Formation Of An Electronics Manufacturing Supply Chain Via Information Models

Ronald E. Giachetti
Department of Industrial and Systems Engineering
Florida International University
Miami, FL 33174

Abstract

The agile electronics manufacturing enterprise must rapidly develop new products by close interaction with their supplier network. Design for manufacturing must occur in this extended and distributed enterprise across traditional organizational boundaries. This paper proposes the use of information models to support this activity. A manufacturing model is built using the EXPRESS information modeling language to model the manufacturing process capabilities of the vendors. Compatibility ratings based on possibility theory search the vendor's information models to compare the product profile requirements and the manufacturing process capabilities. A multi-attribute decision model is invoked to weigh the importance of the selection criteria and aggregate the multiple compatibility ratings into a single metric that ranks the vendors according to their ability to manufacturing the product. The system provides feedback exposing why certain compatibility ratings were assigned. The contribution of this paper is to model the information requirement of an agile enterprise and provide an approach for dynamically selecting vendors.

Keywords*: Agile manufacturing, supply chain management, concurrent engineering, design for manufacturing, vendor selection, multi-attribute decision making.*

Introduction

Electronics are appearing in markets that were primarily mechanical less than a decade ago. Their emergence is due to increasing market demand for more features, product variation, and increased expertise in designing and fabricating electronic products. Electronics are the driving technology that support many of the "smart" products that are introduced to the market. The automotive industry is a growing consumer of electronics that are being used to control virtually every aspect of driving [Fine et al., 1996]. The household appliance industry now uses electronics for control and diagnostics, and feature enhancements, etc. This is in addition to the traditional markets in computers, electronics entertainment, and telecommunications. As electronics become more prevalent in all products the ability to form partnerships with electronics companies is particularly important. Companies are seeking partners so that they can concentrate on their core competencies. The reason is that no single company can provide the marketing, design, manufacturing and distribution because the product's complexity has grown so much. One of the business realities and factors underlying US PWB manufacturing growth is a continuing trend over the past 20 years for original equipment manufacturers (OEMs) to purchase PWBs from qualified suppliers. Companies are concentrating more on their core competencies and seek vendor partnerships for key inputs. The percent of OEMs producing their own boards (captives) has dropped from 60% in 1979 to 15% in 1995. Likewise, the percent of PWBs produced by independent manufacturers has increased from 40% to 85% today [IPC 1996]. Similar trends are also occurring in Europe as reported by de Graff et al., (1997). As a result companies must now incorporate fuller consideration of suppliers in the product realization process. This is referred to as the extended enterprise and is graphically show in Figure 1.

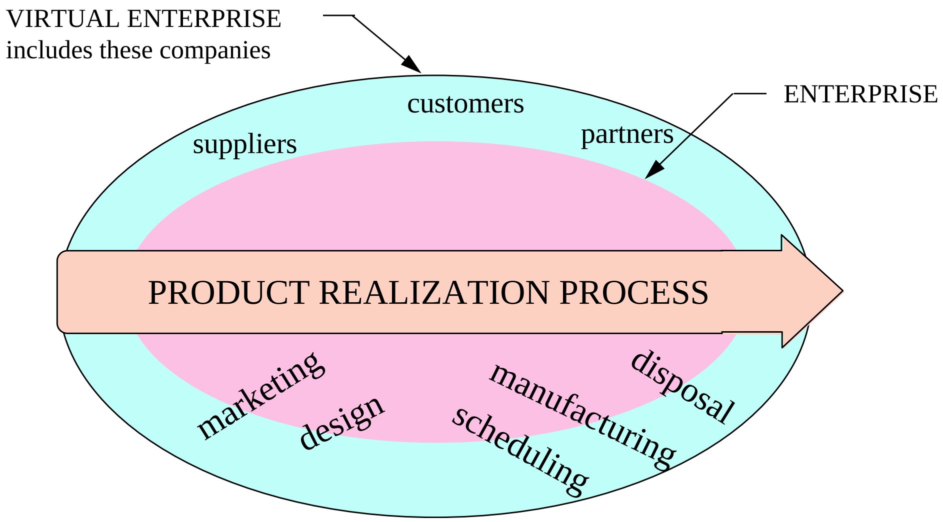

Figure 1. Extended Enterprise Model

Design for Manufacturing in a Distributed Enterprise

Evaluation of the manufacturability of a design concept is usually performed within an organization. Cross organizational evaluation of capabilities posses dynamic and formidable problems. As reported by de Graff and Kornelius (1997) many customers are unwilling to modify procurement and supply chain management policies to facilitate concurrent engineering. A possible solution to this deadlock situation is the use of standard enterprise models for exchanging information. Then the customer is not required to change its systems for a particular vendor and actually the standardization would increase the potential PCB supplier base.

The optimal vendor for a particular order depends on the compatibility between the product profile requirements and the potential vendors manufacturing capabilities. The approach is to evaluate a design against the vendor's capability to meet the product profile requirements. Each comparison is made to obtain a set of compatibility ratings that are aggregated into a single measure of the company's ability to manufacture the product.

This paper focuses on the vendor selection problem for printed circuit boards. Design for manufacturing techniques have been built under the assumption that a single enterprise controls the design and manufacturing. In the extended enterprise DFM must occur across what were traditional company boundaries. A model based approach is advocated such that the vendors make their manufacturing process capabilities available. Then the company performs compatibility evaluation between the product profile requirements and the vendor's manufacturing capabilities. The selection parameters are identified and a possibility measure introduced for obtaining the compatibility ratings. An overall metric is used to rank the vendors according to their ability to deliver the required quantity of product on the due date at a desired price. Following vendor selection DFM can be performed and contract negotiations begun with the selected vendor.

Related Work

Candadai *et al.* (1996) are exploring the application of group technology to select vendors, whereby, each vendor has a set of products they can manufacture and the selection procedure is to classify the current design and find vendors with a matching GT coded product in the set of products they manufacture. In the area of electronics manufacturing a potential drawback of GT approach is the rapid introduction of new technologies and the subsequent ability to update the GT code to reflect the new developments.

Research in modeling manufacturing processes to support DFM has been conducted by Ellis et al., (19xx) and Molina et al., (19xx). They concentrated on modeling machining and injection molding processes to include manufacturing processes, resources, and strategies. The concept of capabilities and methodologies for incorporating the decision making activity in the context addressed here was not explored.

Whitney et al., (1996) studied the forming of virtual partnerships in the automotive and aircraft industries. They call the supplier networks "webs" to reflect the complexity of many tiered suppliers that must quickly form partnerships and interact to bring a new product to market. Trends in the electronics industry that are paralleling these developments include; greater utilization of surface mount technology, mixed technology boards, specialization in certain manufacturing processes, and increased use of more expensive components and materials.

Extensive work has been conducted on the topic of enterprise modeling. In Europe the CIM-OSA cube is a reference architecture used to describe the enterprise throughout the life cycle and is a European pre-standard for enterprise integration (Vernadat, 1992). Three abstraction levels, three model derivations, and four views are supported by this architecture.

Information Model Support for DFM

Extensive research and development has focused on standards for product models. The STEP standard for product modeling is regarded as one of the most ambitious international standards initiative ever conducted (ISO 1995). To some extent sharing process information, especially process capability information, is critical to the operation of manufacturing 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 proprietary models that cannot be utilized by other applications. Modeling activity for manufacturing resources has been conducted by Jurrens et al, (1995) and Kjellberg and Bohlin (1996). 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, Giachetti and Jurrens (1997) and Weston (1996) have individually expressed the need for multiple modeling perspectives of manufacturing systems.

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.
3. A rigorous definition enables conformance measurement.
4. Formal models can be used to develop standards to realize the benefits brought about by standardization.

This project is limited to examination of models to support manufacturing systems. We focus on *manufacturing resources* and their combination to achieve certain *manufacturing process capabilities*. The manufacturing resources are the tools, fixtures, and machines that are combined and arranged into a *manufacturing process* for the fabricating of a product. A manufacturing process capability is the feature producing ability of a manufacturing process to some level of accuracy and quality. Accordingly, we are interested in the non time-varying properties of a manufacturing systems and therefore temporal models as used in simulation studies and scheduling are not reviewed, although it is believed underlying manufacturing resource and capability models will support these activities.

Vendor Selection Decision Factors

Selecting vendors has been studied by xxxx and xxxx. The following criteria are generally used when selecting vendors.

Vendor selection must be performed based on strategic criteria as well as the more traditional criteria.

** This is an important section and must be fully developed. ***

Selection of suppliers should be based on strategic decisions and not cost as was historically performed in the United States. Many authors have reported the need to have greater supplier involvement in product development (See Dyer 1997; Wijnstra and van Stekelenborg, 1996).

Business Factors

The size of the company, is it a competitor, geographical location.

Collaborative Factors

Supplier's willingness to participate in new product development, make cost reduction suggestions.

Technological Factors

These factors include; board material, number of layers, board type, board dimensions, copper weight, hole drilling capability, track dimension capability.

minimum dielectric thickness, maximum finished board thickness, copper thickness, conductor width, spacing, drill hole diameter, minimum land size, hole aspect ratio, location tolerances, surface finish.

Production Factors

These factors include production volume capability, lead time capability.

Financial Factors

These factors are concerned with the financial strength of the company.

Quality Factors

Quality factors include statistical process capabilities, yield, certification.

Support Factors

These capabilities include ability to provide CAD support, reliability, scheduling.

Information Model Support

Two information models are required to support the vendor selection problem; a customer maintained model and a supplier maintained model. The reason two models are required is that some of the selection criteria, related to the supplier's past performance, can only be maintained at the prime's location. This function is typically delegated to the purchasing department within an orgainization. An example of this criteria is the supplier's readiness to cooperate or the number of suggestions for improvement as reportedly employed at Chrysler (Dyer, 1997). This model is termed the Performance Model. The model maintained by the supplier is the

Manufacturing Model. This model contains the manufacturing process capabilities of the supplier as well as financial standing, geographic location, and quality program.

Performance Model

The performance model provides information gathered by company concerning the supplier's past performance. This model represents the internal view of the supplier's performance. Much of the information is of a qualitative and fuzzy nature, such that the supplier's willingness to cooperate as 'good'. A partial performance model is shown in Figure X. It is the Performance Model that identifies companies for strategic partnerships. A company can reward or punish suppliers based on the information contained on the Performance Model. The Performance Model is used to classify suppliers based on their performance. It provides a negotiating tool such that a company can inform a supplier that it is not performing adequately and business will be directed to its competitors unless it improves.

PWB Vendor Manufacturing Model

The manufacturing model must provide information sufficient for evaluating a vendor's compatibility in the domain of the selection criteria identified in the proceeding section. The manufacturing capabilities are represented in the vendor's manufacturing model. The manufacturing model shown in Figure 4 comprises schema level models of the vendor's resources, processes, and capabilities.

Information modeling is the specification of the entities, their properties, behavior, and how they interact with each other within a system (Schenk and Wilson, 1995). In the case of manufacturing systems, the eventual goal is to build an information systems based on this model. The information system supports the activities of the manufacturing enterprise in fulfilling its mission. EXPRESS is used to model the information required for manufacturing process capabilities. EXPRESS is an object oriented modeling language developed by the international standards community for the purpose of information modeling especially with respect to STEP for product modeling (Schenk and Wilson 1995). EXPRESS has both a lexical and graphical representation (EXPRESS-G) scheme. The notation used for EXPRESS-G modeling is included in an Appendix.

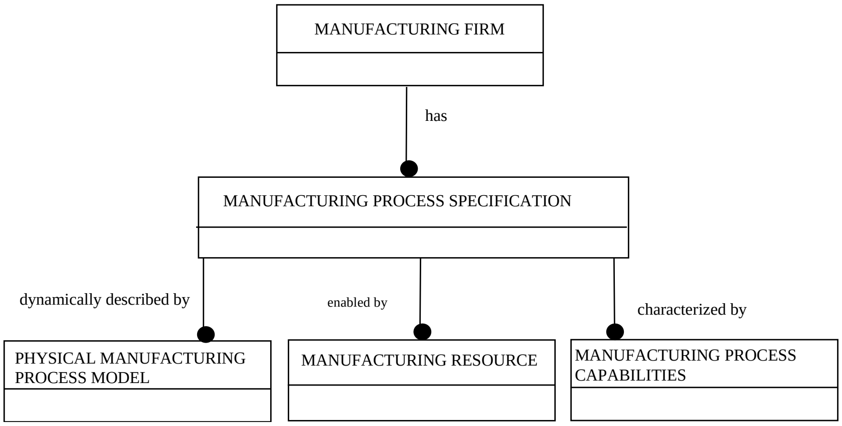

Figure 4. Schema level diagram of PCB Manufacturing Model

PCB Manufacturing Process

The printed circuit board (PCB) manufacturing process depends on the materials used, number of layers, and other requirements, however, the sequence shown in Figure X is generally followed. Each step of the sequence corresponds to a manufacturing process that is represented in the Manufacturing Model.

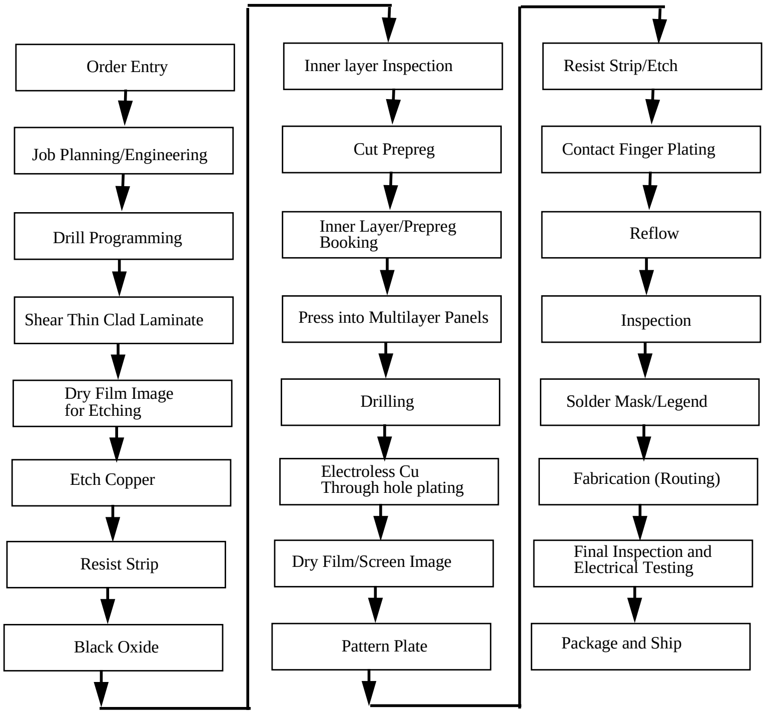

Figure X. Process Flow of PCB Fabrication (Clark, 1985)

Manufacturing Process Capability Representation

A *manufacturing process capability* is the physical ability of a manufacturing process to perform one or more feature-generating operations to some level of accuracy and precision (Algeo, 1994). Manufacturing process capabilities are determined by manufacturing resource factors, process parameters, work part material factors and geometry factors. The *manufacturing resources* are the machines, tool holders, and tools used to achieve process capabilities (Jurrens *et al.*, 1995). Work part material include factors such as substrate material used and geometry factors include factors such as through hole spacing.

An important aspect of the model is the separation of the resources and activities used to attain a process capability and the capability itself. The separation is necessary since companies do not want to unnecessarily divulge proprietary information. PCB manufacturers are more than willing to advertise how many layers they can manufacturing or the tolerances they can achieve on plating operators but they do not want to let their competitors discover their secrets for accomplishing these capabilities. The reason is that these companies compete based on their core competency of manufacturing and product delivery. Some researchers stipulate that the closer interaction within the supply chain requires information sharing at all levels (See Shunk et al., 1997). While this may be a laudable goal it does not harmonize with current business realities. A risk of full disclosure of business and technical practices may enable customers to decide that they could fabricate the PCB.

A *de facto* standard for organizing manufacturing facilities is the four level hierarchy proposed by Mclean and Jones (19xx). The four levels are: factory level, shop level, work cell level, and machine level. The factory level representation is for the manufacturing capabilities of the entire factory and the machine level specific representation is for the capabilities of a single machine. This is an aggregation type relationship whereby the capabilities of the individual machines in a factory combine to determine the overall factory level manufacturing capabilities.

Manufacturing process capability information is commonly presented as characteristic applications and atypical applications. This is illustrated in Groover (1996) for the drill diameter capability. Most applications range between 0.15 mm and 1.27 mm, but some past applications requiring 0.12 mm diameter holes have been accomplished. Generally, products with features near the boundaries of a process's capability are more difficult to fabricate than features well within the process's capability. These two ranges specify a possibility profile of the process capability. It is more desirable to stay within the conservative interval since the designed artifact is better guaranteed of meeting specification. The possibility profile rates the degree of difficulty and thus expense in terms of product yield, quality, and broken drill bits. Smaller holes are less desirable from manufacturer's perspective.

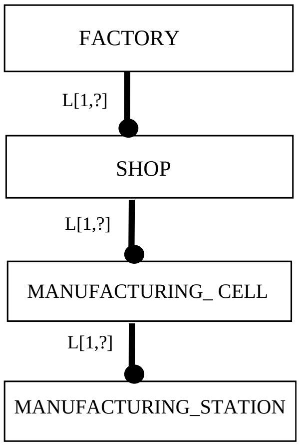

Figure X. Manufacturing Model Hierarchy

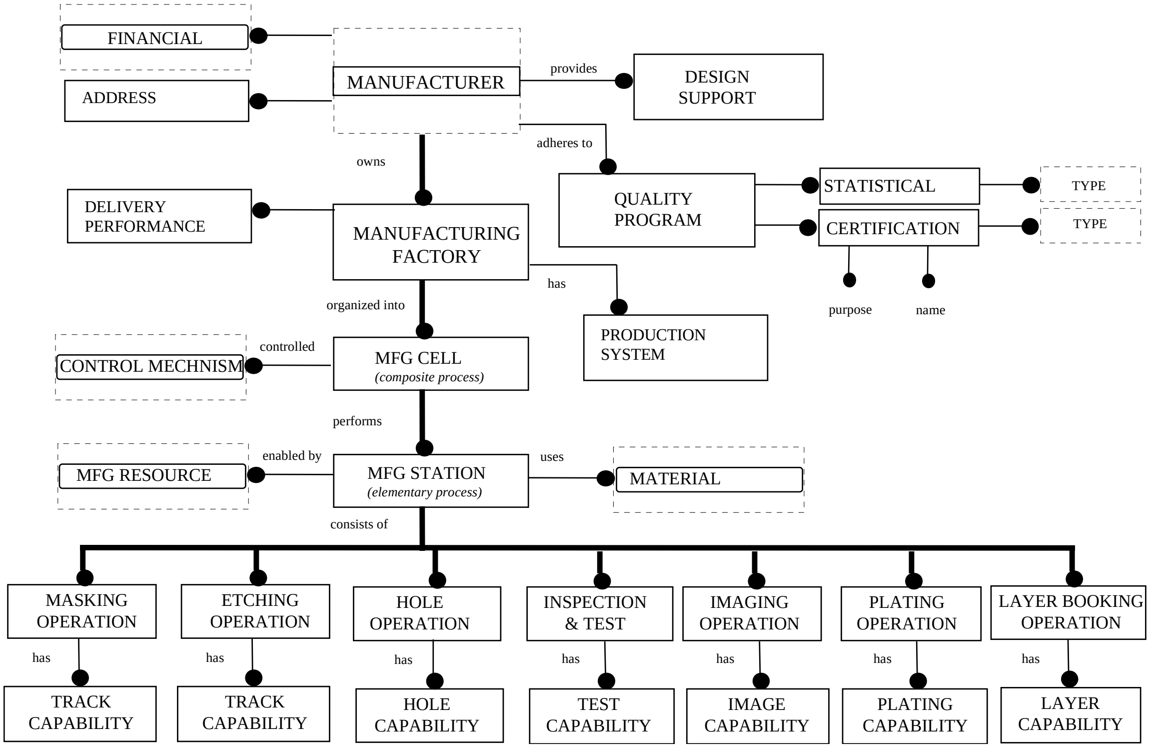

Figure x. Partial EXPRESS-G diagram of manufacturing process capability model

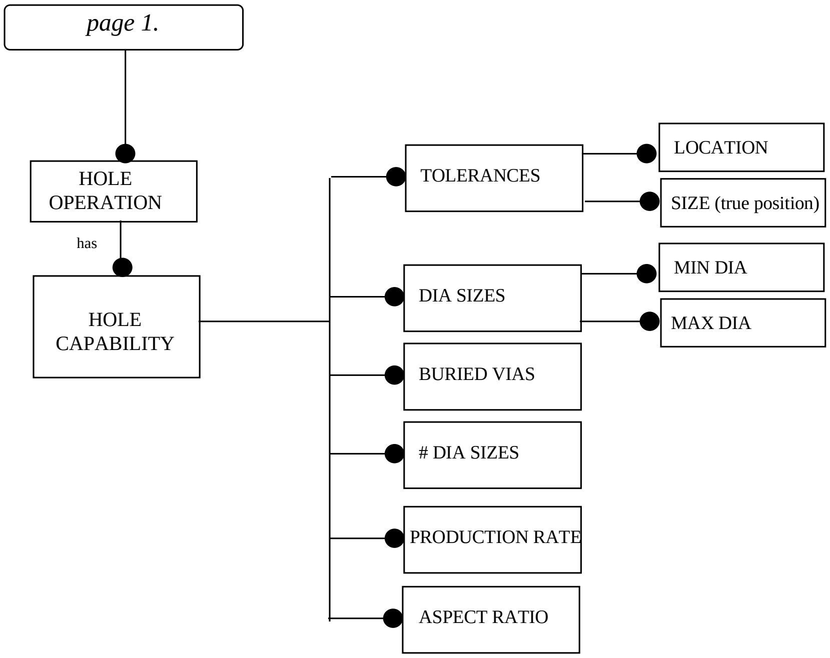

Figure X. Partial EXPRESS-G diagram of hole making process capability

The mapping from the process sequence to the overall manufacturing model and then to the capabilities of a specific process are illustrated. Drilling is one of the steps in PCB fabrication. The drilling step in the process sequence maps to the hole making operation at the lowest level in Figure X. The hole making operation in turn has certain capabilities. Figure X shows a partial breakdown of the process capabilities with respect to producing holes. Hole production capability includes tolerances on location and size, minimum and maximum diameters possible, whether buried vias are possible, the number of different diameters supported without requiring additional setups, the production rate, and the length-to-diameter ratio that is possible. These capabilities are relevant to the vendor selection criteria outlined in Section x. Specifically, the technological factors, the production factors, and quality factors are covered by the hole making process capabilities. A complete mapping from decision criteria to the manufacturing model is shown in Figure X.

FUZZY OBJECT

Often, the data is vague , incomplete, imprecise, uncertain, or all of these. The object oriented modeling paradigm allows for the creation of special data types to represent this imprecision. Giachetti (1997) used a trapezoidal representation for process capabilities for process selection with a relational database. Eversheim et al., (1997) specified a fuzzy object using EXPRESS which will be adopted here. This object would be available to the other objects within the model.

Mapping from Process Model to Information Model

The process model is mapped into the information model.

System Selection Strategy

The objective is to select possible vendors and rank them according to the compatibility of the product profile requirements and their manufacturing process capabilities. Each decision criteria is assessed for each vendor and given a *possibilistic compatibility rating* (PCR). The PCR assesses to what degree the vendor's capabilities are consistent with the product requirements. These criteria are weighed and aggregated into a single metric for comparison with the other vendors.

Vendor compatibility assessment is accomplished via determining PCR on the vendor's manufacturing model. PCR is a flexible rating scheme that supports the incorporation of decision maker's preference, data imprecision, and criteria importance into the selection process. The foundation of PCR is possibility theory (Dubois and Prade, 1988) and is expounded upon in the next section.

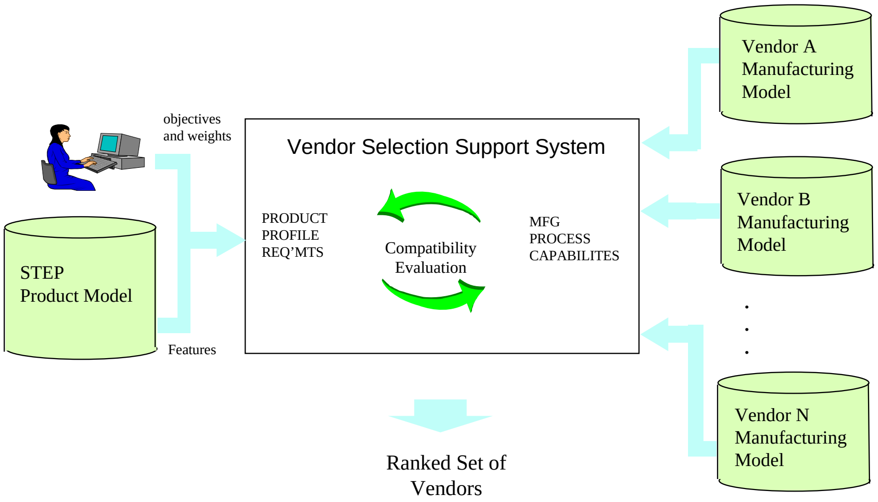

Figure 5. System Architecture

Vendor's Capabilities Compatibility Evaluation

The possibilistic compatibility rating is composed of the possibility and necessity measures which assess the ability of the vendor's manufacturing process to produce the PCB defined by the product profile requirements.

Possibility assesses to what extent the vendor satisfies the product profile requirement, or equivalently the extent the vendor's manufacturing model is consistent with $a \circ \Theta$. The degree that attribute A of the manufacturing model's entity possibly satisfies the product profile requirement defined by $a \circ \Theta$ is,

$$\Pi\left(a \circ \Theta \middle| A_k(d)\right) = \sup_{d \in D} \min\left(\mu_{a \circ \Theta}(d), \mu_{A_k}(d)\right) \tag{3}$$

where D is the domain of attribute A_k. The vertical bar "|" denotes a separation between the requirement and the manufacturing model attribute value. "*Sup*" is the *supremum* or maximal value over a continuous function.

Necessity assesses to what extent the material certainly satisfies the query. It performs this by measuring the impossibility of the opposite event. The opposite event is the complement, $1-\mu_{A_k(d)}$ of the material attribute. The necessity of material record k certainly satisfying the product profile requirement is defined with the complement of μ_A as,

$$\mathrm{N}\left(a \circ \Theta \middle| A(d)\right) = \inf_{d \in D} \max\left(\mu_{a \circ \Theta}(d), 1-\mu_A(d)\right) \tag{4}$$

"Inf" is the infimum oor minimum value over a continuous function. Calculation of the possibility and necessity measures are shown graphically in Figure 4.

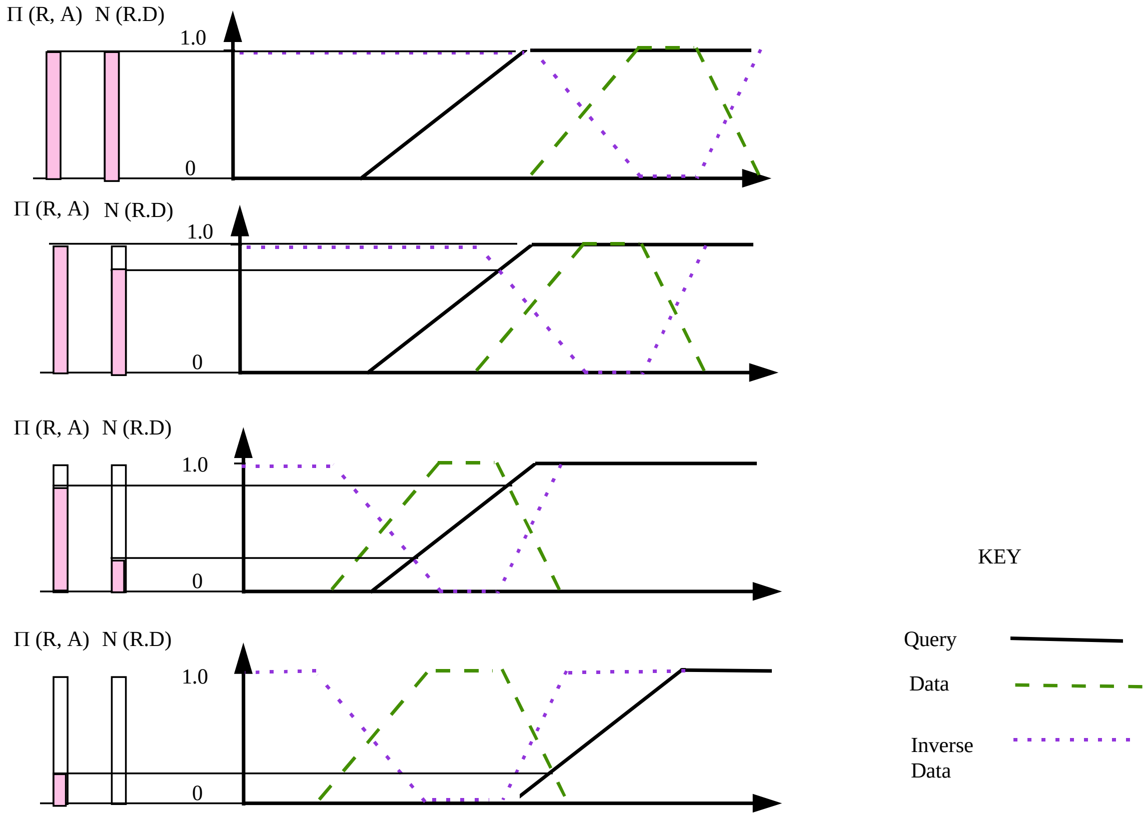

Figure X. Possibility and necessity measures in querying database

The *Poss* and *Necc* both evaluate to the interval [0, 1]. The higher the value the more compatible. The two values obtained from the possibility measure (3) and the necessity measure (4) are combined using a factor β that represents the level of optimism or pessimism of the decision maker (Young, *et al*., 1996).

$$\mu_{ik} = \frac{\beta \text{Poss}\left(a \,\text{o}\Theta \middle| A_k(d)\right) + (1-\beta)\text{Necc}\left(a \,\text{o}\Theta \middle| A_k(d)\right)}{2} \tag{5}$$

An optimistic decision maker would use β = 1, and the other extreme, β = 0 when the decision maker is pessimistic. A balance between these two extremes is attained for $\beta \in (0, 1)$. The possibility and necessity measures are determined between each material requirement *i* and each material alternative *k* to obtain a compatibility rating μ_{ik}. Each material alternative *k* will then have a vector of compatibility ratings $\langle \mu_{1k}, \ldots, \mu_{nk} \rangle$ for the *n* requirements.

Necessity is a better measure of compatibility.

AGGREGATION OF SELECTION OBJECTIVES

The previous section determined a vector of compatibility ratings for each alternative that must be aggregated into a single metric to determine an overall joint compatibility rating for that alternative. The product profile is comprised of requirements which must be exactly met and requirements which are flexible. This breakup of requirements has been observed by Dubois, *et al*., (1995) in scheduling and by Otto and Antonsson (1994) in design. The hard requirements cannot be relaxed, they must be strictly satisfied. Otto and Antonsson (1994) reviewed different methods of aggregating imprecise attributes for mechanical design and found that design problems require the additional axiom of annihilation to account for hard requirements. The axiom of annihilation states that when one compatibility rating, denoted by expression (5), evaluates to zero then no trade-off occurs and the entire alternative is not compatible. A geometric mean is used to aggregate the individual ratings. This method obeys the aggregation axioms of monotonicity, continuity, symmetry, idempotent, boundary, and annihilation (Klir and Yuan, 1995). For *n* criteria the aggregate is,

$$h(\mu_1, \mu_2, \ldots, \mu_n) = \left(\prod_{i=1}^{n} \mu_i \right)^{\frac{1}{n}} \tag{10}$$

This aggregate was also separately developed by Yu, *et al*., (1993) based on empirical studies with engineers in industry who wanted a metric that evaluated to zero when one of the objectives is not satisfied. Expression (10) is termed a *compensatory* operator since higher satisfaction of one objective will partially offset a lower satisfaction of another objective. This aggregate treats all the objectives as if they are of equal importance. Often this is not the case and decision makers desire to assign weights to represent the importance of one objective relative to another. The incorporation of weights into the decision making analysis using this metric was first examined by Yager (1977). The geometric mean with weights is,

$$h(\mu_1, \mu_2, \ldots, \mu_n) = \prod_{i=1}^{n} \mu_i^{r_i} \tag{11}$$

The importance or weights of each objective are specified using linguistic terms of importance. The importance of an objective is relative to the other objectives being considered and for this reason the weights must be normalized.

The user assigned weight is through one of five linguistic terms. These terms are: “very important”, “important”, “medium importance”, “low importance”, and “very low importance”. The user assigned weights are represented by a numeric rank w_i for objective *i*. The normalized rank *r* for *n* objectives is,

$$r = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{12}$$

Expression (11) is used to determine a manufacturing compatibility rating as $\mu_{mfg} = h(\mu_1, \ldots, \mu_m)$ and provides a partially ordered set of compatible material and manufacturing process alternatives.

Design for Robustness with respect to Vendors

Consider taking top four vendor choices and aggregating their compatibilities to create an abstract manufacturing capability model. Then the design for manufacturing proceeds with these aggregated compatibilities forming the manufacturing constraints. Then the company may break up the job between the vendors. This provides robustness with respect to vendor selection since all the vendor’s capabilities were utilized to guide the design it should be compatible with any of their processes.

Illustrative Example

Conclusion

Three contributions are:
Formulation of the vendor selection problem for PCB
Creation of manufacturing model for PCB

Application of Possibilistic Compatibility Selection (PCS) for identifying preferred vendors.
Design for manufacturing across organizational boundaries.

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