MANUFACTURING PROCESS AND MATERIAL SELECTION DURING CONCEPTUAL DESIGN

Ronald E. Giachetti

Manufacturing Systems Integration Division
National Institute of Standards and Technology
Gaithersburg, MD, 20899
giachett@cme.nist.gov
http://www.nist.gov/msidstaff/giachetti/giachett.htm

ABSTRACT

It is important to consider every possible alternative during the design process since design decisions will determine the feasible manufacturing processes and the final product costs. Determining feasible combinations of material and manufacturing processes during conceptual design is impeded since the requirements and product characteristics are only imprecisely known. It is becoming increasingly clear that the tremendous number of materials and manufacturing processes precludes an iterative single point search for alternatives. This paper presents an integrated material and manufacturing process selection procedure. A set-based approach is proposed where materials and processes are organized into a hierarchy. Sets are used to represent material group properties. A relational algebra capable of supporting imprecise queries on the database is introduced. This method allows the early identification of material and process alternatives. The alternatives are ranked enabling the designer to concentrate on those alternatives that have the greatest potential for balancing the product's functional requirements with the economic concerns realized in manufacturing.

Keywords: Manufacturability evaluation, concurrent engineering, material selection, possibility theory.

INTRODUCTION

The design of a product and its processes must be simultaneously pursued in the competitive markets of today. Some of the most important decisions, those with the greatest effect on overall cost, are made in preliminary engineering design [Whitney, 1988]. In mechanical engineering design, the designed artifact's geometry, material, and manufacturing process are tightly coupled [Dixon, 1986]. Once a certain material is selected, this decision often precludes many manufacturing processes and strongly suggests others. Existing systems tend to make these decisions in isolation, rather than simultaneously considering all the life-cycle issues.

Spending more time on analysis and evaluation during conceptual design has the potential of reducing the overall time-to-market by reducing the number of design changes [Boothroyd *et al.*, 1992]. Furthermore, it is indicated that upwards of 70% of a product's cost is determined during the preliminary design stages [Ullman, 1992]. This is when most of the information is characterized by imprecision. Imprecision is the vague and incomplete description of design requirements and design parameters. Unfortunately, most material selection and manufacturing evaluation systems can only work in a domain of well defined features where the parameters are precisely known. This scenario only exists during the later stages of the design process [Pahl and Beitz, 1988]. Thus, even though evaluation is being performed, it is often a post-design review. At this stage of the design process, designers are pressured to optimize an inferior alternative rather than make large modifications to the product specification. Possibly superior alternatives were eliminated early on due to insufficient analysis and evaluation.

RELATED WORK

Boothroyd, *et al.*, (1992) have studied the problem of selecting material and primary processes during conceptual design. Material selection is performed using three predefined queries at different levels of inclusion: "approximately", "precisely", and "more or less". Process selection is performed using production rules and pattern matching. Dixon and Poli (1995) use a guided iterative search methodology for performing material and manufacturing evaluations throughout the design process. This is a formalized handbook approach that extensively uses charts and tables to evaluate designs and select materials.

Commercial software products exist for the selection of materials when the properties are well defined and the criteria are exact [Ashby, 1992]. However, selection for difficult to quantify criteria, such as corrosion resistance, is more troublesome, and existing techniques are inadequate [Abel, *et al.*, 1994]. The systems also do not provide concurrent evaluation of multiple criteria. Rather a sequential decision making process is adhered to, that does not support trade-off between requirements.

Most existing manufacturing evaluation systems do not integrate the material and process selection task and are post-design review systems which cannot operate with imprecise information. Yet, it is critical to provide material and manufacturing knowledge at early product development stages to ensure that manufacturing concerns are being considered.

INTEGRATED MANUFACTURING PROCESS AND MATERIAL SELECTION

The material and manufacturing process selection is performed early in the product development process. At this stage it is inappropriate to select a single material or process without evaluating all the alternatives. The selection of sets of possible candidate materials and processes allow for greater flexibility in the product development process. The more alternatives, the greater the manufacturing flexibility. This is called "least commitment" [Dixon and Poli, 1995] and a variant is reported to be practiced at Toyota [Ward, *et al.*, 1994]. The strategy proposed here follows this concept by identifying sets of feasible materials and sets of feasible manufacturing processes.

The system architecture is shown in figure 1. There are three primary modules that work together. The material selection module and the process selection module are order independent. Both material first and process first selection schemes are supported. Each module accepts design requirements from the user and outputs a partially ordered set of feasible alternatives that satisfy these requirements. The aggregation module performs a join on the two datasets and ranks the alternatives as to how well they satisfy the product requirements. The ranked feasible material and manufacturing process alternatives are then feed back to the designer.

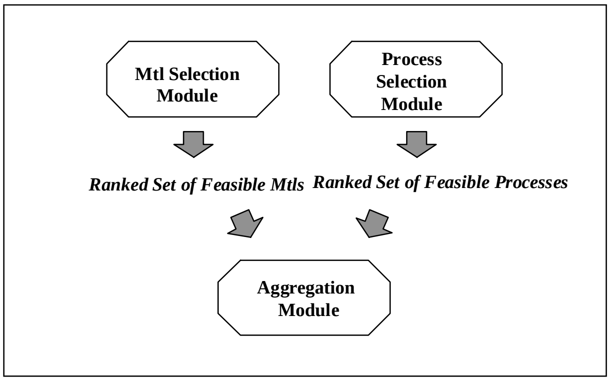


Figure 1. System Architecture

DATA REPRESENTATION

Trapezoidal fuzzy numbers (TrFN) provide a robust representation scheme for both material properties and manufacturing process capabilities. A TrFN is a generalization of a crisp interval that has imprecise boundaries. It is represented by a quadruplet as:

$$\tilde{x} \rightarrow \langle a, b, c, d \rangle \qquad (1)$$

The notation above can be used to represent crisp numbers when all the vertices are equal, *i.e.* $a = b = c = d$. Crisp intervals are represented when $a = b$ and $c = d$. Figure 2 shows a TrFN $\tilde{x} \rightarrow \langle 2.4, 2.5, 2.6, 2.8 \rangle$ Gpa-g/cm^3 representing the stiffness/density ratio of cast aluminum alloys.

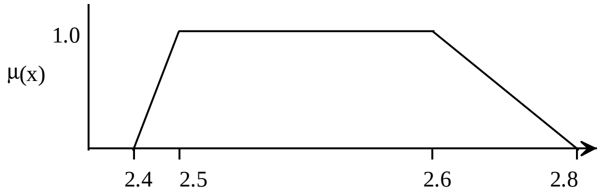


Figure 2. Stiffness/density ratio for cast aluminum alloys

Material properties are characterized by ranges of values. Some difficult to quantify properties are based on linguistic descriptions such as the expert designations of machinability being "good". These linguistic terms divide the unit interval into subsets using expression (1). Other difficulties involve selection based on the environmental characteristics of materials. This is a growing area of concern and many environmental properties still remain ill-defined or undefined. In this scenario, rarely will the designer be able to find a standard material which fully satisfies all of the requirements.

HIERARCHICAL REPRESENTATION OF MATERIALS AND PROCESSES

The number of material alternatives is tremendous (over 100,000), and new materials are continuously being developed [Waterman and Ashby, 1991]. Evaluation of all the potential materials during conceptual design is a computationally intensive task at an unnecessary level of detail. The problem can be significantly reduced by organizing the materials and the processes into sets at different levels of abstraction. The materials are organized into two levels, a group level and a material level. The group level represents the properties of all the materials in that group. Example groups are cast aluminum alloys, magnesium alloys, thermoplastics, etc. The material database stores the information using the set-based representation of expression (1). In each group are specific materials, for example nylon 6/6 is in the thermoplastics group. The material properties of individual materials are also represented with expression (1) although it is likely that they will be more precise.

MATERIAL COMPATIBILITY EVALUATION

The material selection module enables the selection of candidate materials based on the product profile. The material selection module must be able to assess how well the material satisfies each requirement. The materials and their associated properties are stored in a relational database. Product requirements are formulated as queries on the database. Material selection is then the process of querying the database to find materials that satisfy the query. A relational algebra based on a Θ-selection query retrieves the *n*-tuples satisfying a single requirement [Dubois and Prade, 1988]. A selection query on relation *R* with a requirement *a* is denoted by, σ(*R*; *a*). Queries in the domain of material selection are of the form "*A* Θ *a*" where the attribute *A* will be some material property and the requirement *a* is a preference for a particular value. The comparator, $\Theta \in \{<, >\}$ is composed with *a*, and represented by a membership function. The membership function denotes the degree of compatibility between an attribute value and the requirement expressed by the query. It is a mapping from the domain *D* into the interval between 0 and 1.

$$\mu_{a \circ \theta} : D \rightarrow [0,1] \qquad (2)$$

The membership function denotes values in *D* that "strictly satisfy" *i.e.* $\mu(d) = 1$, "strictly violate" *i.e.* $\mu(d) = 0$, and "partially satisfy" *i.e.* $\mu(d) \in (0, 1)$ the query. Consequently, we are able to represent soft and hard requirements.

The Θ-selection query uses possibility theory [Dubois and Prade, 1988] to evaluate the degree to which each material record satisfies the product profile requirement. Two measures, possibility and necessity are used to accomplish the evaluation.

Possibility assesses to what extent the material satisfies the query, or equivalently the extent the material property is consistent with $a \circ \Theta$. The degree that attribute *A* of material record *x* possibly satisfies the requirement defined by $a \circ \Theta$ is,

$$Poss\left(a \circ \Theta \middle| A(x)\right) = \sup_{d \in D} \min\left(\mu_{a \circ \Theta}(d), \mu_A(d)\right) \qquad (3)$$

where *D* is the domain of attribute *A* and $a \circ \Theta$ is the requirement. Calculation of the possibility measure is shown graphically in Figure 3.

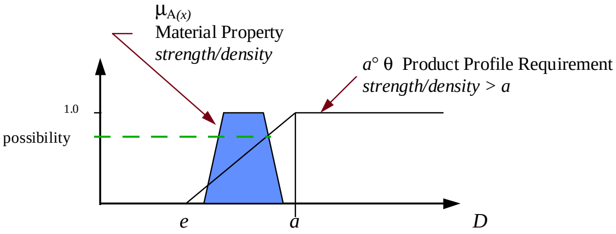


Figure 3. Possibility Measure of material property *A(x)* under requirement $a \circ \Theta$

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, $1 - \mu_{A(x)}$ of the material attribute. The necessity of material record *x* certainly satisfying the requirement is defined with the complement of μ_A as,

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

Calculation of the necessity measure is shown graphically in Figure 4.

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].

$$\mu_{mtl} = \frac{\beta Poss\left(a \circ \Theta \middle| A(x)\right) + (1-\beta) Ness\left(a \circ \Theta \middle| A(x)\right)}{2} \qquad (5)$$

An optimistic decision maker would use $\beta = 1$, and the other extreme, $\beta = 0$ when the decision maker is pessimistic. A balance between these two extremes is attained for $\beta \in]0, 1[$.

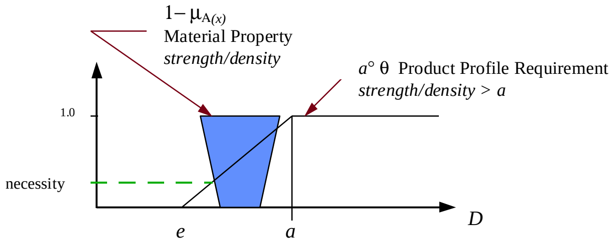


Figure 4. Necessity Measure of material property *A*(*x*) under requirement $a \circ \Theta$

MANUFACTURING PROCESS CAPABILITY EVALUATION

Manufacturing process capability is the ability of the selected process to fabricate the product profile within a certain level of precision and accuracy. The objective is to identify feasible manufacturing processes and rank them according to the compatibility of the product and manufacturing process capabilities.

The process capabilities of many manufacturing processes are not well defined. Information on manufacturing process capabilities is commonly presented as characteristic applications and atypical applications. This is illustrated in Chang and Wysk (1985) for the surface roughness of die casting. Average applications range between 0.8 μm and 1.6 μm, but some less frequent applications range between 0.4 μm and 3.2 μm. Generally, products with features near the boundaries of a process's capability are more difficult to fabricate than features well within the process capabilities. Consequently, manufacturing process capabilities may be represented using expression (1).

Product profile requirements relevant to manufacturing process selection are categorized as geometric, technological, and production properties. Geometric properties include overall dimensions, weight, shape, presence of undercuts, minimum wall thickness and maximum wall thickness. Technological properties include surface finish and tolerances. Production properties include production rate, production volume, and time-to-market. During the early design phases some of these product profile requirements may not be precisely known. For example production volume may only be estimated. It can be represented using expression (1) where *b* and *c* enclose the most likely values, *a* is a lower possible bound and *d* is an upper possible bound.

A compatibility measure between the product profile and a manufacturing process capability is determined using possibility theory [Dubois and Prade, 1988]. Possibility and necessity measures assess the ability of a manufacturing process to produce the part defined by the product profile requirements. Expressions (3) and (4) are rewritten in the context of manufacturing process capability evaluation. The process capability $\tilde{C}$ is possibly compatible with the product profile requirement $\tilde{R}$ to a degree defined as,

$$Poss\left(\tilde{R}\middle|\tilde{C}\right) = \sup_{d \in D} \min\left(\mu_{\tilde{R}}(d), \mu_{\tilde{C}}(d)\right) \qquad (6)$$

Possibility measures the overlap between the product profile requirement and the manufacturing process capability.

Necessity expresses to what extent a manufacturing process capability is certainly compatible with the product profile requirement. The process capability $\tilde{C}$ is necessarily compatible with the product profile requirement $\tilde{R}$ to a degree defined with the complement of $\mu_{\tilde{C}}$ as,

$$Necc\left(\tilde{R}\middle|\tilde{C}\right) = \inf_{d \in D} \max\left(\mu_{\tilde{R}}(d), 1-\mu_{\tilde{C}}(d)\right) \qquad (7)$$

Values from expressions (6) and (7) are combined using expression (5) to obtain a degree of compatibility for a manufacturing process with the product profile requirement.

AGGREGATION OF SELECTION CRITERIA

The previous two sections showed how to determine the degree of compatibility for a single criterion in either material or manufacturing process selection. Material and process selection is a multi-attribute problem which requires an aggregate to determine overall joint satisfaction of these individual requirements. Each μ_i is satisfaction of a single requirement and was determined by expression (5). The likelihood of a material fully satisfying all of the requirements is very small. The aggregation metric is used to rank the overall satisfaction of the materials and the manufacturing processes under all the specified product profile requirements.

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 requirement (expression (5)) evaluates to 0 then no trade-off occurs and the entire alternative is evaluated to 0. 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]. It is,

$$h(\mu_1,\mu_2,\ldots,\mu_n)=\left(\prod_{i=1}^{n}\mu_i\right)^{\frac{1}{n}} \qquad (8)$$

Expression (8) 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 relative 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,

$$h(\mu_1,\mu_2,\ldots,\mu_n)=\prod_{i=1}^{n}\mu_i{}^{r_i} \qquad (9)$$

The importance or weights of each objective are specified using linguistic terms of importance. These terms are: “very important”, “important”, “medium importance”, “low importance”, and “very low 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 weights are represented by a numeric rank w_i for objective i. The normalized rank r for n objectives is,

$$r_i=\frac{w_i}{\sum_{i=1}^{n}w_i} \qquad (10)$$

Expression (9) evaluated for different sets of materials provides a partial order on all the materials being considered. The alternative that has the highest rank is the best candidate based on the product profile requirements.

EXAMPLE

This example shows the use of the relational algebra and aggregation function to select and rank material alternatives. The selection criteria and weights are shown in Figure 5.

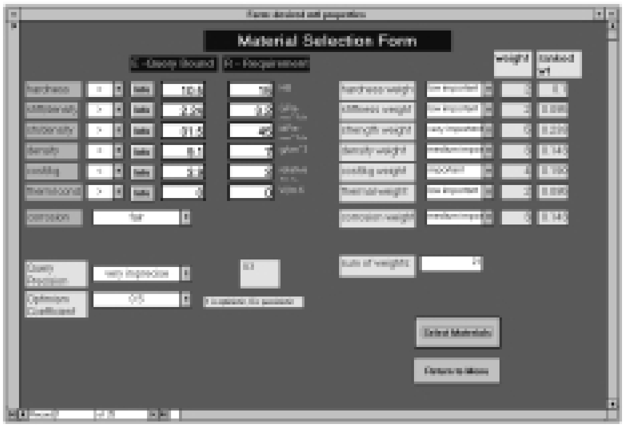
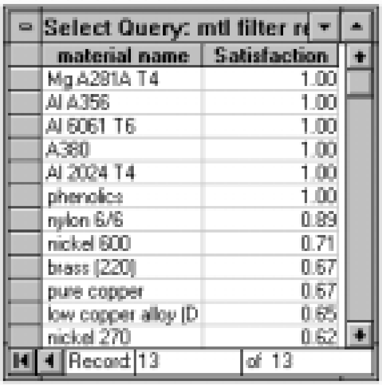


Figure 5. Material Selection Criteria

For example in Figure 5 the first product profile requirement is hardness with θ = “>“ , a = 15, and expression (2) is $\mu_{a\circ\theta}(d)\rightarrow\langle 10.5,15,15,\infty\rangle$. The hardness property of each material is assessed against this product profile requirement using expressions (3), (4), and (5). This provides the compatibility μ_1 for hardness. Similarly each product profile requirement i is assessed to obtain μ_i. Expression (9) is used to obtain an aggregate for each alternative. The aggregate values for the material alternatives are shown in Figure 6. Six of the materials fully satisfy all the requirements and seven materials partially satisfy the requirements. Similar queries would be formulated based on the product profile requirements to select a manufacturing process.

CONCLUSION

Many concurrent engineering and design for manufacturing systems concentrate on speeding information flow between functional groups. The approach described here is to simultaneously explore more manufacturing process and material alternatives using a set-based approach. The problem is formulated as a multi-attribute decision making problem in an imprecise environment. Material properties and manufacturing process capabilities are represented in a relational database. A relational algebra was presented to allow imprecise queries on the database. Compatibility of a process with the product is assessed using possibility theory. The degrees of compatibility for the requirements are aggregated to produce a final ranking. This information presents multiple alternatives satisfying the product profile requirements. This strategy allows a more efficient search of the design space by identifying material and process alternatives early in the design process when it is easier to make design changes.



material name	Satisfaction
Mg A281A T4	1.00
Al A356	1.00
Al 6061 T6	1.00
A380	1.00
Al 2024 T4	1.00
phenolics	1.00
nylon 6/6	0.89
nickel 600	0.71
brass (220)	0.67
pure copper	0.67
low copper alloy (D	0.65
nickel 270	0.62

Record 13 of 13

Figure 6. Material Selection Results

ACKNOWLEDGMENTS

The author gratefully acknowledges the support provided by the National Research Council through a postdoctoral research associateship at NIST.

REFERENCES

Abel, C.A., Edwards, K.L., and Ashby, M.F., (1994). "Materials, processing and the environment in engineering design: the issues," *Materials and Design*, vol. 15, no. 4, pp. 179-193.

Ashby, M.F., (1992). *Material Selection in Mechanical Design*, Pergemon Press, Cambridge, UK, 1992.

Boothroyd, G., Dewhurst, P., and Knight, W., (1992). "Selection of materials and processes for component parts," *Proc. of the 1992 NSF Design and Mfg. Sys Conf*, Atlanta, GA, January 8-10, pp. 255 - 263.

Chang, T.C., and Wysk, R.A., (1985). *An Introduction to Automated Process Planning Systems*, Prentice-Hall, NJ.

Dixon, J.R., and Poli, C., (1995). *Engineering Design and Design for Manufacturing a Structured Approach*, Field Stone Publishers, Conway, MA.

Dixon, J.R., (1986). "Artificial intelligence and design: A mechanical engineering view," *Proceedings AAAI-86*, vol. 2, Philadelphia, PA, August 1986, pp. 872-877.

Dubois, D., Fargier, H., and Prade, H., (1995). "Fuzzy Constraints in Job-Shop Scheduling," *Journal of Intelligent Mfg.*, vol. 6 pp. 215-234.

Dubois, D., and Prade, H., (1988). *Possibility Theory*, Plenum Press, New York.

Klir, G.J., and Yuan, B., (1995). *Fuzzy Sets and Fuzzy Logic*, Prentice Hall, NJ, 1995.

Pahl, G., and Beitz, W., (1988). *Engineering Design*, The Design Council, Springer Verlag, London.

Otto, K.N., and Antonsson, E.K., (1994). "Modeling Imprecision in Product Design", *1994 IEEE Int'l Conf. on Fuzzy Systems*, vol. 1, pp. 346-351.

Ullman, D.G., (1992). *The Mechanical Design Process*, McGraw Hill, New York.

Ward, A.C., Liker, J.K., Sobek, D.K., and Cristiano, J.J., (1994). "Set-based concurrent engineering and Toyota," *Design Theory and Methodology-DTM '94*, vol. DE68, pp. 79-90.

Waterman, N.A., and Ashby, M.F., (1991). *Material Selector*, vol. 1, CRC Press, Boca Raton, Fl.

Whitney, D.E., (1988). "Manufacturing by Design," *Harvard Business Review*, vol. 66, no. 4, pp. 83-91.

Yager, R.R., (1977). "Fuzzy decision-making including unequal objectives," *Fuzzy Sets and Systems*, vol. 1, pp. 87-95.

Young, R.E., Giachetti, R.E., and Ress, D., (1996). "Fuzzy constraint satisfaction in design and manufacturing," to appear *6th IEEE Int'l Conf. on Fuzzy Systems*.

BIOGRAPHICAL SKETCH

RONALD E. GIACHETTI, is an Industrial Engineer Postdoctoral Research Associate in the Manufacturing Systems Integration Division at NIST. This position is funded by the National Research Council. His research interests are in the areas of computer integrated manufacturing, design-for-manufacturing, and fuzzy set applications in manufacturing. His current research is focused on modeling manufacturing process capabilities to support computer integrated manufacturing. He is a member of IIE, SME, and ASME.