An Expert System for Selection of Environmental-Friendly Manufacturing Processes

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***Abstract*--Manufacturing process is one of the major phases of product life cycle which can be a contributing factor to significant environmental pollution and energy consumption. In this study a rule-based expert system model for manufacturing process selection is proposed by focusing on environmental impact of selected processes. Several environmental parameters including CO_2 emission, energy consumption, material waste, excessive heat and noise are taken into decision making process. The proposed expert system model can serve as a manufacturing knowledge management tool by encoding knowledge acquired from academic and industry experts as well as printed/online sources.**

I. INTRODUCTION

As an ethical responsibility, the product engineers and manages must try practicing sustainability in any product development project for maintaining the integrity of natural ecological systems and to insure that resources continue to be available for human use. One of the major opportunities for such practices is in production phase of product life cycle. That is, to apply an environmentally-centered approach for selecting a manufacturing process.

A considerable amount of work has been published in recent decade on the subject of environmental aspects of industrial materials through their life cycle phases. A closely related subject is the impact of material processing on environment. As a 2012 data shows (Fig. 1), U.S. manufacturing operations consume energy for various functions including in-process heating/cooling, machine drives and electrochemical processes. The data also point to carbon dioxide emission by various manufacturing activities and supporting systems. As figure 1 shows, almost half of manufacturing sector end use emissions are resulted from process heating applications. The next highest contributor of emissions is machine-driven uses.

It is estimated there are at least 1000 different methods of manufacturing [2]. Such vast number of processes and large volume of environmental performance data, can create a challenging task for manufacturing firms in determining how environmentally-friendly are their current operations and how to make such determination for future operations they might be considering. A small sample of such environmental performance data including energy usage and CO_2 emission for selected metal casting processes is shown in table 1.

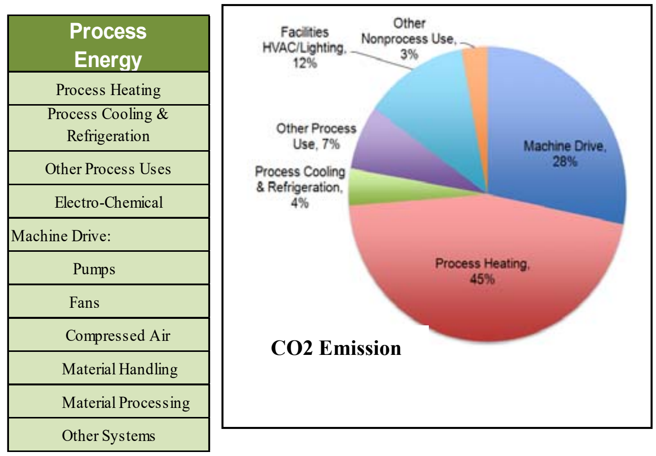

Figure 1. Energy use and CO_2 emission breakdown in U.S. manufacturing (Adapted from reference [1])

Considering such number of processes and associated environmental data, this study is aimed in developing a framework for a decision support expert system with the following features:

a) a knowledge base capable of storing environmental attributes of major manufacturing process categories (forming, casting, material removal, composite fabrication, polymer molding) and variations of processes in each category

b) an inference engine to search and recommend the most environmental-friendly processes based on a set of metrics

TABLE 1. ESTIMATED METAL CASTING ENERGY USAGE AND CO_2 EMISSIONS DATA
(ADAPTED FROM REFERENCE [3])

Casting Process	Tacit Energy 10^6 Btu/Ship Ton	Tons 10^3 CO2	2003 Estimated Ship Tons
Al Die Casting	60.6	6,217	1,585,720
Al Permanent Mold/Sand	99.4	1,372	373,266
Al Lost Foam	81.9	1,613	304,014
Mg Die Casting	67.8	486	106,600
Zinc Die Casting	23.4	515	344,000
Copper-Base; Sand casting	37.3	780	311,600

Though the scope of environmental impact of manufacturing operations extends to all phases of product life cycle, from material extraction, production, transportation, use and disposal, the focus of this study is on production phase, more specifically on an environmentally-centered decision making support for selecting a manufacturing process.

II. ENVIRONMENTAL METRICS

For the purpose of this study the following environmental attributes of manufacturing processes are taken into consideration.

Energy Consumption: Energy consumed in producing parts can be divided into direct energy use for processing material and the energy needed for ancillary systems. For instances, the energy is directly used to apply force in forging process, to melt a metal in casting and to shear material in a material removal process. Examples of energy consuming ancillary systems are hydraulic and coolant pumps in material removal and injection molding machines. Figure 2 shows energy measurement data for machining operations at a Toyota facility [4]. As can be seen most of the energy is consumed even while a machine is idling. Much of this energy is related to the pumping of coolants, lubricants, and hydraulic fluids that are later treated as wastes.

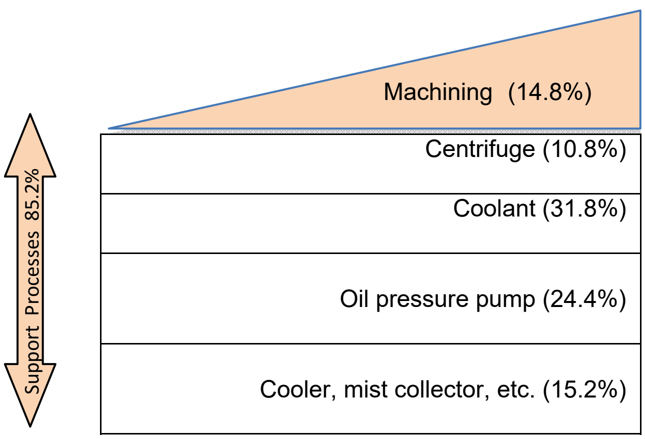

Figure 2. Energy use breakdown for machining in Toyota

CO_2 Footprint: There is a degree of international agreement and commitment to a progressive reduction in carbon emissions, generally interpreted as meaning carbon dioxide, CO_2 [5]. This gas is typically generated as a result of chemical reaction directly taken place during a process or burning fossil fuel. Examples of such process are various types of metal casting processes and electro-discharge machining process. Also heating coolant and lubricant during a material removal process can generate CO_2 among other gases.

Material Waste: Material waste can be a significant cost burden for a business and minimizing it is one of the common product design and manufacturing considerations. If it is not recycled, it can impact the environment by polluting landfills. Recycling the waste is a step toward a sustainable natural resources available for human use.

Excessive Heat: While heat generated during a process has direct impact on energy consumption, its excess may not be tolerable in certain facilities. Example of high temperature processes are heat treatment, metal casting and hot forging.

Excessive Noise: The traditional definition of noise is "unwanted or disturbing sound"**.** The persistent and escalating sources of sound can often be considered an annoyance [6]. Excessive noise can be unsafe and unbearable in certain facilities, working environment or nearby community.

III. METHODOLOGY

Step 1: Knowledge Database

An expert system is an interactive computer-based decision tool that employs both facts and heuristics to answer hard decision problems founded on the knowledge obtained from experts [7]. A knowledge-based decision support system such as rule-based expert system can assist product designers and facility managers in searching a large database for best alternative manufacturing method that minimizes negative impact on environment. The proposed expert system in this study captures environmental data associated with a broad range of manufacturing processes. Table 2 depicts a data sample for a subset of the processes along with levels of environmental impacts for the five metrics under study. A three-level performance rating is used as a rough estimate of a process's environmental performance.

TABLE 2. ENVIRONMENTAL METRICS/DATABASE FOR SELECTED PROCESSES

Processes	Energy Use	CO2 Emission	Material Waste	Excess Heat	Excess Noise
Sand casting	M	H	M	H	M
Die Casting	M	M	L	H	M
Powder Pressing	M	M	L	H	L
Machining	L	L	H	L	M
Wire EDM	H	L	L	M	L
Die Sink EDM	H	L	H	M	L
Water Jet	L	L	L	L	M
Injection Molding	M	L	L	M	L
Thermoforming	M	L	M	M	L
Tube Piercing	M	M	M	H	M
Centrifugal Casting	M	H	M	H	M
Investment Casting	M	H	M	H	M
Hot Forging	H	L	L	H	H
Hot Extrusion	M	L	L	M	L

L: low impact M: moderate impact H: high impact

Step 2: Decision Logic Tree

Decision logic tree diagram is commonly used in expert system-based studies because of its capability in visualizing all factors that must be considered in reaching a decision. For the proposed system in this study, a list of candidate manufacturing processes is entered through a user interface screen. For each candidate process the system database is searched for extracting the related environmental data. At this stage a decision logic is applied to determine whether the candidate process is recommendable or not. Figure 3 displays the decision logic for the proposed system.

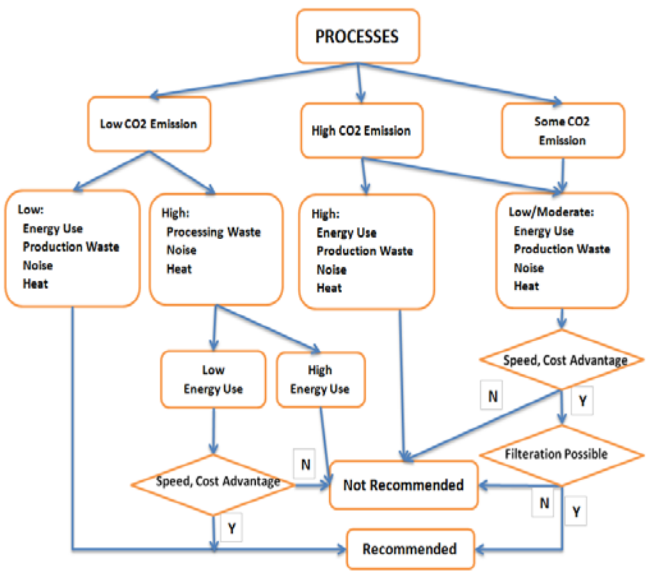

Figure 3. Decision Logic Tree

In this decision logic tree, processes are classified in three categories: low CO_2 emission, high CO_2 emission, some CO_2 emission. Below is the interpretation of one of the branches of the decision tree.

Low CO_2 emission: processes that produce little or no CO_2 emission are divided in two categories:

a) those which are low in energy use, producing waste, noise and heat. If a match is found through the database search, a process is recommended.

b) those which are high in producing waste, noise and heat but low in energy use. In this case since the candidate process satisfies both primary environmental performances, it is recommended by the system only if the user prefers this process because of its production speed and/or capital cost advantage.

Step 3: Logic Rules

Rules of the following types will be coded in the knowledge base, mimicking the ways in which human expert analyze the data and making decision:

IF CO2 Emission is LOW
AND Waste is HIGH
AND Heat is HIGH
AND Noise is HIGH
AND Energy Use is High
THEN Reject the candidate process

IF CO2 Emission is LOW
AND Waste is HIGH
AND Heat is HIGH
AND Noise is HIGH
AND Energy Use is LOW
AND Speed/Cost Advantage is YES
THEN accept the candidate process

IV. USER INTERFACE DESIGN

Interaction between the user and the proposed expert system is supported through a graphical user-system dialogue as conceptualized in figure. 4. At top of the screen, the user enters the importance rating for the five environmental metrics. Next, the candidate processes are entered. Based on these entries, the system displays the initial recommendations by accepting or rejecting a process. Next, system asks for user's preference regarding production speed and cost of a candidate process. The final recommendation is then displayed along with a justification remarks.

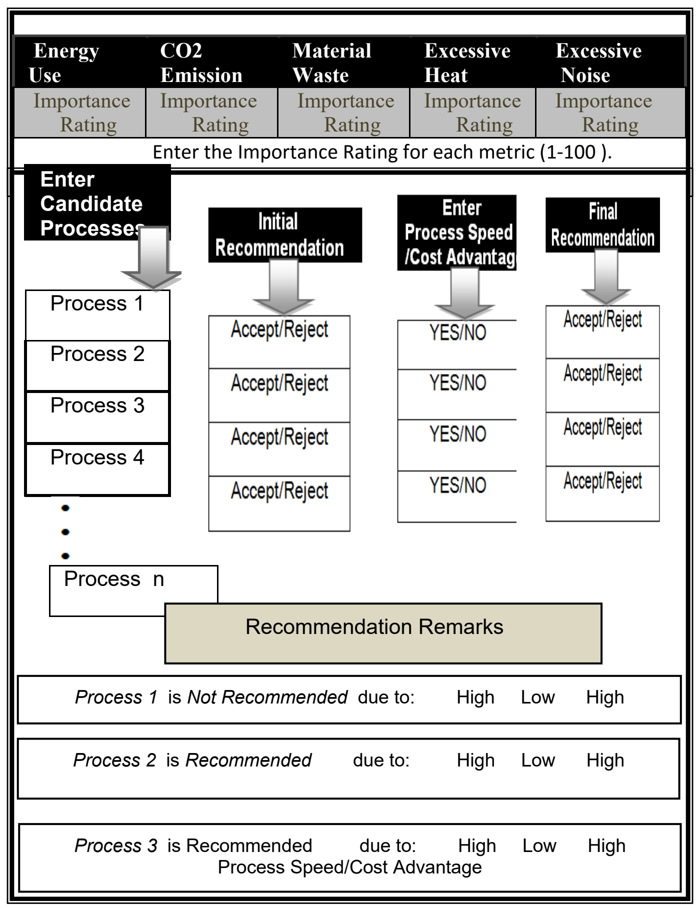

Figure 4. User interface screen

IV. SYSTEM TESTING

To verify the functionality of the proposed expert system, several trial runs will be conducted. For illustration purpose, a hypothetical case is presented here. This case involves identifying an environmentally-friendly manufacturing process for producing a spur gear as part of an oil pump (Fig. 5). This pump is part of drive system of a construction equipment. Based on design features of the part and process capabilities, the following processes have been identified as feasible candidates for manufacturing this part:

Sand Casting
Forging
Milling
Investment Casting
Wire EDM
Powder Pressing

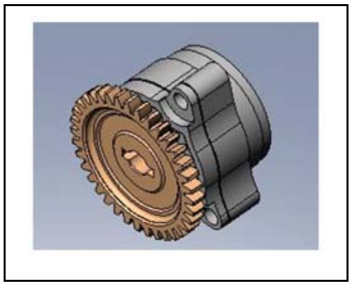

Figure 5. Oil pump example

Figure 6 shows a possible outcome of consultation with the expert system.

Energy Use	CO2 Emission	Material Waste	Excessive Heat	Excessive Noise
30%	20%	10%	20%	10%

Enter Candidate Processes	Initial Recommendation	Process Speed/Cost Advantage	Final Recom.
Sand Casting	Reject		
Invest. casting	Reject		
Forging	Reject		
Milling	Recommend	No	Reject
Wire EDM	Recommend	No	Reject
Powder Pressing	Recommend	Yes	Recom.

Figure 6. Expert system recommendations

V. CONCLUSION

In this study, we presented the framework of an expert system for an environmental focused manufacturing process screening as a foundation for developing a functional and quick decision making tool. The system recommends or rejects a process based on a set of environmental metrics including energy use, carbon dioxide emission, material waste, excessive heat and noise while meeting the production speed and budget constraints. The decisions made based on the recommendations of a completed expert system can contribute to a cleaner environment and a sustainable ecosystem.

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