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Computer-based approach to material and process selection

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Abstract

Purpose – The purpose of this paper is to provide a perspective of computer-aided material and process selection (MPS) software tools for product development purpose and present a practical approach for manufacturers and other decision makers involved in MPS.

Design/methodology/approach – A multi-criteria deductive approach for MPS is applied to a case study by taking into account the technical performances and environmental constraints. A resource-based cost modeling is also deployed to examine the implication of selected material and process on overall product cost.

Findings – The paper demonstrates the capabilities and shortcoming of existing computerized MPS software tools in assisting product managers and designers for handling the growing volume of material/process data.

Research limitations/implications – Applying computer-aided MPS approach to complex shape products with multiple features is not a straightforward task and requires further development in existing MPS software tools.

Practical implications – Computer-aided MPS systems can assist decision makers in solving many material/process selection problems by following a systematic process.

Originality/value – Given today's rapid technological changes, it is important for decision makers to understand the capabilities of computer-aided MPS software tools in handling a growing volume of data. Very limited research has been done to explore the capabilities and limitations of existing material/process selectors. It is the first in the literature that demonstrates the application of multi-criteria deductive approach in MPS using a software tool.

Keyword(s):

Materials management; Software tools; Internet; Operations and production management.

Introduction

Selection of materials and manufacturing processes for industrial applications is a long-standing, complex decision-making problem with potential impact on entire life cycle of a product including manufacturing, distribution, consumer use, recycling, and disposal. Materials and processes selection may indirectly influence widely varying aspects of company management, such as company policies and the availability of facilities and trained personnel (Lovatt and Shercliff, 1998). Such selection is also integral to every product development process since deciding how a product should be made relies heavily on the nature of the materials selected. Typically, materials account for as much as 50 percent of the overall cost of manufactured goods (Ullman, 2002, p. 3) and it is estimated that there are between 40,000 and 80,000 materials available today with at least 1,000 different ways to process them (Ashby *et al.*, 2004). Such vast number of materials and processes and variety of requirements in the design process is the root of difficulty of the selection problem (Brechet *et al.*, 2001). The problem is further compounded by rapid technological changes, increasing level of sophistication and growing volume of technical data both in materials and processes.

Data sources can be classified into three categories:

1. hard copy (e.g. data in handbooks, datasheets, etc.);

2. computerized knowledge bases; and

3. computer-aided databases (Ermolaeva *et al.*, 2002).

The primary source of data for material and process selection has traditionally been hard copy, requiring the employment of literature searches to identify data in printed handbooks and data sheets. This method is usually time consuming, tedious, and may not be effective considering the vast number of materials and processes from which to choose, and the multifaceted nature of the selection task.

Computerized knowledge base systems (KBS) provide expert knowledge and interactive capabilities which assist the user in solving various problems and queries (Sapuan, 2001). KBS improves the material and process selection (MPS) task by using a rating criteria to rank alternative materials and processes (Giachetti, 1998). These systems are typically composed of a search engine and a basic database that can be expended by the users.

Computer-aided databases have advantage over printed sources which have several drawbacks as they often outdated and difficult to be indexed for finding answers (Sapuan, 2001). Since early 2000s, several online and offline material and process databases systems have emerged. Most online materials databases have been developed by industrial materials suppliers, such as Du Pont (2007) and GE (2007). These databases typically serve a particular sector of the manufacturing industry compared to general purpose databases which provide users with a wider breadth of data. However, among existing databases, only a few of them can be qualified as material or process selector *per se* due to their interactive search and optimization capabilities. The need for such capabilities is rapidly growing considering first, in most cases the selection of the best material/process for a particular product can be a challenging task due to vast variety of available materials and processes. Second, with an ever increasing pressure to reduce time-to market on products, there is a demand for systematic MPS approach which produces results in a reliable, repeatable and quick manner. Therefore, given the nontrivial task of MPS, it is important that product managers and designers to employ a software tool to handle the best fits between design requirements and material/process characteristics.

The purpose of this study is to provide a perspective of computer-aided MPS systems and to present a practical approach for performing such selection. The author first, reviews the general characteristics of MPS systems with their associated criteria and constraints. Second, a systematic material/process selection approach will be discussed along with a resource-based cost modeling to examine the implication of selected material or process on overall product cost. Finally, a case study is presented to explore the capabilities and limitations of an emerging MPS software tool.

Characteristics of material/process selectors

Computer-aided material and process selectors can be divided into two sub-categories of web-based and off-line systems. At the present time, the only general purpose web-based material selector is MatWeb (2007), developed by Automation Creations, Inc. MatWeb is intended for use by industry subscribers who are interested in quick data retrieval and material selection.

The off-line MPS systems are usually available on CD-ROM. One of the most widely publicized off-line systems in recent years was developed by Ashby (1999) and commercialized by Granta Design Limited as Cambridge Engineering Selector (CES). Originally conceived as an educational tool, CES's evolution into a user-friendly software system, combined with the quantity of technical data it offers, allows for its application to any industrial situation (Ferrante *et al.*, 2000). It also provides graphical selection and ranking methods as well as an in-depth analysis tool for research and education.

MatWeb and CES share two major features:

1. material property data for metals, polymers, ceramic, and composites; and

2. material selection using multiple attributes.

In addition to these features, CES provides a process selector module and ecology/environmental screening functions.

These functions allow the evaluation of material impact on its environment during its entire life cycle from initial extraction to eventual disposal and recycling stages. Table I lists the general characteristics of computerized MPS systems and the various capabilities and functions of the two selector systems, as well as their commonality and differences.

To compare the results of a material search using the two selector systems the author applied a three-attribute material search case: density$\leq$0.09 lb/in^3; tensile strength, yield$\geq$9,500 psi; and hardness, Vickers$\geq$80. As can be seen in Table II, MatWeb generated a list of 20 materials, all magnesium in various grades and treatments. CES generated data for 68 materials including 10 aluminum composites, 12 beryllium alloys, 16 magnesium alloys, 10 ceramic composites, and several magnesium composites. The sharp contrast in selection results produced by the two selector systems can be attributed to the fact that each database covers certain material types and grades, which may not be included in the other system.

Interrelated selection criteria

A product design process is an iterative process, which begins with the formulation of a need and follows with the definition of a function, the specification of a shape, the selection of a material, the option for a fabrication process (Matos and Simplicio, 2006). Figure 1 depicts material and manufacturing process selection in a wider context and as a multifaceted decision making problem that may require the consideration of several interrelated technical, business, and managerial issues.

Application requirements. Each product application requires that a material to possess certain properties and meets a certain level of performance (e.g. strong materials for impact resistance, or low electrical conductivity for good insulating property). The customer and market, engineering design standards, and/or safety regulations mandate these requirements.

Manufacturing process. A process can be selected from three broad categories, namely shaping, joining and surface treatment. Selection of process and material are interdependent. The process chosen must work well with the selected materials. For instance, selection of a diecasting process would be appropriate for the manufacturing of an aluminium part, but not for a part made of tool steel.

Product and material shape. Typically product designers determine product shape based on product function, processing feasibility, etc. Materials are available in bulk form and in standard stock geometric shapes (rod, tube, etc.) of various sizes and tolerances.

Economic considerations. The common elements in economic analysis of MPS are the cost of materials, capital equipment, and overhead (labor, energy, research and development, etc). Although these costs may not be issue in the preliminary MPS stage, it is essential for the economic evaluation of a product development project and the impact on overall product cost.

Business/management implications. A decision for material and/or processes selection often influences the upper level business/management decisions and a company's profitability. For instance, market's demand determines the production rate which in turn affects the selection of a manufacturing process. If an environmental impact analysis is part of a product business plan, then issues such as waste and pollution prevention, energy recovery, and material recovery must be included in the MPS process.

Material selection methodology

Generally, MPS approaches can be categorized as deductive and progressive approaches. A deductive approach requires a strict definition of constraints and the objectives. A progressive approach involves screening the possible candidates, ranking them according to their ability to optimize the objectives (Brechet *et al.*, 2001).

In this study, we applied the deductive approach by comparing the design and economic requirements of a product with the attributes profile of all materials in a material/process selector database, and finding the best match. Figure 2 shows a sequence of steps that may be followed to determine whether or not a particular material meets a set of product specifications voiced by the product designer or manager. These steps can be applied sequentially or simultaneously. The technical and economical requirements data can be entered into a MPS system in different fashions. For instance, in MatWeb and CES the user can enter the upper and/or the lower limits of material properties into the selector software for filtering a large number of material options. CES also offers graphing capabilities in which a bar chart or bubble chart is used to display screened materials. The user may then select the best one using a selection box or a selection index (Figure 3).

Manufacturing process selection methodology

The manufacturing process selection activity has traditionally been accomplished using the printed data sources and general knowledge and expertise of technical staff. However, the growing number of processes and sub-processes in recent decades demands a more elaborate selection process which takes into consideration the material, equipment, product design constraints, and environmental constraints while meeting capital and operating cost limits.

As with material selection, we applied the deductive approach to process selection. This approach identifies feasible processes by screening and eliminating those that do not satisfy certain constraints. Figure 4 shows a sequence of constraints that may be applied to a process selection problem.

It should be noted that process selection is a prerequisite to equipment selection. Often engineers and facility managers are involved in equipment selection and consider only the capacity analysis, equipment size, operating costs, and so forth. They cannot select equipment without knowing the type of shaping or assembly process. For example, the decision to acquire a milling machine with a certain size and power is made based on the assumption that material removal by milling is the best method for shaping the product.

Economic consideration

In many cases, economic is an inseparable component of any material/process selection. That is, it is important for a company to know whether the material cost and capital expenditures meet volume and cost goals. Moreover, a good business planning should provide investors with the implications of materials and process selection on the company's bottom line. The ability to extract various cost data such as capital costs and tooling costs from a process selector database facilitates such economic analysis. The author used a resource-based cost modeling approach developed by Esawi and Ashby (2003) to rank the relative cost of investing on a manufacturing process. This model takes into account the cost of resources associated with manufacturing a component. This cost model does not provide an accurate cost estimate for bidding purpose or calculating profit and loss. It is basically a broad indicator for competing processes for shaping a product at the early stage of product development and/or business planning. The model is comprised of the cost of common factors in the manufacturing of a product, including materials, capital equipment, and overhead (labor, energy, research and development, etc). Other parameters included in the model are expected production volume, product mass, and capital equipment, and overhead (labor, energy, research and development, etc).

Based on this cost model a relative cost index (RCI) is defined by Esawi and Ashby (2003) as shown in equation (1). In this equation, RCI represents the overall cost per unit of product. The definitions of parameters used in the expression are shown in Table III. The table also indicates which data can be extracted from the material selector database and which data must be provided by the user. A case study for selecting material and manufacturing process for a mechanical fastener is discussed in the next section. The author applied the selection processes depicted in Figures 2 and 4 using the CES software. The built-in cost modeling function of the software is used for analyzing the impact of material and/or a process selection on total product cost: Equation 1

Case study

In this section, the application of the MPS method previously presented is exemplified through a case study. This case involves the selection of material and process for a new design of an oil pump (Figure 5). This pump is part of driving system of a construction equipment and includes a new spur gear that is the focus of this case study. From a user's standpoint, the desirable attributes of this component are good wear resistance, high fatigue strength, good corrosion resistance, and moderate cost. From a manufacturing standpoint, it is desirable to choose a material that can be shaped easily with minimal equipment and energy costs. Figure 5 displays a number of application requirements including physical, mechanical, and environmental requirements for the spur gear under study.

The questions of interest to the management include what are the material options, how a new material affects the product cost, what are options for a production method and how the choice of such method affects the product cost as well as the capital cost.

Material selection

To find the best material for the spur gear we followed the deductive searching and screening stages as shown in Figure 2. In this case, two mechanical property constraints; hardness and fatigue strength; and one environmental property constraint; processing energy; have been specified by product designer (Figure 5). After entering the numerical values for these constraints in CES, six materials including a supperalloy, stainless steel and a low-alloy steel are found to meet all design requirements.

To compare the alternative materials in terms of cost, we used a simple bar chart to display the cost data (Figure 6). A search for the least expensive materials yields medium carbon steel at about $0.30/lb. However, because the low-alloy steel with its chromium content offers a good corrosion resistance at almost the same cost, this material is selected as the best alternative for the spur gear. This indicates that the user's expertise is still needed to complement the capabilities of a computerized material database.

Process selection

To find the best manufacturing process for the spur gear under study we applied the deductive searching and screening sequence (Figure 4) as follows.

Stages 1 and 2. Material class and physical constraints

An essential data for any process selection is the material class that in this case is the low-steel alloy. It is also important to know the mass of the product since each manufacturing process can handle a certain mass range. Based on the density of the material and physical volume of the spur gear we calculated the mass of the gear as approximately equal to 3.5 ounces.

Using these data we plotted material class vs product mass (Figure 3). A selection box for the mass range at around of 3.5 ounces is shown at the bottom of the plot. The selection box identifies 14 shaping processes that satisfy the product application requirements for the specified material class (low-alloy steel) and product mass (3.5 oz). For the sake of clarity, only a portion of result is shown in Figure 3 including two casting processes, a hot forming process, two material removal processes and a powder pressing process.

Two additional physical constraints which have been specified by the product designer are surface roughness and tolerance (Figure 5). Inputting the related numerical data into the program, reduces the number of qualified processes to nine.

Stage 3. Shape constraint

To narrow down the list of processes, two shape-related constraints namely shape class which in this case is prismatic/cylindrical shape and minimum section thickness of the spur gear were entered into the program. Three processes of electrodischarge wire machining, investment casting and powder pressing pass this stage.

Stage 4. Economic analysis

At this stage the author ranked the final three shaping processes based on economic requirements. Figure 7 displays a bubble chart of economic batch size vs overall product cost (RCI) for the final three processes. The parameters used in the calculation of RCI are shown in the same figure. Each bubble represents a range of batch size (horizontal axis) and overall cost (vertical axis). As can be seen, the bubble for powder pressing and sintering indicates this process has the lowest overall cost ($0.20-$0.80 per unit) while it has an economic batch size over 8,000 parts. Notice that the investment casting process at the upper left corner of the chart is the most expensive ($20-200 per unit) with an economic batch size less than 10,000 units.

Figure 8 shows a bar chart of equipment cost for the three processes under consideration. Although the powder pressing process has the best overall product cost, it is somewhat more expensive in terms of machinery cost ($25,000-$200,000), while the wire EDM category requires less expensive equipment ($8,000-$90,000). These data have a significant business planning implication since it provides an estimate of required initial capital outlay. Two conclusion can be made: first, over five years of capital write-off and the production of 50,000 parts per year, the powder pressing process is the most economical process for the spur gear under study. Second, although the upper limit of capital cost range for powder pressing process is significantly higher than the cost of the other alternatives ($200,000 compared to $90,000), less expensive powder pressing equipment is available for as low as $25,000.

Sensitivity analysis

To test the sensitivity of our final selections to the type of materials used, the author replaced the low-alloy steel with stainless steel, which was among the top six qualified materials for the spur gear. The outcome was somewhat similar to what was obtained for low-alloy steel. The powder pressing process is still the best process, however, the unit product cost (RCI) is somewhat higher when stainless steel is selected ($0.60/unit compared to $0.45/unit).

To analyze the effect of material cost on the total cost of the product, the author generated a plot of material cost vs RCI (Figure 9). This plot is particularly useful in a broad analysis of the economical impact of material selection on total cost of production using a particular shaping process, in this case powder pressing. As it can be seen, when material cost is under $0.60 per pound, the total production cost remains steady within the $0.05-0.60 range. Under the same condition, the total cost depends more on the cost of powder pressing equipment and tooling and less on material cost. When material cost is above $0.60 per pound, then the total cost of using the powder pressing process relies more on the cost of material and less on the cost of equipment and tooling.

Observations and conclusion

In this study, a deductive MPS approach was employed to examine the capabilities and limitations of an emerging computer-aided material and process selector. Several observations can be made from this study. First, while computer-aided MPS software tools can be an effective tool at the early stages of product development and business planning, the decision makers must be aware of the limitations of these tools. One such limitation is the breadth of data coverage. Although there is some overlapping of information in material selectors, most focus on specific types and grades of materials.

Second, currently there are only a few MPS systems with manufacturing process searching capability. Application of these systems to complex product development projects can be a challenging task. For instance, a product with sophisticated design requirements may need multiple manufacturing operations on different equipment. As a result, it may require numerous screening stages for reaching to a final solution. In this kind of applications, the use of a software tool must be coupled with the user's expertise for effective search and screening functions.

Finally, while computerized process selectors can be used as a searching tool for finding an appropriate process, they are not equipment selectors. As it was shown in the case study, the capital cost of final selection, powder pressing process, ranges from $25,000 to $200,000. This wide price range indicates the availability of a wide range of equipment in the market. However, more specificity in type of equipment and a narrower range of cost might be needed for business/management decision making on variety of issues including budgeting, facility planning, operator training, waste, and environmental management. Therefore, the use of MPS systems must be complemented with additional technical and cost/benefit analyses before a final decision on acquiring a specific piece of equipment is made.

References

1. Ashby, M.F. (1999), *Material Selection in Mechanical Design*, 2nd ed., Butterworth Heinemann, Oxford.

2. Ashby, M.F., Brechet, Y.J.M., Cebon, D., Salvo, L. (2004), "Selection strategies for materials and process", *Materials & Design*, Vol. 25 No.1, pp.51-67.

3. Brechet, Y., Bassetti, D., Landru, D., Salvo, L. (2001), "Challenges in materials and process selection", *Progress in Materials Science*, Vol. 46 No.3/4, pp.407-28.

4. DuPont Material Selector Page (2007), available at: plastics.dupont.com/myplastics/Mediator?id=524&locale=en_US.

5. Ermolaeva, N.S., Kaveline, K.J., Spoormaker, J.L. (2002), "Material selection combined with optimal structural design: concept and some results", *Materials & Design*, Vol. 23 No.5, pp.459-70.

6. Esawi, A.M.K., Ashby, M.F. (2003), "Cost estimates to guide pre-selection of processes", *Materials & Design*, Vol. 24 No.8, pp.605-16.

7. Ferrante, M., Santos, S.F., Castro, J.F.R. (2000), "Material selection as an interdisciplinary technical activity: basic methodology and case studies", *Material Research*, Vol. 3 No.2, pp.1-9.

8. GE Material Selector Page (2007), available at: www.geplastics.com/gep/Plastics/en/Home/Home/home.html.

9. Giachetti, R.E. (1998), "A decision support system for material and manufacturing process selection", *Journal of Intelligent Manufacturing*, Vol. 9 pp.265-76.

10. Lovatt, A.M., Shercliff, H.R. (1998), "Manufacturing process selection in engineering design. Part 1: the role of process selection", *Materials & Design*, Vol. 19 pp.205-15.

11. Matos, M.J., Simplicio, M.H. (2006), "Innovation and sustainability in mechanical design through materials selection", *Materials & Design*, Vol. 27 No.1, pp.74-8.

12. MatWeb Material Property Data (2007), available at: www.matweb.com/index.asp?ckck=1.

13. Sapuan, S.M. (2001), "A knowledge-based system for materials selection in mechanical engineering design", *Materials & Design*, Vol. 22 No.8, pp.687-95.

14. Ullman, D.G. (2002), *The Mechanical Design Process*, 3rd ed., McGraw-Hill, New York, NY.

Equations

Equation 1

$$\mathrm{RCI} = \frac{M_{\mathrm{c}} \times C_{\mathrm{m}}}{M_{\mathrm{u}}} + \frac{T_{\mathrm{c}}}{Q} \times \left(1 + \left(\frac{Q \times C_{\mathrm{l}}}{T_{\mathrm{l}}}\right)\right) + \left(\frac{C_{\mathrm{l}}}{P_{\mathrm{r}} \times 60}\right) \times \left(O_{\mathrm{v}} + \left(\frac{E_{\mathrm{c}}}{T_{\mathrm{cw}} \times 24 \times 365 \times E_{\mathrm{u}}}\right)\right). \tag{1}$$

Figures

Figure 1*:* Technical and managerial considerations in MPS process

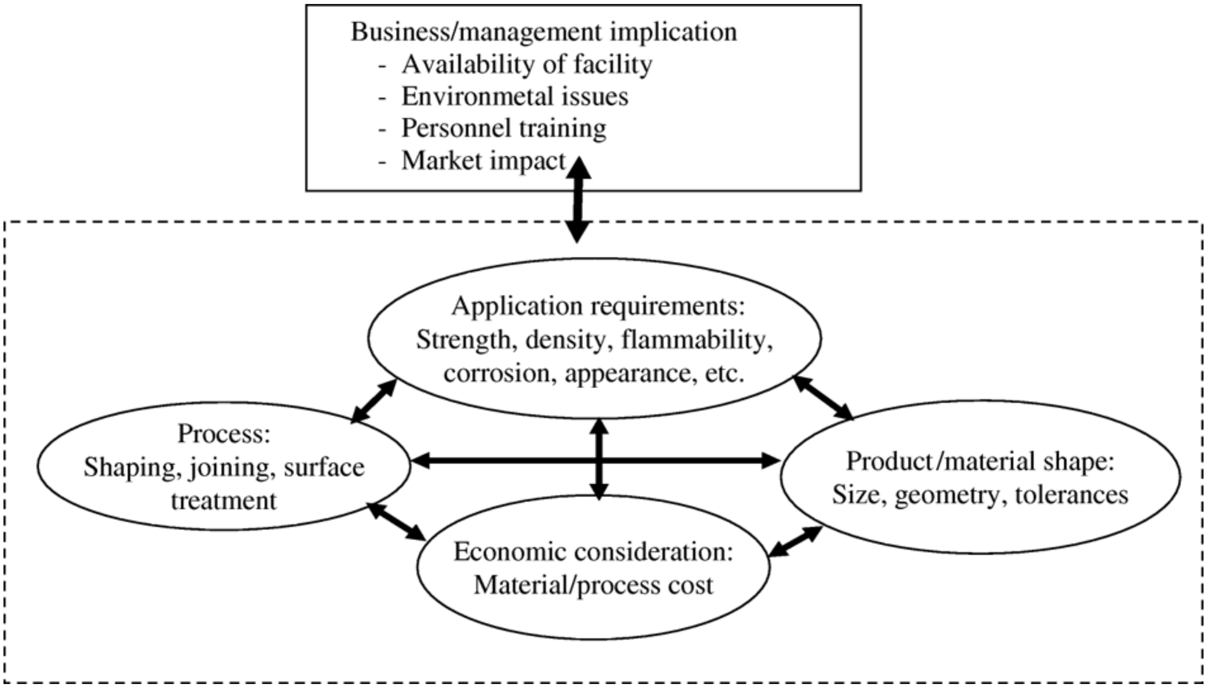
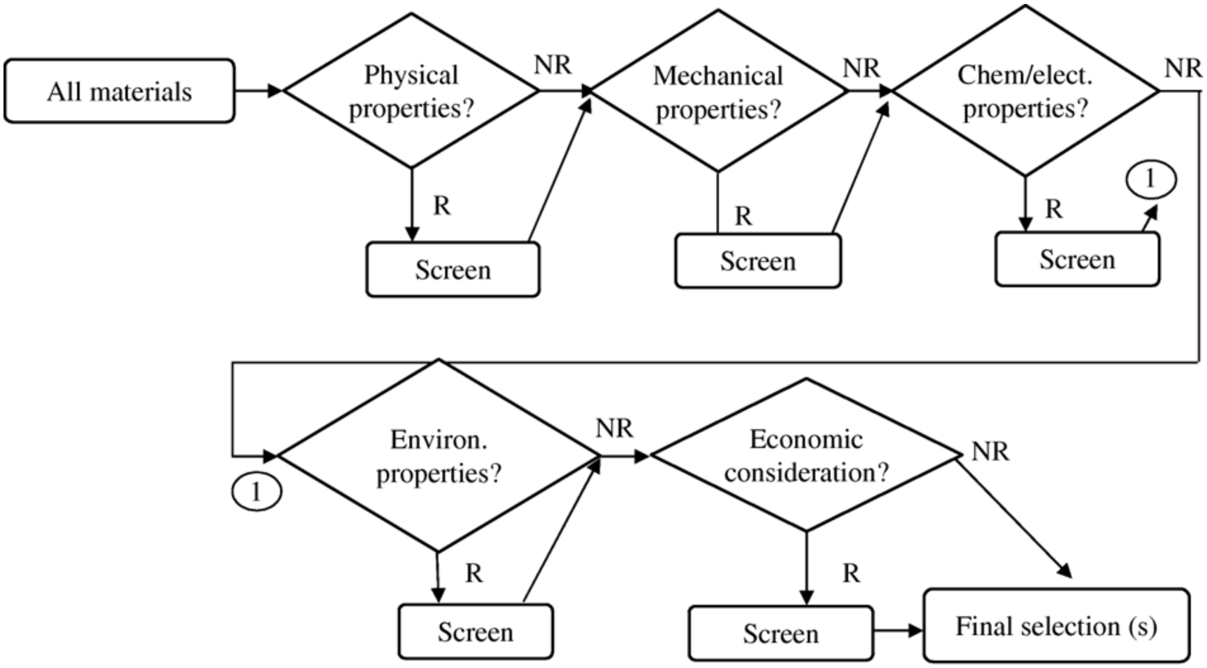


Figure 2*:* Materials selection process



Notes: R, relevant; NR, not relevant

Figure 3: Product mass vs material class

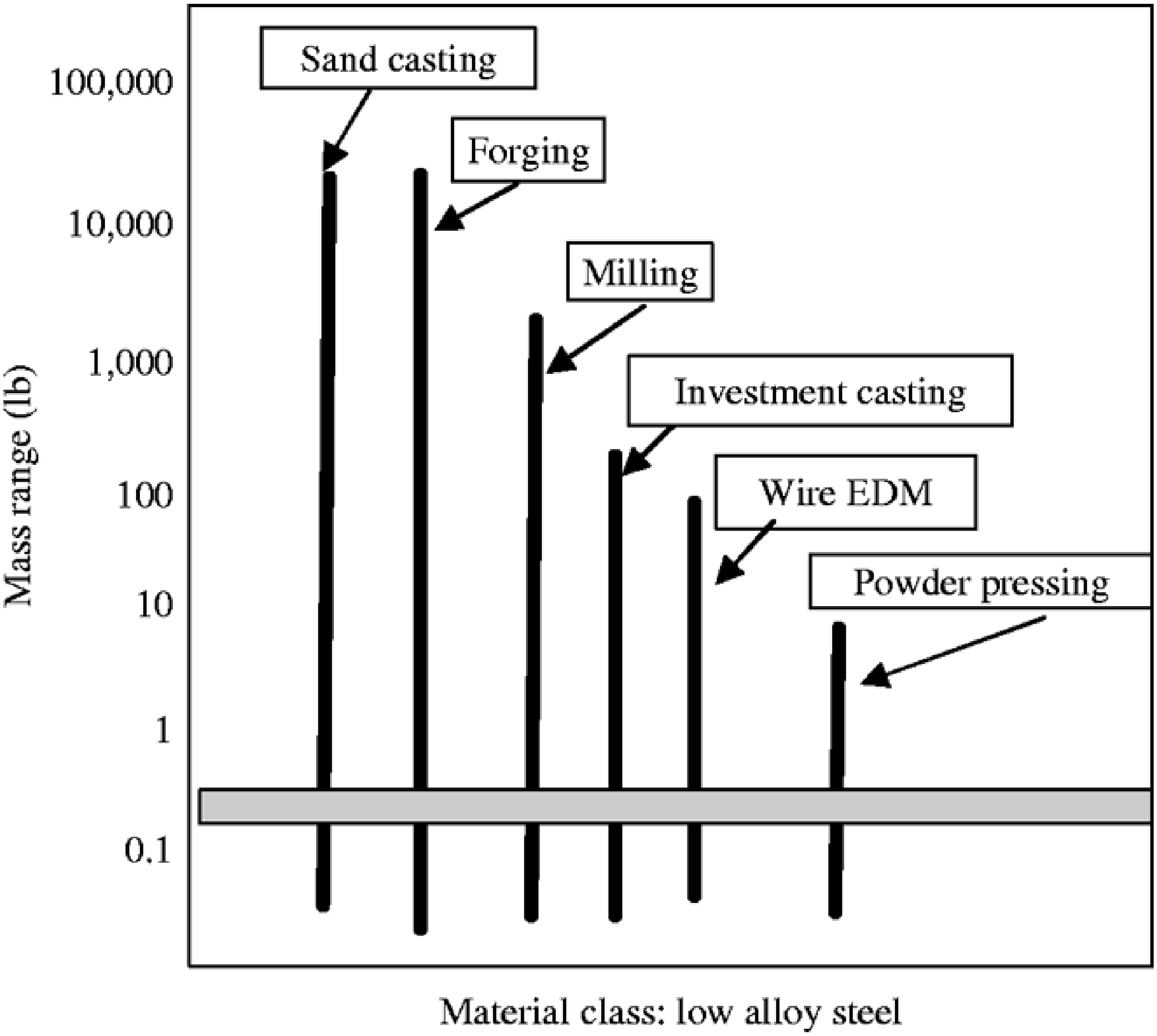
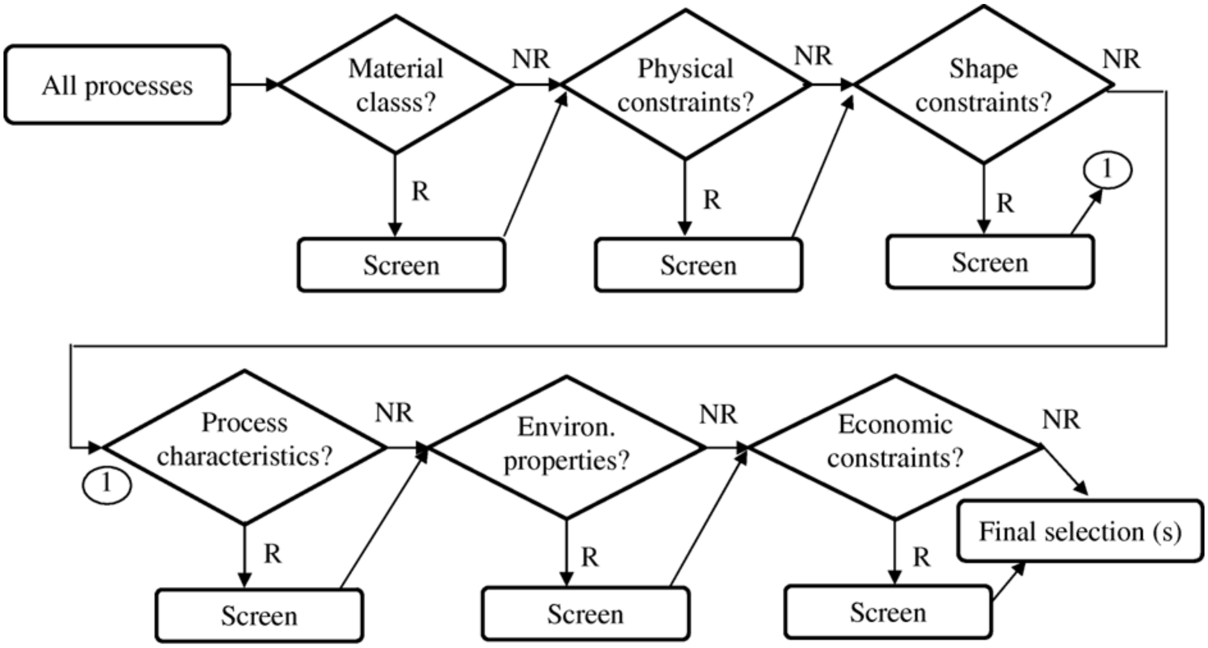
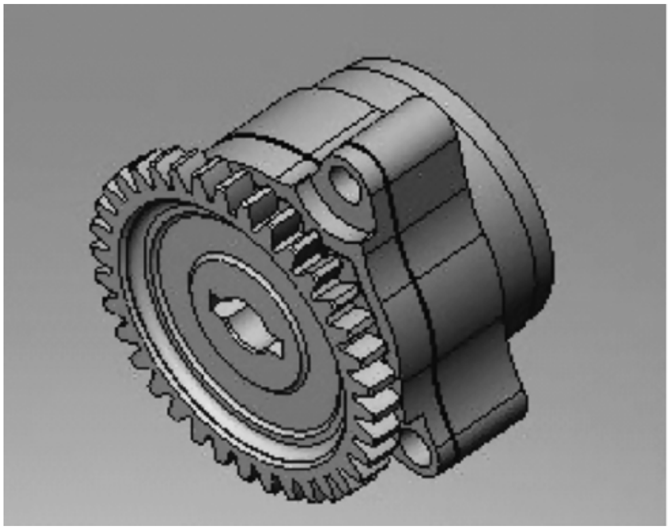


Figure 4: Manufacturing process selection



Notes: R, relevant; NR, not relevant

Figure 5: Design data for the spur gear



Hardness:	>220 Vickers
Fatigure strength:	>50 ksi
Shape:	Prismatic, solid
Section thickness:	<0.25"
Tolerance:	<0.002"
Surface roughness:	<250 µin
Processing energy:	<2700 kcal
Expected demand:	~50,000/year

Figure 6: Ranking of materials by price

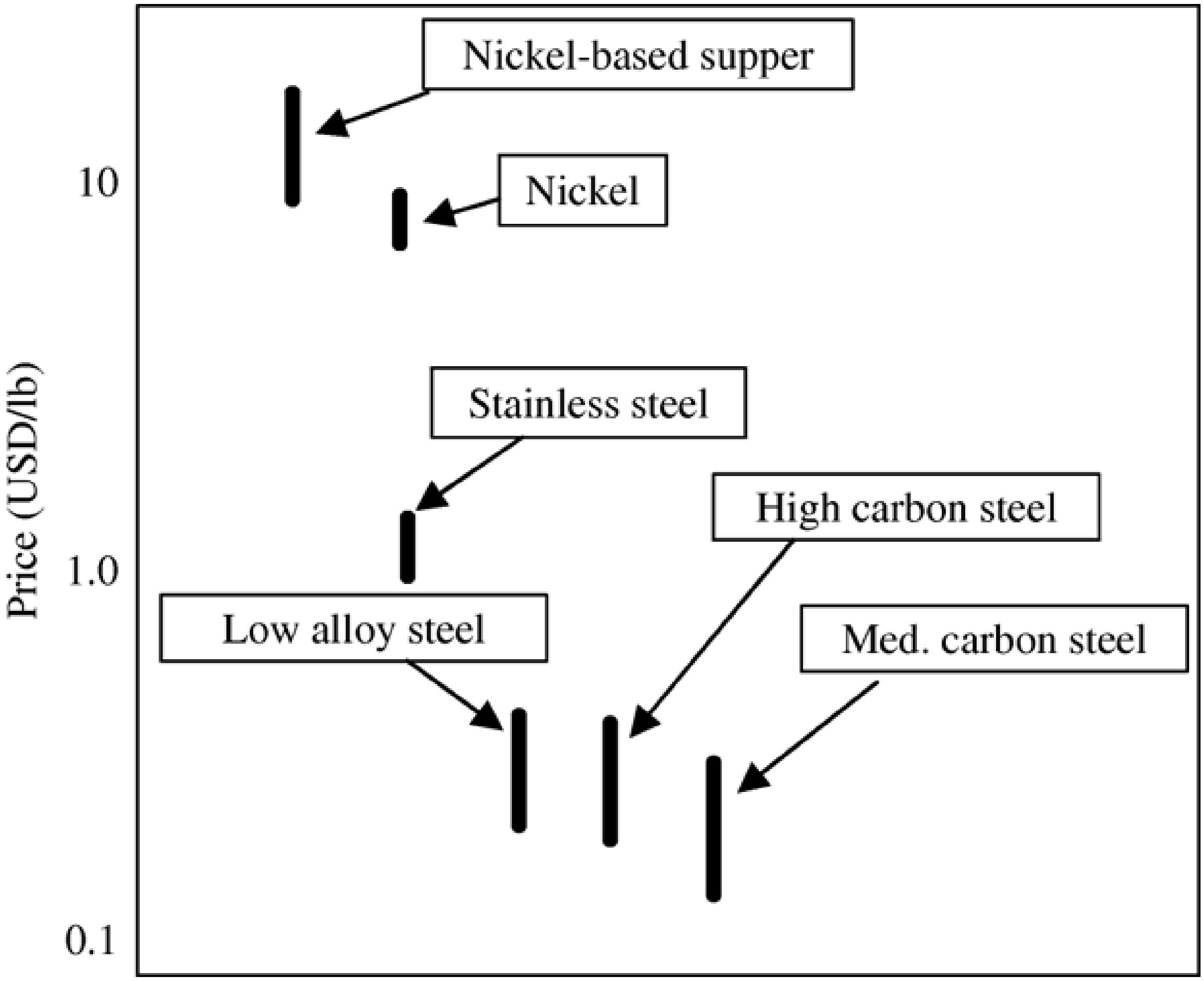


Figure 7: Ranking the final processes based on overall cost

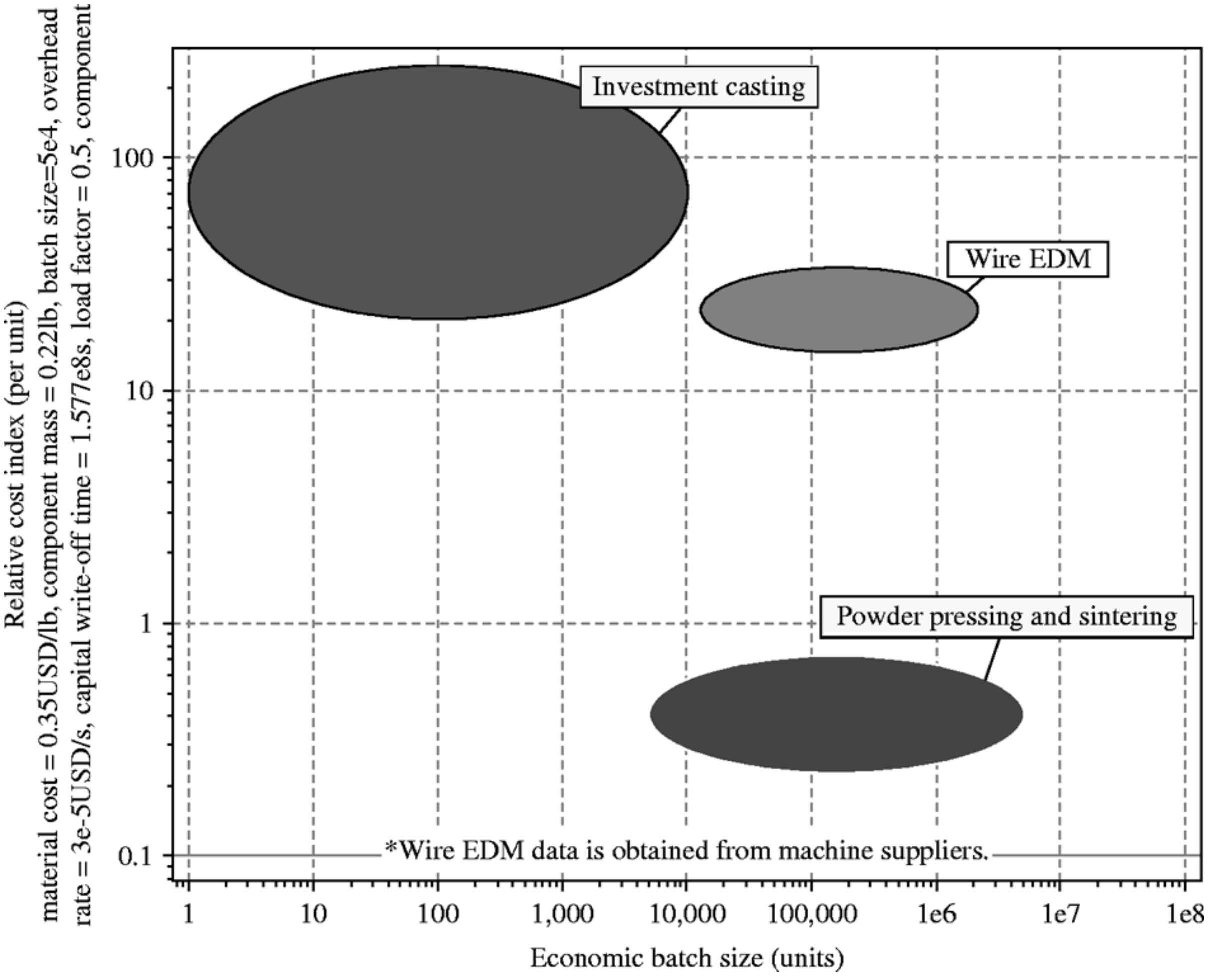


Figure 8: Equipment costs for final three processes

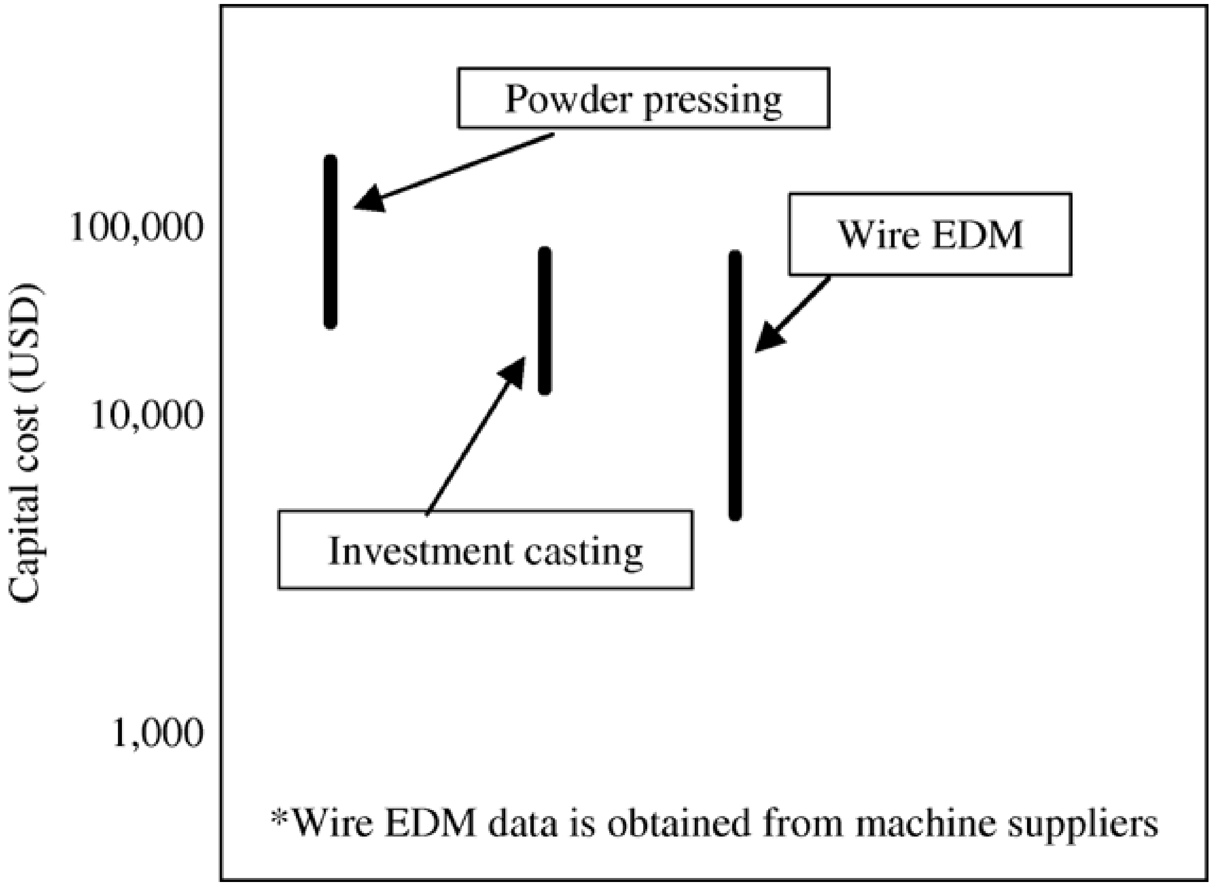
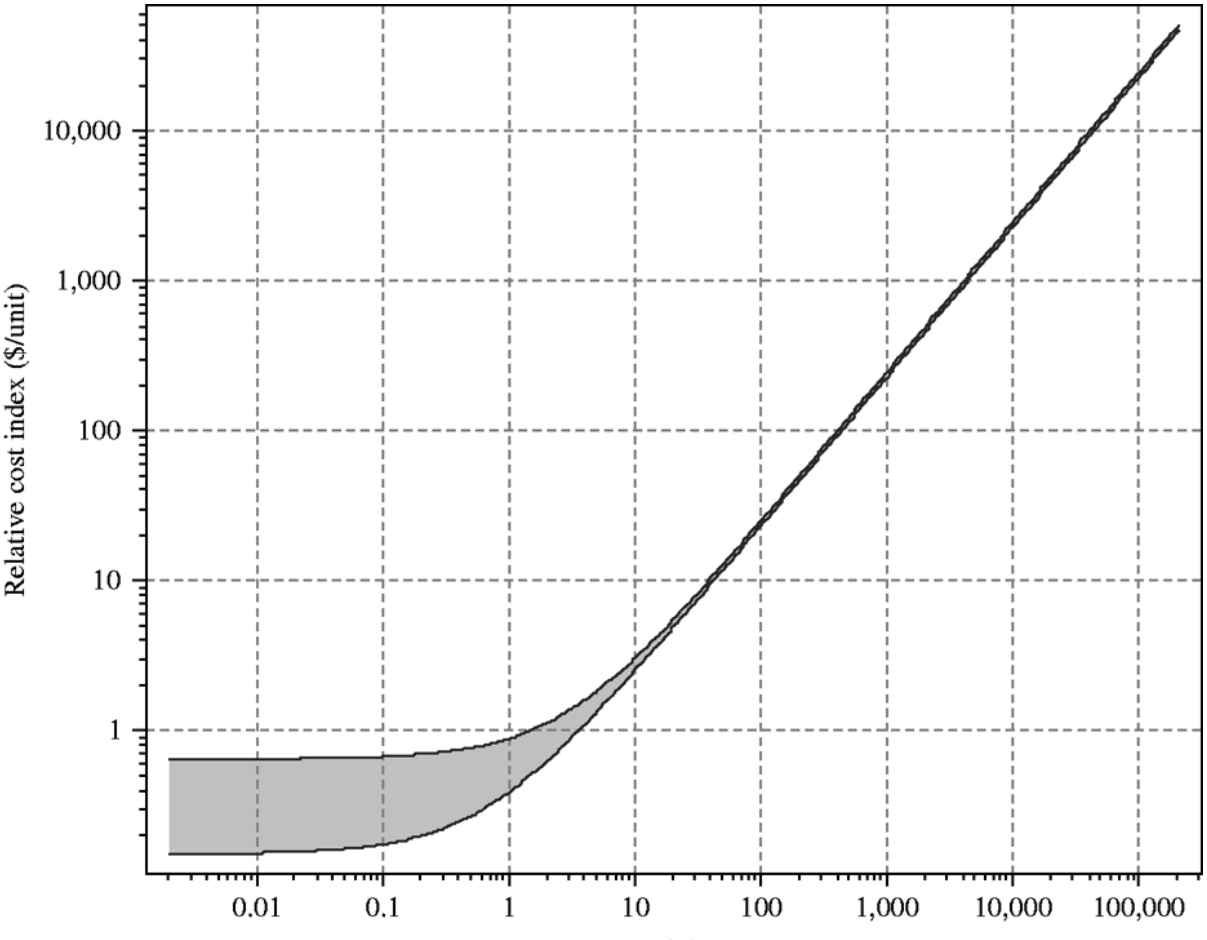


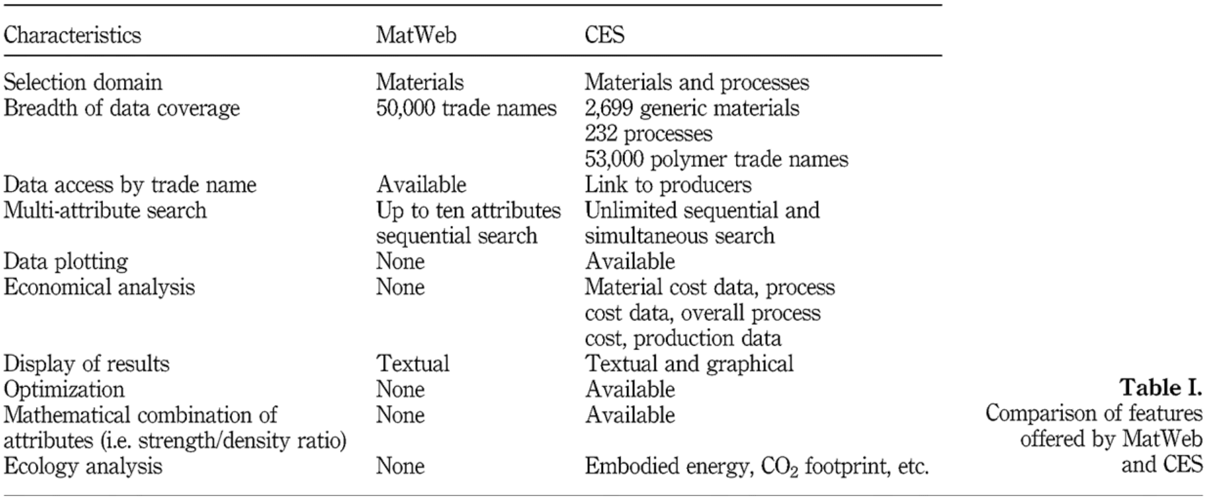
Figure 9: Material cost vs overall product cost for powder pressing process



Batch size = 5e4, component mass = 0.22lb, overhead rate = 3e-5USD/s, capital write-off time = 1.577e8s, load factor = 0.5

Tables

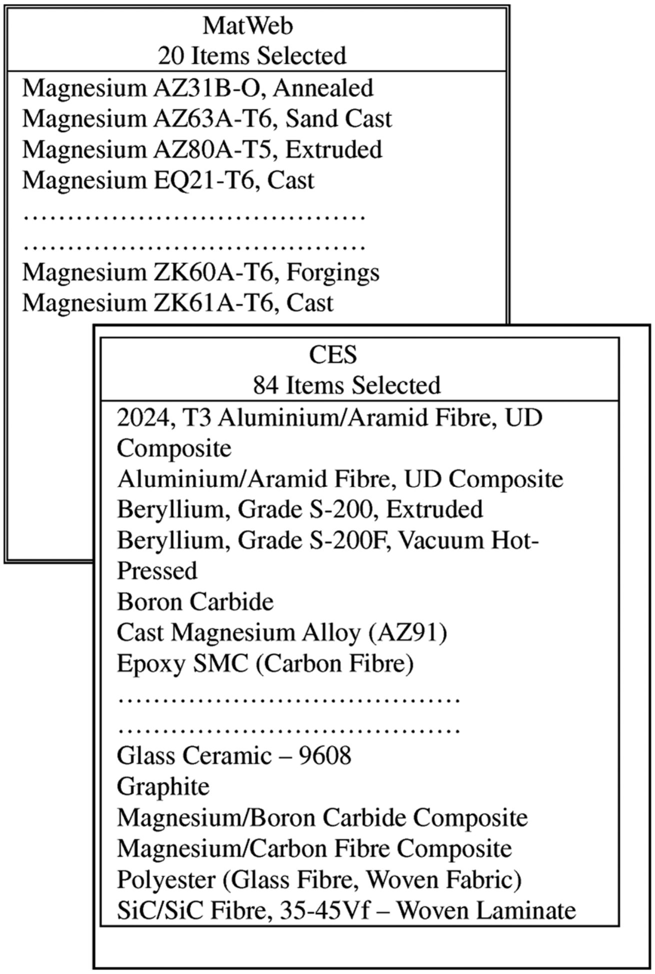
Table I*:* Comparison of features offered by MatWeb and CES



Characteristics	MatWeb	CES
Selection domain	Materials	Materials and processes
Breadth of data coverage	50,000 trade names	2,699 generic materials 232 processes 53,000 polymer trade names
Data access by trade name	Available	Link to producers
Multi-attribute search	Up to ten attributes sequential search	Unlimited sequential and simultaneous search
Data plotting	None	Available
Economical analysis	None	Material cost data, process cost data, overall process cost, production data
Display of results	Textual	Textual and graphical
Optimization	None	Available
Mathematical combination of attributes (i.e. strength/density ratio)	None	Available
Ecology analysis	None	Embodied energy, CO_2 footprint, etc.

Table I.
Comparison of features offered by MatWeb and CES

Table II: Materials selection results produced by MatWeb and CES



MatWeb 20 Items Selected
Magnesium AZ31B-O, Annealed
Magnesium AZ63A-T6, Sand Cast
Magnesium AZ80A-T5, Extruded
Magnesium EQ21-T6, Cast
…………………………………
…………………………………
Magnesium ZK60A-T6, Forgings
Magnesium ZK61A-T6, Cast

CES 84 Items Selected
2024, T3 Aluminium/Aramid Fibre, UD Composite
Aluminium/Aramid Fibre, UD Composite
Beryllium, Grade S-200, Extruded
Beryllium, Grade S-200F, Vacuum Hot-Pressed
Boron Carbide
Cast Magnesium Alloy (AZ91)
Epoxy SMC (Carbon Fibre)
…………………………………
…………………………………
Glass Ceramic – 9608
Graphite
Magnesium/Boron Carbide Composite
Magnesium/Carbon Fibre Composite
Polyester (Glass Fibre, Woven Fabric)
SiC/SiC Fibre, 35-45Vf – Woven Laminate

Table II.
Materials selection results produced by MatWeb and CES

Table III: Parameters used for economic consideration

Table III.
Parameters used for economic consideration

Parameter	Full name	Data provided by user	Data provided by CES
C_m	Component mass	√	
C_l	Component length	√	
Q	Production vol.	√	
O_v	Overhead rate	√	
T_cw	Capital write-off time	√	
Eu	Load factor (machine utilization)	√	
M_c	Material cost		√
M_u	Material utilization fraction		√
T_c	Tooling cost		√
E_c	Equipment cost		√
T_l	Tool life		√
P_r	Production rate		√