A STANDARD MANUFACTURING INFORMATION MODEL TO SUPPORT DESIGN FOR MANUFACTURING IN VIRTUAL ENTERPRISES

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ABSTRACT

Manufacturing enterprises are being forced into greater collaboration with customers and suppliers in order to produce quality products in smaller batches, shorter lead times, and with greater variety. Consequently, the design-for-manufacturing task must be conducted in these virtual and distributed enterprises across traditional organizational boundaries. This paper proposes the use of standard information models to support the product realization process. While extensive work has been performed in developing product data models little effort has been performed in developing a manufacturing model. Different modeling approaches used to address various aspects of manufacturing are reviewed and found inadequate for supporting the design for manufacturing task. The development of a standard manufacturing systems information model written in EXPRESS and based upon the modeling methodology adhered to by STEP is proposed to fill the void. Initial development in this area is discussed and the potential benefits to manufacturing reviewed.

Keywords: information modeling, information management, supply chain, design-for-manufacturing, agile manufacturing, STEP, EXPRESS, virtual enterprises.

1. INTRODUCTION

Global competition, shorter lead times, and customer demands for increasing product variety have collectively forced manufacturing enterprises to rapidly develop and introduce new products to obtain a quick return on their investment. The overwhelming market conditions have lead enterprises to focus on their core business and increasingly cooperate with suppliers and customers (Teeuw, et al, 1995; Dyer, 1997). This is referred to as the virtual enterprise and its conceptualization is shown in Figure 1. The inclusion of suppliers in the product realization process calls for greater collaborative work than what has previously occurred. Activities must now be performed across organizational boundaries throughout the product realization process. Information technology (IT) is regarded as a means for these geographically dispersed companies to collaborate on new product development, manufacture, and delivery. This paper is concerned with the creation of information models to facilitate information management for design-for-manufacturing in virtual enterprises.

Concurrent engineering and more specifically design-for-manufacturing (DFM) has emerged as a critical task integrating the design function and the manufacturing function during the product realization process. The objective is that by considering manufacturing early in the design process, the design can be favorably influenced to improve quality, reduce cost, and decrease time-to-market. DFM is the process whereby design teams access manufacturing process capability knowledge and information to assess the manufacturability of the product. The successful realization of DFM requires the availability of both product and process models. Traditionally only internal manufacturing capabilities were necessary to support DFM but current virtual enterprises must also consider the capabilities of their vendors during the product realization process. There are many different software applications in use by each company in the virtual enterprise. Hence, there exists an industry-wide demand for information technology solutions capable of sharing design and manufacturing information between applications.

Extensive research and development has focused on standards for product models. Information protocols such as STEP and CORBA are being developed so that geographically dispersed companies can collaborate on design and manufacturing (Bloom and Christopher, 1996.) The STEP standard for product modeling (ISO, 1992a) is regarded as one of the most ambitious international standards initiatives ever conducted. Industry is strongly promoting this effort. For example, automotive suppliers now play a more prominent and active role in new product development that requires greater exchange of product information via STEP (Haag and Vroom, 1996). To some extent sharing process information, especially process capability information, is also critical to the formation and operation of virtual enterprises. Meanwhile, as noted by Feng et al., (1996) little effort has been made to develop standard process models. Process information has been represented in an *ad hoc* manner in vendor specific models that cannot be utilized by other applications. Meanwhile, prominent researchers have vocalized a concern that there is no scientific base for manufacturing (Suh, 1984; Sohlenius, 1984). Formal models of manufacturing systems have the following advantages: (1) Formalization often leads to the discovery of inconsistencies, omissions, ambiguities, and contradictions, (2) Guide systems development methodologies, and (3) A rigorous definition enables conformance measurement. Formal models can be used to develop standards to realize the benefits brought about by standardization. The benefits of standardization are to increase the speed, efficiency, and effectiveness of collaborative work. Companies that predominantly design the product can share the product design information while companies that manufacture the majority of the product can share manufacturing information. DFM embodies the essence of integrating design and manufacturing. Information management systems play an important role in enabling collaborative multi-enterprise DFM. We contend that in order for information management systems to work in the virtual enterprise first standard information models of manufacturing process capabilities must be made available.

1.1 DFM Information Management System Issues

Virtual enterprise DFM requires more flexible and better integrated information models than what currently exist. The following are some of the important issues that must be addressed.

1. Distributed System

A monolithic model and control strategy is inappropriate for the virtual enterprise environment. Current information systems development for product realization is based on distributed architectures (Olsen et al., 1995).

2. Collaborative Design

Design is a collaborative task of synthesis, analysis, evaluation, and decision making (Sriram et al., 1990). Thus, information management solutions must support collaboration between human agents as well as collaboration between disparate software systems. Due to the evolutionary implementation of information technology heterogeneous software systems have been created with internal representations that hinder collaboration.

3. Separation of Capabilities and how those capabilities are attained

Companies are willing to exchange process capability information to perform DFM yet they still wish to protect proprietary manufacturing methods and procedures (de Graff and Kornelius, 1996). Therefore, a separation is necessary between the capabilities and the processes such that the capabilities are made available to other organizations but the resources and methods for attaining them are not disclosed.

4. Multiple Abstraction Levels

Information management systems must enable interaction at different levels of engagement (Upton and McAfee, 1997). Abstraction levels are important to modeling languages and models. The ability to view information at varying levels of detail is critical to natural decision processes. A good model matches the abstraction level to the detail necessary for decision making.

5. Multiple Sophistication Levels

Information management systems must support multiple levels of sophistication since there may be a low level job shop supplier with a PC in the corner as well as the engineering design department with high end workstations (Upton and McAfee, 1997).

Issues regarding the management of communication among distributed and heterogeneous IT applications is an ongoing research and development activity in industry. Collaboration in product development besides sharing information must also establish information sharing agreements (Olsen et al., 1995) such as those provided by ontologies within agent-based architectures. However, even autonomous agents need to reason with product and manufacturing models. In the product modeling arena STEP is intended to serve as a neutral format. Each separate IT application would translate to and from the STEP format. Likewise, a neutral manufacturing model is required for DFM among other tasks in the virtual enterprise.

1.1.1 Organization of Paper

This paper reports on the development of manufacturing process capability models so that designers can benefit from information management systems in a virtual enterprise. The paper is organized as follows: Section 2 examines the product realization process, corresponding DFM tasks, and their information requirements. Section 3 introduces a product model and a manufacturing model. Various methodologies for modeling manufacturing process capabilities are reviewed. In section 4 a manufacturing model integrating different perspectives is described in detail and identified as a suitable methodology. Preliminary results in applying information modeling to support DFM are also discussed. In Section 5 conclusions are drawn.

2. PRODUCT REALIZATION PROCESS

It is generally acknowledged that the design process consists of stages of progressively finer detailed designs (Pahl and Beitz, 1993). Typically, four stages are used: clarification of task, conceptual design, embodiment design and detailed design. Clarification of task is a problem formulation activity where the functional requirements are specified. Conceptual design is the synthesis of an abstract structure that can be a solution to the design problem. Embodiment design is the development of an abstract concept into a preliminary scaled engineering drawing. Detailed design involves the specification of attribute values to the design parameters. Clearly, design is an iterative process that generates more detailed and complex product models at each stage until a final complete product specification emerges (Giachetti et al., 1997). Similarly, manufacturing evaluation also occurs in recognizable stages, yet there is scant documentation placing DFM within the context of a design process model. A structured approach to DFM at various abstraction levels is promoted by Dixon and Poli (1996). However, it does not explicitly document the role information management assumes in the process. In this section, we identify the sequence of manufacturing evaluation tasks, their correspondence to the design stages, and the information requirements for accomplishment. These activities are, material and manufacturing process selection, high level process planning, manufacturing process capability evaluation, and product/process specific manufacturing evaluation. This perspective of DFM as part of the product realization process is shown in Figure 2.

Material and manufacturing process selection is the first decision making activity that involves manufacturing. Suitable materials and manufacturing processes are selected based on criteria such as overall dimensions, material properties, maximum tolerances, product volume required, etc. (Ashby, 1992; Yu et al., 1993). The criteria is based upon the product profile requirements from the clarification of task design stage. The manufacturing information is represented at a high abstraction level such as that found in handbooks and is therefore generic to all manufacturing facilities. Although new materials are developed and processes are improved the information model's structure remains invariant. An embellishment is that during this stage the suppliers and/or partners must be selected to participate in the new product development. The decision should reflect the strategic importance of the collaborative effort with criteria based on the preliminary product profile requirements, financial considerations, quality, design support, and engineering capabilities. Following vendor selection DFM can be performed and contract negotiations begun with the selected vendor. *High level process planning* (Gupta et al, 1995) specifies aggregate process plans or sets of operations to be carried out by manufacturing facilities. High level process planning generates alternative process flows based on an overall evaluation of the facility level manufacturing capability model and the conceptual design product model. This is in accordance with Kusiak and He (1997) who argue DFM must consider the entire manufacturing system and not just individual processes as traditionally performed. *Manufacturing process capability evaluation* is a process specific evaluation of each product feature contained in the preliminary engineering product model. Each feature is evaluated against the process capabilities, often, the vendor's manufacturing capabilities. For example, holes must be checked for meeting depth-to-diameter ratio constraints specific to a certain drilling operation. Consequently, the process capability information requirements are more detailed and contingent upon a particular process. *Product/process specific manufacturing evaluation* is the last stage and typically utilizes process simulations or analytical models. These activities usually require a detailed product model including geometry, i.e. a CAD model as input as well as specific process parameter set point values. For example, determining tool chatter during a machining operation is performed by a process simulation model and requires precise product geometry, cutting tool data, feed rate, and speed provided at the equipment detail information level. Consequently, product information and product/process interaction information are necessary content to perform this detailed level evaluation. The integrated design process and manufacturing evaluation process model presented here provides a framework to guide information model development.

3. INFORMATION MODELING FOR DFM

Prior to building an integrated technical information management system, information modeling is necessary. Information modeling is the specification of the entities, their properties, behavior, and how they interact with each other within a system (Schenck and Wilson, 1994). In the case of manufacturing systems, the eventual goal is to build an information management system based on this model. The information management system supports the activities of the manufacturing enterprise in fulfilling its mission. Two different information models are required for DFM: product models and manufacturing models.

3.1 STEP PRODUCT MODEL

The Standard for the Exchange of Product model data is referred to as STEP and is embodied in the ISO 10303 standard for the representation of product data in a computer-interpretable format, and to exchange data between systems. STEP provides a means to describe a product model throughout its lifecycle. A series of related standards are used to accomplish this task. Integrated resources (IR) are parts 41-199 and are general representations, independent of any implementation. Application Protocols (AP) are parts 201-299 and are a specialized portion of STEP for a particular application, such as AP 203 for mechanical parts.

3.2 MANUFACTURING MODEL

Manufacturing information has typically been collected on an ad hoc basis for each application. There is little consensus on the structure of the manufacturing models. Most manufacturing models concentrate on representing *manufacturing resources* and their combination into *manufacturing* *processes*. The manufacturing resources are the tools, fixtures, and machines that are combined and arranged into a manufacturing process to fabricate a product. Modeling activity for manufacturing resources using EXPRESS has been conducted among others by (Jurrens et al, 1996) for cutting tool data and Kjellberg and Bohlin (1996) for a 5-axis machining center. However, manufacturing resources only capture the physical resources and do not model the behavior of the equipment, tools, and fixtures when employed in a manufacturing system. Indeed, Weston (1996) has expressed the need for several modeling perspectives of manufacturing systems. MANDATE (ISO 15531-1, 1996) is an international standards activity to describe the process whereby a product is fabricated. What this model lacks is manufacturing process capability information. A *manufacturing process capability* describes the behavior of manufacturing resources and is defined as the feature producing ability of a manufacturing process to some level of accuracy and quality. It unifies design and manufacturing and consequently is necessary for DFM. Molina et al. (1995) use an object-oriented information model of manufacturing resources, processes, and strategies. The process capabilities are defined as tool motions for material removal processes. Some process capability information is captured, such as minimum tolerances. However, as noted by Giachetti (1997a) such minimum representations cannot capture all of the complex interactions between product geometry, material properties, and process technology that define the process capabilities. Consequently, modeling effort is required to model manufacturing process capabilities. The next section discusses different approaches to modeling manufacturing process capabilities.

3.3 MANUFACTURING PROCESS CAPABILITY MODEL CLASSIFICATION

Models can be classified based upon their viewpoint: physical, functional, static behavior, or dynamic behavior. A mapping between the four viewpoints and their corresponding manufacturing model is shown in Figure 3. A functional viewpoint describes the manufacturing process, including all the activities to change an input into an output. A physical model describes the resources required to perform the process. The behavior of the process can be subdivided into static behavior and dynamic behavior. The dynamic behavior is the time-varying aspect whereas the static behavior is a description of the capabilities without reference to time. These models can contain both declarative and procedural knowledge. *Declarative models* explicitly represent the process information whereas *procedural models* implicitly represent the process information through rules, expressions, and equations through which input parameters infer the desired output parameters or process capabilities. While other authors note the lack of sufficient integration between these different viewpoints (Malhotra and Jayaraman, 1992), the separate viewpoints are beneficial for concentrating on a single aspect of the enterprise. The next section reviews three approaches to modeling manufacturing information for DFM systems.

3.3.1 Analytical Process Models

Analytical process models define mathematical relationships between design features and process parameters (Soyucayl and Otto, 1997). Manufacturing process capabilities such as tolerances or surface finish are predicted by mapping machine control set point values through the analytical process model. Giachetti (1997b) utilizes an analytical model of injection molding that relates process parameters temperature, pressure, and specific volume to process outputs such as shrinkage which determines optimal tolerance allocation based on the process capabilities. Analytical models are primarily useful during the product/process specific evaluation stage because the mathematical expressions require precise design and process parameters. Difficulties encountered with analytical models are: they can be difficult to integrate on a systems wide basis since they are generally narrowly focused on a single process, they are based upon empirical data and thus are inherently imprecise, and they do not employ standard representation structures.

3.3.2 Process Simulation Models

Process simulation models provide a computer representation of the process for predicting relevant process capability information. Process simulation provides useful process capability information tailored to the current part being evaluated. Commercial simulation packages are available for machining, mold flow analysis, and a few other processes. Busick et al. (1995) develop a methodology based upon an injection molding process simulation to assess tolerance capability. Process simulation models require a completed or nearly completed product model and thus are only used in the product/process specific evaluation stage. Disadvantages are: the time requirements to complete a simulation, simulation packages require specialized expertise and knowledge, and they suffer from integration with existing systems.

3.3.3 Process Information Models

Information models represent the entities, attributes, and relationships between the entities. Two methodologies are used, generally based upon the final application platform of either a relational or object-oriented database. The IDEF modeling methodology recognizes three viewpoints, the functional, information, and the dynamic. The information model component IDEF1x is based on the relational data model. While it has been widely and successfully applied to CIM systems design it does have several limitations: poor abstraction since only atomic attributes are allowed, difficulty in capturing domain constraints, and instance identification through attribute values (Malhortra and Jayaraman, 1992). Object-oriented approaches have been used by many authors in order to overcome these limitations (Ngwenyama and Grant, 1994). There exist several object-oriented model definition languages, one of which is EXPRESS, used for defining the STEP standard. Information models are useful for representing the manufacturing capabilities at several abstraction levels for DFM at the material and process selection, the high level process planning, and the manufacturing process capability evaluation. However, they are not well suited to detailed evaluation of specific product models.

3.4 OVERVIEW OF MODELING METHODOLOGIES

Information models support rapid querying of the information but cannot capture the complex interactions between the product characteristics and process parameter specification required for product/process specific evaluation. Analytical models and simulation models can accurately model the complex relationships but require a greater amount of input and tend to be narrowly focused. Consequently, many analytical models are required for each manufacturing process and task being studied. The declarative information provided by an information model is useful for much of the higher level reasoning. When a designer requires a more sophisticated evaluation for a particular design, either analytical models or simulation models will be necessary. Consequently, a combination of the approaches is most suitable to support the DFM process in virtual enterprises.

4. MANUFACTURING MODEL

This section presents the manufacturing capability model being developed at NIST. EXPRESS is used to model the manufacturing process capabilities. EXPRESS is a modeling language developed by the international standards community for the purpose of information modeling especially with respect to STEP for product modeling (ISO, 1992b). EXPRESS has both a lexical and graphical representation (EXPRESS-G) scheme. It supports super-type and sub-type relationships and has semblance to object-oriented models. While it is possible to implement an EXPRESS model with a relational database, it is better suited to implementation using an object-oriented database.

An EXPRESS model consists of one or more schemata. Each schema defines a set of entities, data types, constraints, and algorithms in a formal computer interpretable description. The entire manufacturing model is organized into schemata as shown in Figure 4. Each schema represents a single perspective, and importation of one schema or a partial schema into the current schema is possible.

Manufacturing Firm (MF) Schema

The manufacturing firm schema contains information on the manufacturer's name, geographical location, and other information pertinent to the company.

Manufacturing Process Specification (MPS) Schema

A manufacturing process uses manufacturing resources to transform material inputs into an output. The manufacturing process schema describes processes. Work is being performed to develop a *process specification language* to specify a process or flow of processes composed of a schema, a grammar, and one or more notations (Schlenoff et al, 1996).

Manufacturing Resources (MR) Schema

This schema describes the manufacturing machines, tools, and fixtures (Jurrens et al., 1996). This work complements ongoing standards development for manufacturing resources being performed by the ISO TC29/WG34 standards group. This group is responsible for development of the ISO 13399 international standards for "computerized machining data exchange" that will define an electronic representation for the exchange of cutting tool data.

Physical Manufacturing Process (AMP) Schema

This schema includes models of specific manufacturing processes for a company. These may be analytical models or process simulation models. These models accept product information and process specifications to predict process capabilities. The output is specific to the product and can be used by the DFM software system to perform an analysis.

Manufacturing Process Capability (MPC) Schema

A description of the capabilities of a manufacturing resource, or the manufacturing resources organized into a process. These are the general manufacturing process capabilities independent of product characteristics.

The models support various abstraction levels by using a manufacturing hierarchy shown in Figure 5. This hierarchy was also used in the MOSES project (Molina et al., 1995) and was originally developed at NIST by Simpson et al., (1982) for control of manufacturing systems.

A one-to-one correspondence exists between the manufacturing hierarchy and the DFM stages. Vendor selection uses factory level and shop level information from the MF, MR, and MPC schemas. Material and manufacturing process selection uses factory level information from the MR and MPC schemas. High level process planning uses factory level information from the MR and MPC schemas. Manufacturing process capability evaluation uses manufacturing cell level information from the MR and MPC schemas. Product/process specific evaluation uses manufacturing station level information from the PMP schemas.

4.1 ILLUSTRATION OF MANUFACTURING PROCESS CAPABILITY MODEL FOR DFM

DFM systems interact with both the STEP product model and the manufacturing process capability model. The nature of the manufacturing evaluation system depends upon the DFM stage but a general conceptualization of this system is shown in Figure 6.

DFM for hole-making is examined in detail in order to clarify the structure of the manufacturing model, its components, and system architecture. Producing holes in non-standard materials such as printed circuit boards (PCB) is a tricky operation due to the composite material, small diameters required, and high depth-to-diameter ratio. Quality concerns for highly accurate hole location, smooth hole walls, and the absence of burrs further complicates the process. Thus, assessing hole-making process capability is a significant factor in the manufacturability of PCBs.

Figure 7 shows a partial EXPRESS-G diagram of cutting tool data for a drill (Jurrens et al., 1996). Each rectangular box represents an object or entity of interest. Thick lines connecting the entities indicate a super-type and sub-type relationship that represents inheritance of attributes. Solid circles indicate the cardinality of the inter-entity and entity-attribute relationships. Dashed rectangular boxes denote a relationship with entities modeled in another schema. Many of the attributes shown are relevant to assessing the manufacturability of a design, such as cost, drill material, and cutting diameter. However, DFM evaluation requires additional information as contained in the manufacturing process capability model. Tolerance and surface finish information is necessary for proper evaluation; for example, drilling alone may not be sufficient and a secondary reaming operation may also be necessary for achieving fine finishes.

A portion of the EXPRESS-G manufacturing process capability model for hole-making is presented in Figure 8. Note that the hole-making capability is described independently of the process used to produce the holes, e.g. drilling or punching. This is appropriate since the designer’s concern is design features and the ability to achieve them and not necessarily the mechanism.

To demonstrate the interactions between product model and manufacturing model at each stage of the product realization process consider the following example. A product model specifies fifty 0.230 cm (0.090 inch) diameter holes, ten 0.318 cm (0.125 inch) diameter holes, and fifty 0.254 cm (0.100 inch) diameter holes. The product material is an epoxy, FR4 and is 0.356 cm (0.140 inch) thick. Of the many steps in fabricating PCBs, in concentrating on hole-making, the high level process planning system would determine that there exist two alternative process flows to produce the holes: drilling or punching. Cleaner holes are produced by drilling but faster production rates are possible with punching. This information is contained at the factory level of the MPC. The next DFM task would extract additional information from the product model concerning required tolerances and surface finish of each hole. Each hole is individually checked with the diameter attribute values from the MR model to find the drill size. Then related tolerance capabilities from the MPC model are compared to the product requirements. Likewise, a similar evaluation could be performed for punching. An additional DFM concern during the next stage may be the possibility of tool chatter. Such information is at a more detailed level than the information models of Figures 7 and Figure 8. A process simulation or analytical model is required to determine if tool chatter for the particular product will occur using a given drill. An analytical model may also be used at this point to estimate tool wear and thus provide useful cost information.

Although this is a relatively simple problem, it serves to illustrate how the architecture and standard manufacturing model would support information management of disparate applications in accessing relevant information for DFM.

5. CONCLUSION

The issues regarding the current global competitive environment were reviewed within the context of the new manufacturing paradigm, called the virtual enterprise. The virtual enterprise poses many new challenging tasks for product development and this paper concentrated on the design-for-manufacturing activity. Information technology has become an integral part of communication in virtual enterprises. Yet, these applications have been developed separately, have proprietary internal representations, and consequently, may even aggravate collaboration during DFM instead of promoting it. Information management is greatly facilitated by standard product models; we also strongly advocate standard manufacturing process models to enhance information sharing between organizations. DFM is performed at various abstraction levels by comparing design requirements, specifications, and features versus manufacturing process capability models. Little work has been performed to categorize the DFM tasks, their chronological order, correspondence to the design function, and their information requirements. Prior modeling activity was mainly limited to modeling the manufacturing resources. Yet, it is the behavior of these resources, i.e. their capabilities, that is necessary to the performance of DFM. Information models are appropriate for much of the higher level reasoning tasks but for specific evaluations greater detailed knowledge contained in analytical and simulation models is required.

The manufacturing model proposed here addresses the issues and requirements raised concerning management of DFM information. The STEP modeling language EXPRESS enables the creation of a neutral information format for easy exchange of manufacturing process capability information. It is envisioned that DFM applications among other applications would access the manufacturing model just as CAD systems are being built to exchange STEP file format. Thus, application developers would only need to build translators to and from the neutral manufacturing model. Many of the existing architectures and those under development such as agent-based are able to realize the benefits of a neutral file format for the exchange of manufacturing process capability information. Companies can protect proprietary processes and methods while still participating in information exchange by maintaining the process capability information in a separate schema. Multiple abstraction levels are supported by the model through the four level model hierarchy. A standard manufacturing model has benefits beyond DFM. It is a requirement to support information management within a virtual organization. Moreover, such a model would support scheduling, design of flexible manufacturing systems, control architectures, facility layout, and computer integrated manufacturing in general.

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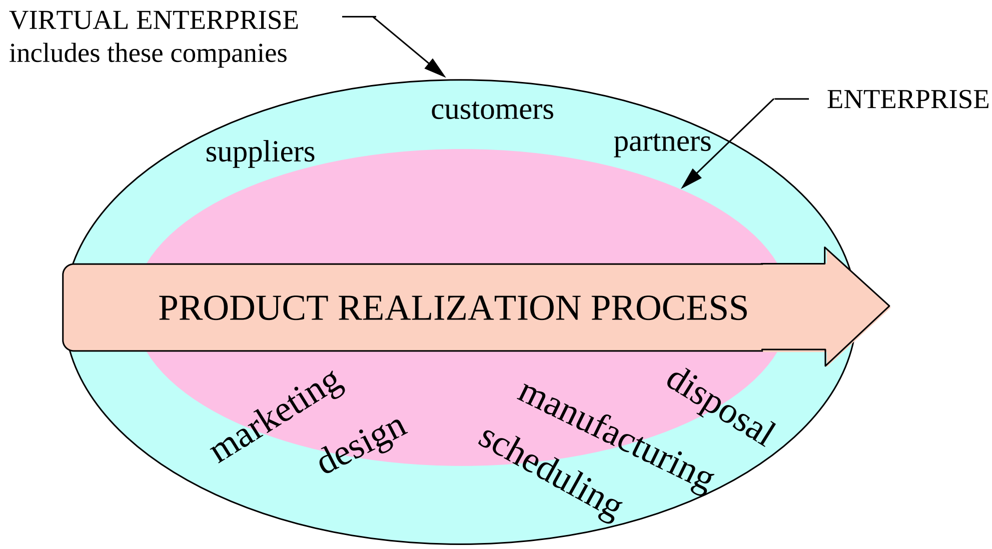

Figure 1. Virtual enterprise model

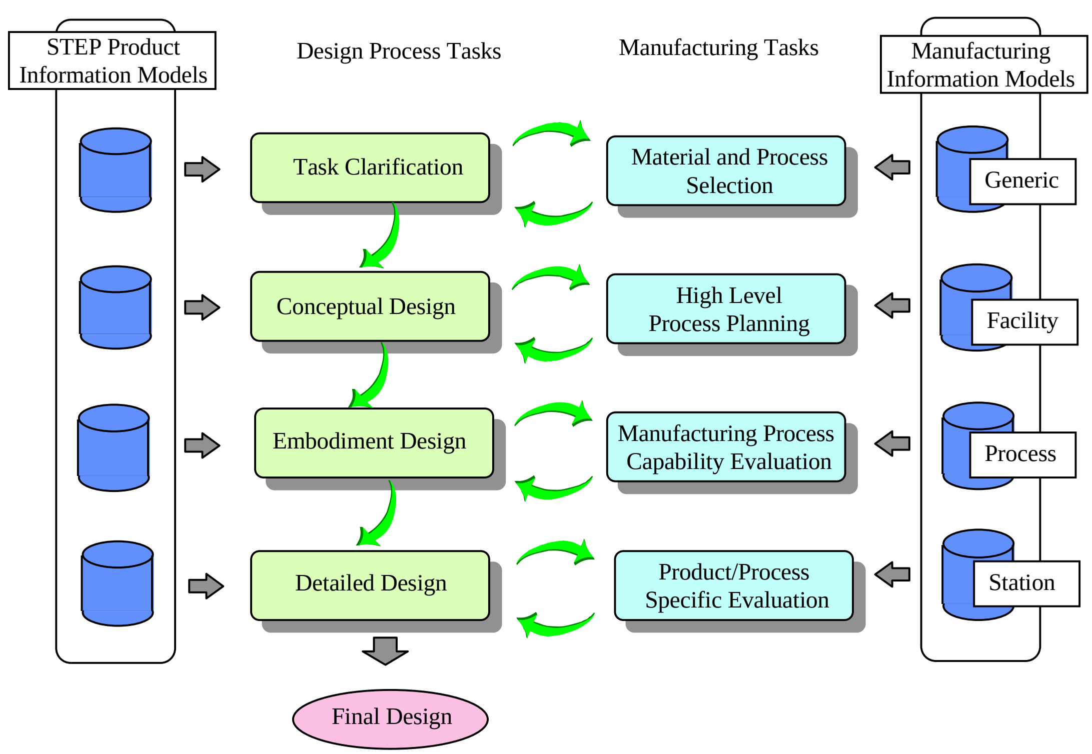

Figure 2. Information model support for design-for-manufacturing

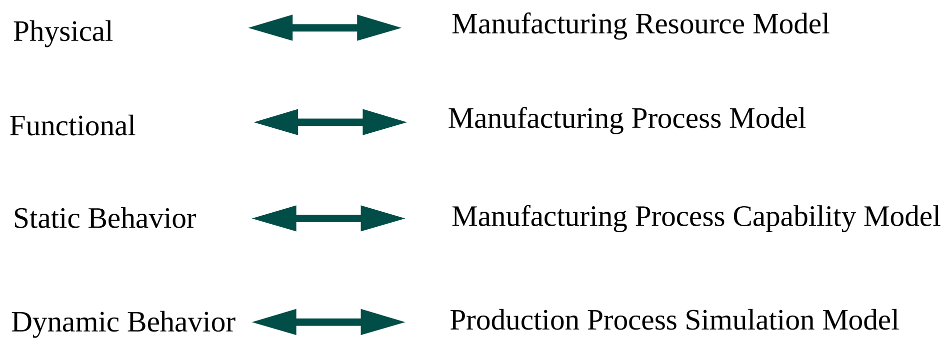

Figure 3. Mapping information characterization to Manufacturing Model

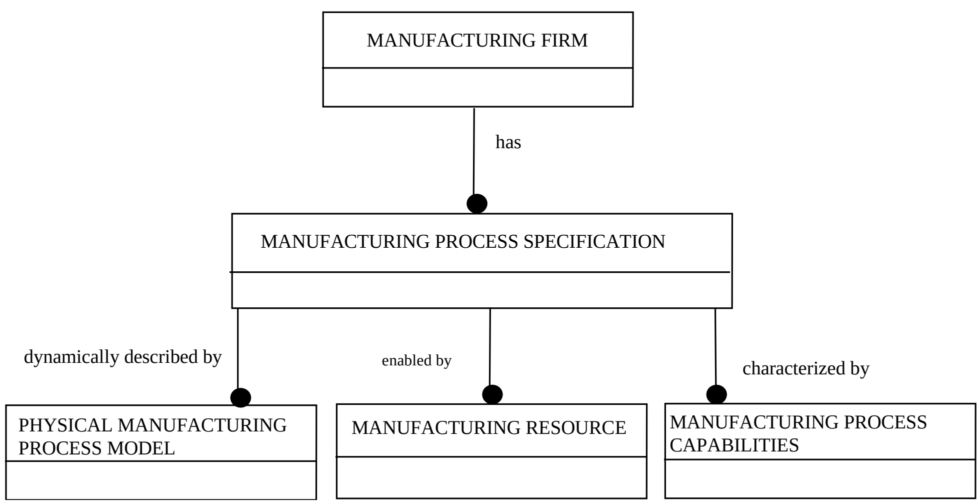

Figure 4. Schema level description of Manufacturing Model

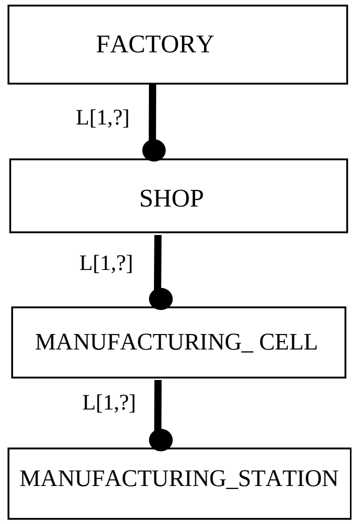

Figure 5. Manufacturing model hierarchy

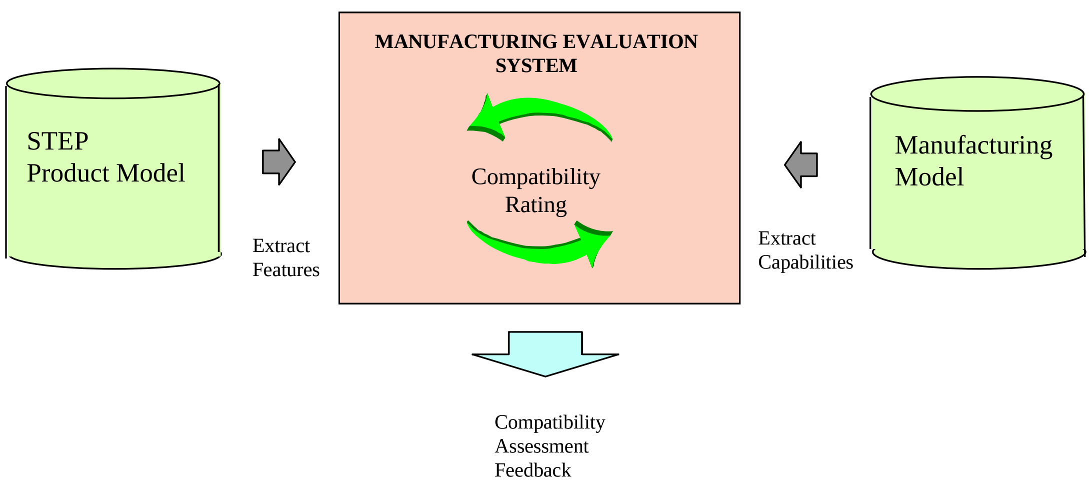

Figure 6. Manufacturing evaluation system architecture

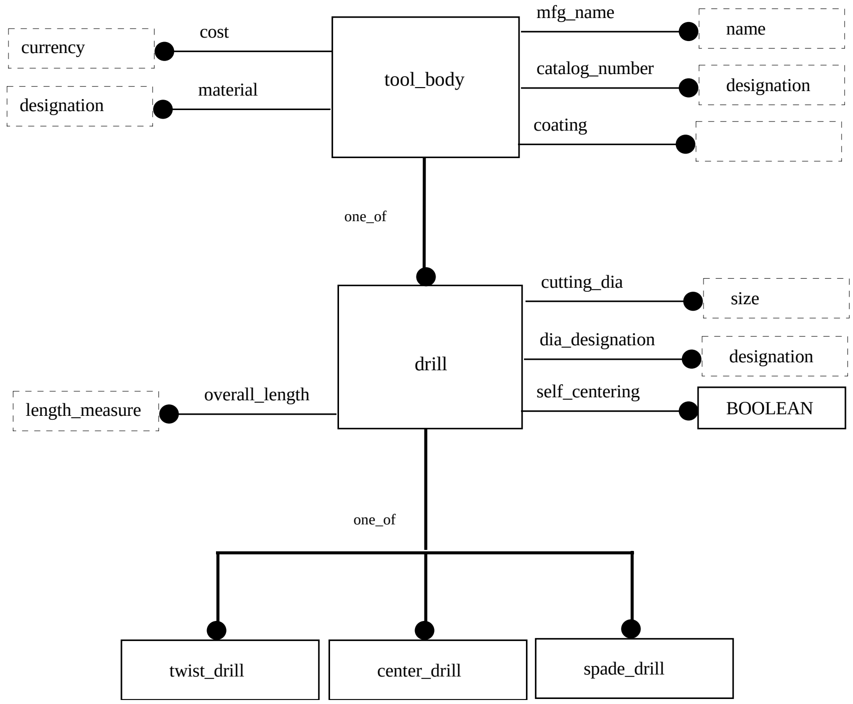

Figure 7. Partial EXPRESS-G diagram of manufacturing resource model for cutting tool data (Jurrens et al., 1996)

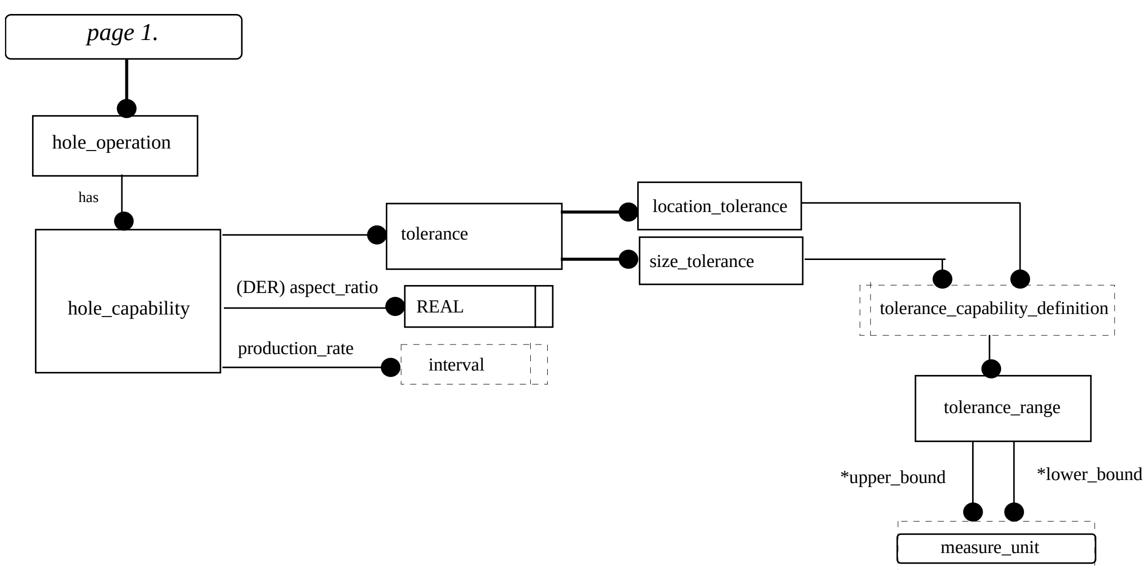

Figure 8. Partial EXPRESS-G diagram of hole-making process capability model