A Computer-Based Approach to Material and Process Selection Using Sustainability and Ecological Criteria

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Abstract--Decision on selecting a material or process for a particular product is a common task in product engineering and facility planning. Such decision may have a significant impact on entire product life cycle including raw material acquisition, product manufacture, use, disposal, and environment. Traditional factors for decision making are economical, functional and aesthetical properties of the product. However, the issues of sustainability and environmental impact of materials and manufacturing processes have gained a growing attention in recent decade by general population as well as academicians and industrial practitioners.

The objective of this study is to explore a software tool for material selection with focus on sustainability and ecological issues. To achieve this objective, first a number of sustainability/ecological attributes of materials will be reviewed. Second, a methodology for evaluating materials sustainability using an emerging software tool known as Cambridge Engineering Selector will be introduced. Finally a case study will be presented to exemplify the sustainability/ecological aspects of material/process selection.

I. INTRODUCTION

It is undeniable that the interest among practitioners and academicians for research and education in sustainability has been in the rise. This is because the products we produced have a huge impact on the environment of which we are all a part. These products make use of natural resources for their manufacturing and leave man-made footprints in the ecological environment which surround us. As the designers, and manufacturers of these products, we hold the power to make them more sustainable, so that they meet the needs of society without compromising the needs of others or jeopardizing the future survival of humanity on earth. However, this poses a challenge considering increasing population and associated demand that exceeds the ecological capabilities.

As an ethical responsibility, the product engineers and manages must try practicing sustainability in any product development for maintaining the integrity of natural ecological systems and to insure that resources continue to be available for human use. Material selection can play a key role in achieving ecological sustainability if it is done in such a way as to minimize adverse impact on natural environmental systems as a result of using the materials. In particular, this means selecting materials which minimize environmental degradation over the whole life cycle of the material, from initial extraction of raw components from the environment, to eventual disposal or recycling of the material.

It is estimated that there are between 40,000 and 80,000 engineering materials available today and at least 1,000 different ways to process them into various shapes [1]. Considering such variety of materials and manufacturing processes, an eco/sustainability analysis for selecting a material or process may require handling a large amount of data and performing numerous calculations. The use of conventional data sources, e.g., handbooks and datasheets can be cumbersome for extracting and managing the growing volume of data for the purpose of materials and manufacturing process selection. The users can be also overwhelmed by searching and screening of tons of information on internet. This signifies the need for software tools that provide users with a rather quick and efficient search and screen functions for material/process selection and performing eco/sustainability analysis.

In recent years, a computer-aided material selector known as Cambridge Engineering Selector (CES) has been introduced by Ashby [2] and commercialized by Granta Design Limited. Originally conceived as an educational tool, CES's evolution into a user-friendly software tool, combined with the quantity of technical data it offers, allows its application to any industrial situation [3]. The software provides graphical selection and ranking methods as well as an in-depth analysis tool for research and education. It offers several capabilities including a) material property data for metals, polymers, ceramic and composites, b) a multi-attribute material/process selection module, and c) an eco/sustainability auditing module. This study provides a perspective of application of the CES software tool for material/process selection with focus on materials' eco/sustainability characteristics.

II. SUSTAINABILITY WITH RESPECT TO MATERIALS

Minimizing negative environmental impacts as a result of materials use is an important objective of sustainable material selection, since the environment consists of ecosystem whose ongoing health is essential for human survival on earth [4]. Ecosystem survival is essential for human survival, since it serve as the ultimate source or raw materials for all human activities. Thus eco-friendly materials which minimize negative environmental impact are those which are created with non-polluting manufacturing processes, whose raw components come from stable ecosystems and are sustainably harvested, and which are reusable or recycled [5].

Looking at the broad picture of product life cycle analysis (PLA) is a great way to identify a phase or phases that materials contribute to the overall environmental impact. For a product manufacturing process, a PLA analysis identifies the energy and waste associated with each relevant stage, including [6]:

- Raw material extraction
- Material processing
- Component manufacturing
- Assembly and packaging
- Distribution and purchase
- Installation and use
  - Maintenance and upgrading
- End-of-life:
  - Maintenance and upgrading
  - material recycling
  - product reuse
  - landfilling
  - incineration

The important attributes which can be used to measure the contribution of material to eco/sustainability is the degree to which the material consumes energy and releases emissions throughout its entire life cycle. To this end, the embodied energy and CO_2 footprint of the material are two primary attributes of the ecological sustainability of materials [5]. The embodied energy is defined as is the energy consumed in various life cycle stages of a material. The CO_2 footprint is the mass of carbon dioxide produced and released into the atmosphere during the material's full life. It should be noted that, there is a degree of international agreement and commitment to a progressive reduction in carbon emissions, generally interpreted as meaning CO_2. At the national level the focus is more on reducing energy consumption, but since this and CO_2 production are closely related, reducing one generally reduces the other. Thus there is a certain logic in basing eco auditing on energy consumption or CO_2 generation.

III. METHODOLOGY

The goal of this study has been to explore an emerging software tool as a way to choose material/process with emphasis on eco/sustainability consequence of such decision. Doing so requires a two-part strategy. The first part is searching and screening the material/process database to identifying those which meet all technical requirements for intended use of a product. The selection methodology presented here is based on a deductive search and screening decision making. This provides inputs to the second part: that is eco audit. In this stage all qualified materials and processes are evaluated to determine those which minimize the energy and carbon dioxide emission over the full life.

The first part of the strategy can be broken down into two stages of material and process selections. A typical material selection problem involves screening a database of materials by evaluating the technical and economic requirements of a product against the material attributes profiles. Figure 1 shows a sequence of steps that may be followed to determine whether a particular material meets a set of product requirements voiced by the product designer or manager.

In manufacturing process selection stage the feasible processes are identified by screening and eliminating those which do not satisfy certain constraints. With growing number of processes and sub-processes, an elaborated and systematic selection method is needed to take into account the various factors such as material type and product's shape, while meeting capital and operating cost limits. Figure 2 shows a sequence of typical steps involved in a manufacturing process selection.

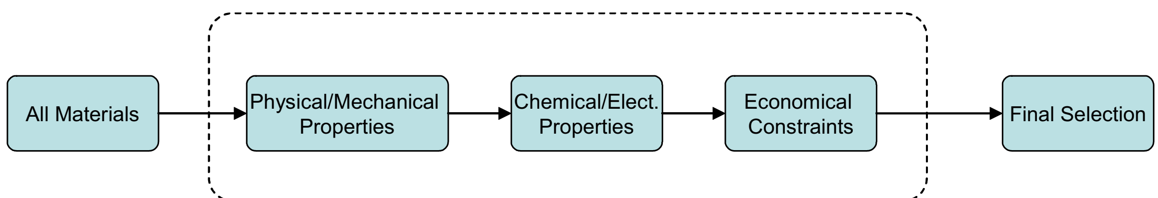


Figure 1. Material selection stages

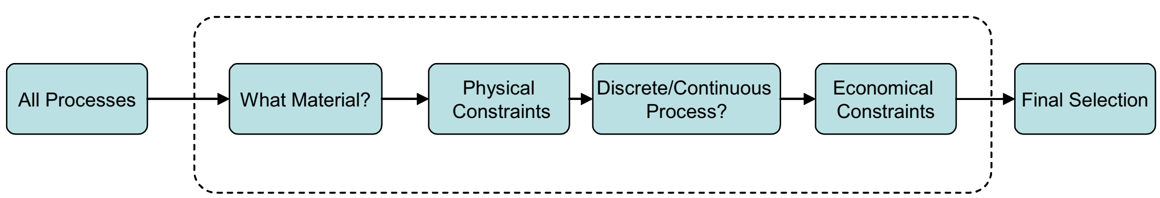


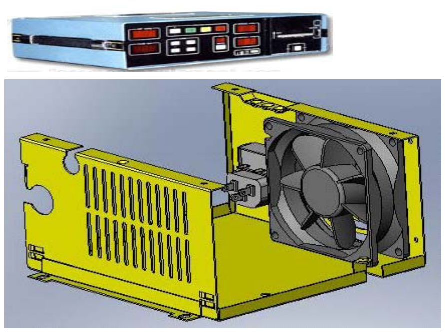
Figure 2. Process selection stages

Life Cycle Eco/Sustainability Audit

The second part of material/process selection strategy is eco/sustainability audit. This audit is a broad and quick initial assessment. It identifies the phases of life – material, manufacture, transport and use – that carry the highest demand for energy or create the greatest burden of emissions. Often, one phase of life is, in eco terms, overwhelmingly dominant, accounting for a high energy consumption and carbon dioxide emission. It then makes sense to focus first on this dominant phase, since it is here that the potential innovative material choice to reduce energy and carbon are greatest (Ashby, 2008). In addition to generating bar charts for displaying embodied energy and CO_2 footprint, the eco audit tool of CES provides a database containing data for both virgin and recycled material, and values for the typical recycled fraction in current engineering materials supply. This function causes the audit tool to calculate energies and carbon values for materials containing the recycled fraction, in place of those for virgin materials. Since material use can have a direct ecological impact, the use of materials with higher recycled content could be considered to have a positive sustainability impact.

IV. CASE STUDY

In this section, the application of a computer-aided material/process selector (CES) with eco/sustainability considerations is exemplified through a case study. This case involves the selection of material and process for a new design of a portable medical diagnostic equipment (Fig. 3). For the sake of illustration, we focused on the principal component of the device - its casing. This is the heaviest component of the device and it make sense to assume that it will have the highest impact on material use, therefore, highest impact on eco/sustainability. This type of casing is similar to ones used in many electrical hardware such as PCs, audio/video equipment and laboratory testing devices. From a user's standpoint, the desirable attributes of this component are good wear resistance, be stiff enough, and not to be too heavy. From engineering standpoint, this component should conduct heat very well, withstand moderate heat generated by internal electrical circuits, and be made with specified tolerances and surface smoothness. From company's management standpoint, it is desirable to select a material and associated process that produces high quality parts, at minimum cost, with least possible ecological pollution and contribution to material sustainability.



Technical Performances:

Mass:	18 lbs
Density:	< 0.2 lb/in^3
Hardness:	>60 Vickers
Stiffness: (E-value)	>60,000 ksi
Thermal conductivity:	>50 Btu/ft/h/°F
Service temp.	>200°F
Shape:	Sheet, Flat, Cut-outs
Section thickness:	<0.125"
Tolerance:	<0.005"
Surface roughness:	<250 μin

Figure 3. Technical data for the casing of a medical diagnostic equipment

A. Material and Process Selection

To find the best material for the casing of the medical diagnostic equipment we followed the deductive searching and screening stages as shown in figure 1 by entering the technical performance data (Fig.3) into CES software, including material's density, hardness, stiffness, thermal conductivity and service temperature data. As a result, 11 materials including an aluminum alloy, magnesium alloy, silicon carbide, and aluminum/silicon carbide composite are found to meet all design requirements. A search for the least expensive material yields aluminum alloys at about $1.20/lb.

As with material selection, we applied the deductive approach to process selection (Fig. 2). This approach identifies feasible processes by screening and eliminating those that do not satisfy certain constraints. We entered the technical performance data (Fig. 3) into CES software including shape of product, maximum section thickness, dimensional tolerance, and surface roughness data. As a result, the CES identified "stamping" as a process that satisfies all technical performances.

B. PLA Eco Audit

The medical diagnostic equipment under study is often installed on board of ambulances to monitor the medical conditions of patients. On average, a vehicle travels 220 days/year and 60 miles/day. Expected life of the device is 10 years which amounts to 130,000 miles of trips. To investigate the eco/sustainability effect of using different materials we entered the aforementioned data into the software for the top two materials identified in previous stage: aluminum and magnesium alloys. Figure 4 displays a snap shot of the CES's Eco Audit screen for data entry. The software allows entry of the mass, the material and primary shaping process. For each component, the material and manufacturing process are

chosen from pull-down menus. The software retrieves the associated embodied energy and CO_2 footprint per pound and multiplies that by the component's mass. Additional information such as type of transportation vehicle, distance traveled and use energy can be entered for calculating total energy consumption
and CO_2 emission. Based on the data entered, the software generates bar charts and data tables for embodied energy and CO_2 emission, examples of which are shown in figure 5 for the component under study. This is a product that uses energy during its life in two distinct ways. First, there is the electricity required to make it function. Second, there is the energy penalty that arises because it increases the weight of the vehicle that carries it by 40 lbs. Since all charts in figure 5 show energy use at the material production stage (extraction from a metal ore) and product use outweigh all other source of energy consumption, therefore, we focus our discussions on these two stages of product life cycle.

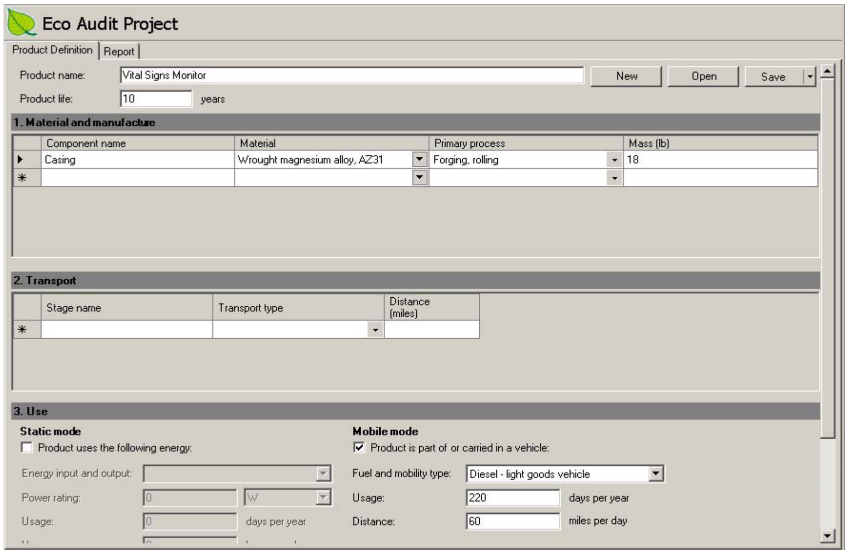


Figure 4. Eco audit screen for the medical devise casing

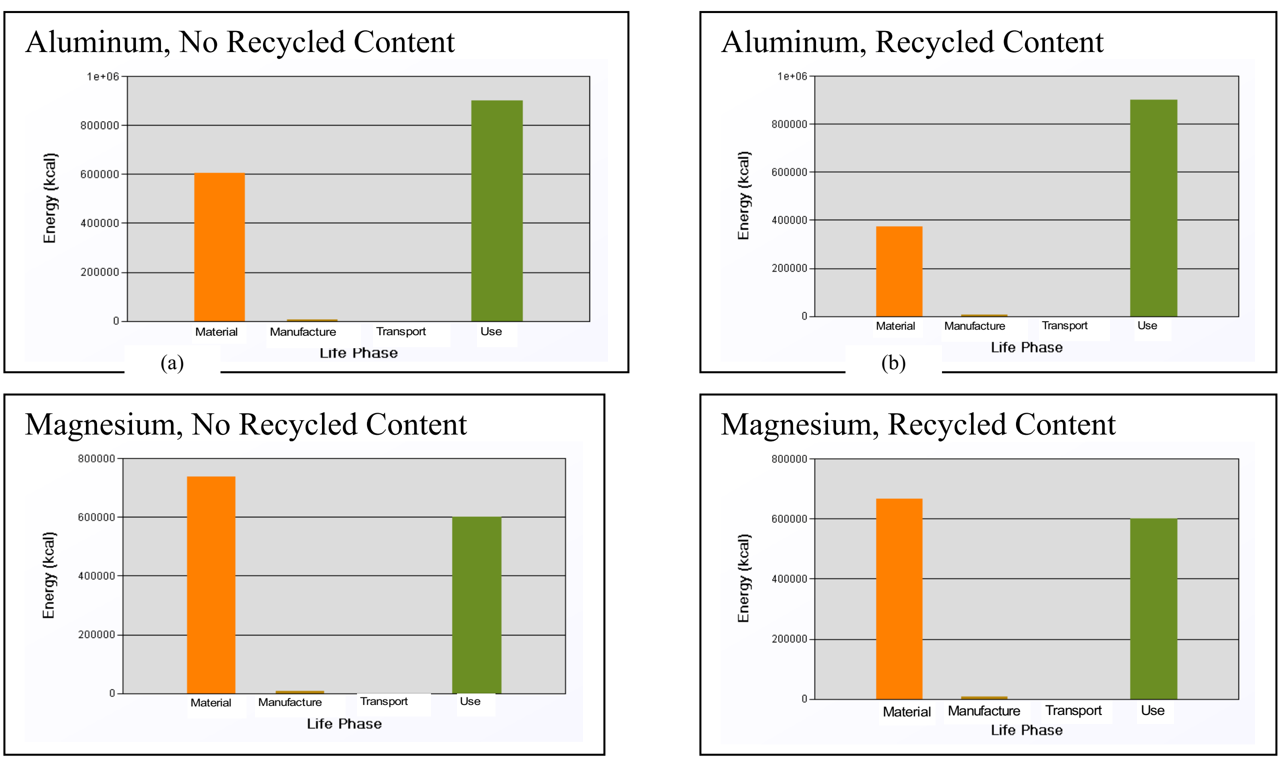


Figure 5. Energy consumption over life of top two materials

As it can be seen aluminum requires less production energy compared to magnesium by about 20%. However, since magnesium is lighter than aluminum by almost 30%, the magnesium proportionally contributes less to energy consumption. Thus far, magnesium seems to be more eco-friendly material than aluminum, since it has a lower embodied energy total by about 11%.

Let's examine the effect of a material sustainability factor - recycled content. Based on data in CES, aluminum and magnesium alloys in the current market supply, have about 42 and 10 percent of recycled content respectively. When this factor is taken into account, the energy saving in producing aluminum is considerably high (about 38%). However, when both sources of energy consumption (material production and use) are taken into account, there is no significant difference between aluminum and magnesium. Nonetheless, when we consider the second eco/sustainability factor, CO_2 footprint, aluminum outperforms magnesium by at least 50% in emission of CO_2 gas. Therefore, the aluminum alloy meets all technical and economical requirements for this product while overall, it offers a better eco/sustainability performance.

Table 1 summarizes the data used in this analysis.

As a common sense rule, if material production is the phase of concern, decision to select a material should be based on minimizing production energy or the associated emissions. However, if it is the use-phase that is of concern, selection should be based instead on light weight which is relevant to our medical device case. In cases where a product generates heat or conduct electricity during use, thermal insulation, or electrical conductivity are the technical attributes of interest for material selection.

TABLE 1. ECO/SUSTAINABILITY DATA FOR TOP TWO MATERIALS

	Virgin material			With recycled content			
	Primary Production Energy		CO2 Footprint	Primary production Energy		Recycled fraction in current supply	CO_2 Footprint
	kcal	%	lb/lb	kcal	%		lb/lb
Aluminum Alloy	606189	40	12	371455	29	42%	7
Weight: 27 lb							
Use: 200,000 miles	900944	60		900944	71		
Total	1507133	100		1272399	100		
Magnesium Alloy	738157	55	23	667020	52	10%	21
Weight: 19 lb							
Use: 200,000 miles	600629	45		600629	48		
Total	1338786	100		1267649	100		

V. CONCLUSION

This work provided an insight to a software tool for material and process selection with sustainability and environmental properties considerations. We examined the phases of material life that cause greatest concern. Dealing with all these requires data not only for eco attributes, but also data for cost and technical properties. The use of computer-aided material/process selection provides the users with a tool for accessing and managing a large amount of data in an efficient manner. As we demonstrated, a software tool can provide the decision makers with data about materials that cost less, while meeting technical specifications. With environmental and sustainability concerns in mind, the software also provides additional data including recycled content, energy consumption and polluting emissions which contribute to reusing or recycling materials and cleaner environment.

Given the importance of environmental and sustainability impact of materials and processes, this paper represents a welcome first step towards more experimental and case studies for application of computer-aided material/process selection and associated eco/sustainability auditing. Although such application is growing in academia, and to some degree in industrial situations, however, this is an evolving technology which at its current capacity can only offer a broad and quick assessment at early stage of product development. Definitely a robust commercial application of such computer-aided approach requires further software development and database expansion.

REFERENCES

[1] Ashby, M. F., Bréchet, Y. J. M., Cebon, D., & Salvo, L. (2004). Selection strategies for materials and processes. *Materials and Design*, *25*(1), 51-67.

[2] Ashby, M. F., & Cebon, D. (2003). Granta Design. *Cambridge Engineering Selector, CES4 Software for Materials Data Management,*

Product Overview.
[3] Esawi, A. M. K., & Ashby, M. F. (2003). Cost estimates to guide pre-selection of processes. *Materials and Design*, *24*(8), 605-616.
[4] Goodland, R. (1992). The Case that the World has Reached Limits. *Population, Technology, and Lifestyle: The Transition To Sustainability*.
[5] Pearce, A. R., Hastak, M., & Vanegas, J. A. (1995). A Decision Support System for Construction Materials Selection using Sustainability as a Criterion. In *Proceedings of the NCSBCS Conference on Building Codes and Standards* (pp. 1-4).
[6] SolidWorks Corporation. (n.d.). Sustainable Design-Not Just for Architecture Any More. Retrieved February 2, 2009, from http://www.solidworks.com/sw/docs/SustainableDesign_WP_ENG.pdf.