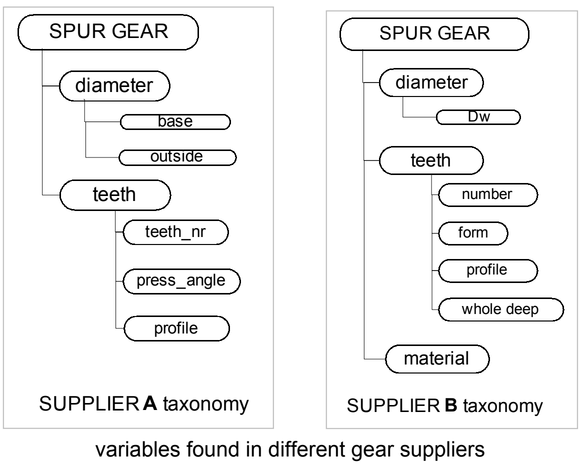

Figure 5 –Scenario of different taxonomy practice regarding same mechanical component.

In this context, two or more communities (e.g., organizations, teams), operating in the same domain may have different views on the same concept, leading to different underlying taxonomies, and consequently conducting to problems of interoperability. At a first level this problem comes out in the communication between humans, then between humans and computer systems, and finally between computer systems [Uschold *et al*, 1996, Fox, 1997].

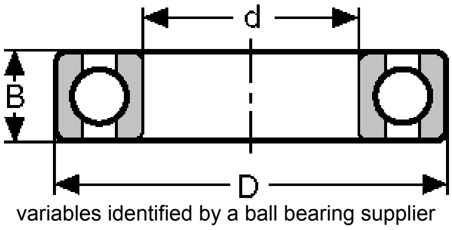

Figure 6 – Simplified technical drawing of a ball bearing component.

For example, when a design team talks with the suppliers searching for a specific component, they all need to understand each other. If for any reason this is not the case, humans are able to reason and combine their knowledge attempting to converge to a common understanding, and hence communicate.

In opposition to this interactive and intelligent human to human process, computer systems communicate under a well established syntax, through rigid communication protocols. The inclusion of semantics in the communication protocol under a well established classification mechanism will complement the information exchanged, thus contributing for an enhanced understanding between the systems.

Therefore, interoperable systems, that seamlessly communicate and understand each other, require comprehensive understanding of the meaning of the data exchanged within the domains involved. This can be possible, if the communication process is supported by an ontology developed under global consensus [Uschold *et al*, 1996, Jardim-Gonçalves *et al*, 2004].

This way, waste of effort in protocol elaboration should be avoided through a consensual procedure, were concepts are defined in an universal manner. Recently, the PLib approach [Pierra, 2003] established such a methodology, which, being a standard, enables and improves the interoperability and interchangeability of the mentioned data models supported by an ontology.

PLib is a standard developed by ISO TC184/SC4 with the objective of supporting the representation of Parts Libraries, and suitable for electronic representation of catalogues of components. The proposed architecture suggests the use of ISO13584–PLib standard for the representation of the catalogue of modules stored in a standard repository in ISO10303 STEP format, adopting the available standard mechanisms developed to interface between STEP and PLib, e.g., the STEP services.

2.2. Manufacturing knowledge

The PLC phases have been using computational systems to assist in their tasks. However, files shared by manufacture teams quite often require mapping and translation operations, to make interoperable the data format and semantics of the applications that gave support to manufacture. This could be labeled as a first level of integration between applications, which efforts of both ISO 18876 IIDEAS [West, 2001] and STEP technologies are overcoming quite satisfactorily. Recently, computerized machine tools are able to receive data files using STEP-NC data [ISO14649, 2002], bringing the level of standard integration down to the machine.

The manufacturing phase is usually a significant repository of product and process knowledge, though its archive or representation is not always engineered. The manufacture process will be responsible for the definition of the best sequence of activities in order to optimize the fabrication of a component. Although different sequences of operations will successfully materialize a designed component, process knowledge will be determinant to define a particular shop floor suitable for its available machining resources.

Nowadays, many manufacturing engineering and business software applications already use process information, including manufacturing simulation, production scheduling, manufacturing process planning, workflow, business process reengineering, product realization process modeling, and project management. Since each of these applications utilizes process information in a different way, process information is also represented differently in each application.

This class of problems has been currently addressed by the NIST PSL (Process Specification Language) Project [PSL, 2005] with its manufacturing process ontology, and also by the community working on the Semantic Web [SW, 2005].

3. Using ontologies to enhance PLM

Product and process knowledge is often distributed across separate PLC domains as varied as: product requirement analysis, functionality assessment, quality analysis, cost estimation, or manufacturability evaluation. Problems arise however, when knowledge needs to be shared between domains or between PLC agents, whether they are human or computational. Moreover, iterative PLC phase's sequence, though inefficient, is the typical method employed to solve conflict tasks that result from product and process knowledge concatenation during production phases.

Two recent efforts progressively improve solutions that support knowledge-intensive tasks: the development of Product Lifecycle Management (PLM) technologies, seeking product knowledge capture, and the development of PSL – Process Specification Language, which is focused in the process knowledge capture and was carried out by the National Institute of Standards and Technology (NIST) and resulted as an ISO standard proposal.

3.1. Product knowledge capture

A definition of Product Lifecycle Management, among others, may be "the strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise from concept to end of life – integrating people, processes, business systems, and information" [PLM, 2005]. Furthermore, recent PLM enabling technologies are expected to be next generation technologies, which collect product data to a large extent and turn it accessible to PLC phases [Mocko *et al*, 2004]. In the essence, PLM involves activities from the initial conception to retirement of the product and is focused in the product development process improvement – namely through the integration of product realization activities [Panchal *et al*, 2004].

3.2. Process knowledge capture

NIST has started the Process Specification Language [PSL, 2005] project to overcome integration problems dealing with the representation of process activities and restrictions. In this project they try to define a neutral and standard language for process specification, and more importantly they propose a standard of formal semantic definitions (the ontology) that underlie the language.

The development of PSL was based on the grammar of KIF (Knowledge Interchange Format). KIF is a formal language based on first-order logic developed for the exchange of knowledge among different computer programs with disparate representations [KIF, 2005]. KIF provides the level of strictness necessary to define concepts in the ontology unambiguously, a necessary characteristic to exchange manufacturing process information using the PSL Ontology. Because PSL uses KIF as a grammar, it is based on BNF (Backus-Naur Form) specification, which provides rigorous and precise recursive definition of the class of grammatically correct expressions of the PSL language.

3.3. An ontology approach bridging knowledge gaps

A particular effort of capture of product and process knowledge, and the subsequent knowledge representation, may be considered the application of ontologies on product and process modeling, which has been a recent focus of research community. An ontology consists of a set of concepts, axioms, and relationships that describes a domain of interest. These concepts and the relationships between them are usually implemented as classes, relations, properties, attributes, and values (of the properties/attributes) [Fox, 1997].

Since the use of ontologies was introduced in Computer Science (more specifically in Artificial Intelligence) they have been employed, among other areas, in conceptual and information modeling, information integration and knowledge representation and engineering. Its use proliferate to material domains such as medicine, e-commerce, product catalogue integration, mechanical engineering, knowledge management and geo-information systems, among several other examples [Radeke, *et al*, 1999]. Semantic comparability is a challenge in enterprise engineering due to the lack of interoperability among different (yet coexistent) product and process models.

Sharing common vocabulary of a domain of information among people or software agents is one of the more common goals in developing ontologies. Hence, independently developed models often describing the same entity derive in additional work of comparison and complex mappings elaboration between common models, introducing costly maintenance of meta-models and databases. Basing models on neutral standards rather than on custom-made modeling efforts, has being the foreseen solution. The recent developments in ontology standards are addressed to this class of problems and promise to alleviate such issues.

A 'product' ontology is an encapsulation of information for the purposes of product specification. A 'process' ontology attempts to capture the information related to the process that will influence the product shape or final configuration.

Therefore, the development of an ontology focused in both product and process, extending and refining current undertaken efforts (such as PSL ontology) at the level of a mechanical element (e.g. the mentioned spur gear), will assist knowledge capture and the archive of basic information.

The proposed refinement may avoid the mismatches involved in information exchange relative to product or process models, associating a harmonized taxonomy and semantic to the multiple variables utilized in computational models (shared by early and late phases of a Product Life Cycle like design and manufacture). The equivalence of variables employed (e.g. the designed diameter of the gear shaft and the internal diameter of the ball bearing/journal should be the same) may then become a computational task, necessarily bringing integration and interoperability to computer systems.

Therefore, the proposed ontology development contributes to a gradual replacement of human variables matching (an actual time-spending and bothering commitment) by smooth computer to computer communication, constituting a skillful option. Moreover, collecting basic knowledge (of mechanical elementary shapes) through both the capture of product and process restrictions, increases the potential of existent knowledge repositories, which comprise by know an accurate data support. Hence, such knowledge repository may grow based on capture of simple rules, which, being processed by first order logic applications, clearly identifies troubles or incompatibilities between designed components and particular resources of each supply chain.

The purpose of such ontological environment development is to contribute to PLM technologies enhancement, namely in the capture of manufacture knowledge (existent at the shop floor level) and convey to the involved design teams an unambiguous and computational support.

4. Outlook and further work

Today, to succeed in a global and time-based competition, it is necessary to greatly shorten the time of product development. Organizations face the process of automating the production process, which distributes computational resources, ranging from design to manufacture. Due to this computation distribution, more and more PLC stages are cooperating trough exchange of digital data and information. Nevertheless, several issues at the different data, information and knowledge levels are obstructing computational integration and interoperability between major phases of PLC.

Product shape is a result of all PLC activities, and the best way of get some proficiency is by re-using for update its data and knowledge, which is determinant from the first product shape iteration. This paper intends to contribute in this area, proposing the development of ontologies to capture simple product and process information and knowledge relative to elementary mechanical shapes. Analogously to the spur gear ontology development proposal presented in this paper, the development of ontologies, embedding knowledge and information of a simple mechanical component, strongly enables whispered reuse and integration of knowledge and data, avoiding replication, redundancies and re-work by PLC teams.

The Process Specification Language (PSL) is probably the most developed ontology for manufacturing processes. The proposed ontology development should explore PSL as a neutral ontology for the manufacturing knowledge capture, which will enable reuse in the diversity of environments along PLC.

Having one of these ontologies the capability to describe the knowledge associated with a shape, it can be reused promptly and integrated with upper level ontologies. This can be of effective support for the management of complicate processes of product life cycle management.

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