Integrating Axiomatic Design Principles into Sustainable Product Development

Lee Guang Beng^{1,#} and Badrul Omar¹

¹ Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia

Corresponding Author / E-mail: hd110141@siswa.uthm.edu.my, TEL: +65-91470188

KEYWORDS: Axiomatic Design, Sustainable Product Development, Design for EOL Management, Green Supplier Selection, Sustainable Manufacturing

Owing to mounting environmental issues, coupled with public pressure and stringent regulations, firms and companies have to alter their ways of developing new products. Three key areas i.e. end-of-life (EOL) management, green supply chain and sustainable manufacturing have to be considered during design stage. The purpose of this paper is to propose a framework based on axiomatic design (AD) principles to facilitate sustainable product development by aiding the decision making process in the abovementioned key areas. Several examples have been provided in this paper to demonstrate the application of crisp and fuzzy AD approaches with the aim of assisting analysis and/or decision making process. Results show that axiomatic design principles are able to guide designer/engineer in selecting functional embodiment that facilitates product recovery and fuzzy axiomatic design approach can be effective when dealing with problems concerning green supplier selection and optimization of manufacturing solution. Hence, a framework for sustainable product realization is proposed in the last section of this paper with a vision of providing guideline for companies in designing and developing products that are less harmful to the environment.

Manuscript received: January 16, 2014 / Revised: March 16, 2014 / Accepted: March 17, 2014

NOMENCLATURE

AD = axiomatic design
 DP = design parameter
 EOL = end of life
 FR = functional requirement
 HPJAM = high pressure jet assisted machining
 I_i = information content
 p_i = probability of fulfilling FR_{*i*}
 S_{OP} = operational sustainability
 S_{SHE} = safety, health and environment
 TFN = triangular fuzzy number
 w_j = weight factor for criterion *j*

currently contain a total of 30 million people. Each year, 7 billion tons of carbon dioxide is added to the atmosphere by worldwide human activities.¹ In 2006, the U.S. manufacturing sector recorded an output with gross value of \$5.3 trillion (in the form of a variety of products).² About 84% of energy-related carbon dioxide emissions and 90% of the energy consumption can be attributed to these products.³ More and more products are being produced to provide services or to be consumed by people directly as a result of population growth and the improvement in the quality of life,⁴ which further complicates environmental sustainability challenge and thus, it is important to reduce environmental footprints associated with these products in order to address environmental issues.⁵

Worsening environmental issues, together with public pressure and more stringent regulations are the fundamental factors that impact the way firms/companies design and release new products globally.⁶ Hence, firms/companies are being held responsible for producing products in an environmentally friendly way.⁵ This demands proper training in the context of sustainability (along with a global perspective) for the next generation of engineers with the aim of solving sustainability problems on multiple scales.⁷ Another area of future importance is the seamless integration of sustainability into design practices.⁵ Potentially, axiomatic

1. Introduction

The human population increased from less than 2 billion to over 6 billion people during the 20th century and the largest cities in the world

design can be utilized to achieve the aforementioned purpose owing to its advantages stated as follows:⁸

- Differentiates between objectives (or requirements) and means (or solutions).
- Allows structured approach to decomposition, making possible step-wise, consistent operationalization and specification of objectives and means.
- Allows cause-effect relationships and objectives-means hierarchies to be systematized.
- Aids visualization and communication.

2. Literature Review

2.1 Sustainable Product Development

Other than end-of-life (EOL) management and recycling of products, sustainable product development requires a shared responsibility to implement and realize sustainability throughout the life cycle. Fig. 1 shows the necessary considerations to be taken account during the design stage to attain sustainable product development which include downstream issues such as supply chain and manufacturing.⁵

End-of-life(EOL) management is described as a process of converting EOL products into re-marketable products, components, or materials⁵ and product design is the most important factor in achieving profitable EOL management.^{5,9}

Green purchasing can be defined as an environmentally conscious purchasing practice that reduces sources of waste and promotes the recycling and reclamation of purchased materials.¹⁰ It is a boundary-spanning function within the supply chain.¹¹⁻¹³ Furthermore, it is deemed as a firm's gate-keeper that influences forward flow and material quality.¹⁴ Green et al. highlighted that purchasing is potentially a more powerful agent of change as compared with any other corporate function.¹⁵ Quite similarly, Preuss suggested that purchasing is an important agent for changing environmental initiatives in the supply chain¹⁴ and Min and Galle also stated that incorporating a company's environmental goals with purchasing activities is essential because purchasing is at the beginning of the green supply chain.¹⁶

Fig. 1 Design decisions affect every stage of a product's life⁵

The product manufacturing process is seen as the main stage in the life cycle that involves direct resource consumption and is responsible for producing environmental pollutant. Also, in terms of sustainable development, it is the main factor that impacts the result of company's performance.¹⁷ Process improvement and optimization is one of the efforts to minimize the environmental impacts of manufacturing processes.⁵ Process optimization allows trade-off among performance and sustainability measures to be made, and therefore to provide the optimal combinations of operating parameters and to propose ways of enhancing and improving sustainability level.¹⁸

2.2 Axiomatic Design

Axiomatic design (AD) system is a design model based on product attribute in which two axioms are utilized for design. The first axiom highlights the necessity to maintain independence of functional requirements (FR) while the second one is to minimize the information necessary to meet the FRs.¹⁹ In other words, a good design should fulfill its various FRs independently and simply.²⁰

The relationship between functional requirements and design parameters (DPs) can be expressed mathematically as follows:

$$\{FR\} = [A]\{DP\} \quad (1)$$

where,

$\{FR\}$ is the functional requirement vector;

$\{DP\}$ is the design parameter vector; and

$[A]$ is the design matrix that characterizes the design

The type of design being considered is defined by the structure of $[A]$ matrix. To fulfill the independence axiom, $[A]$ matrix of a design should be uncoupled or decoupled. FR-DP relationships according to matrix $[A]$ are shown in equations (2), (3) and (4). If the design matrix is a diagonal matrix, it is an uncoupled design which perfectly satisfies the independence axiom because each DP can satisfy a corresponding FR. When the design matrix is triangular as shown in equation (3), the design is a decoupled design. A decoupled design satisfies the independence axiom if the design sequence is correct. Under this circumstance, DP_1 is first determined for FR_1 and fixed. FR_2 is satisfied by the choice of DP_2 and the fixed DP_1 . DP_3 is determined in the same manner with the fixed DP_1 and DP_2 . When a design matrix is neither diagonal nor triangular (see equation (4)), the design becomes a coupled design in which FRs are unable to be satisfied independently by any sequence of DPs.¹⁹

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \quad (4)$$

According to the information axiom, the best design among all design alternatives that satisfy independence axiom is the one that has the smallest information content (I_i). As represented by the following equation, I_i can be related to p_i , which is the probability of satisfying the given functional requirement FR_i , and the relationship between I_i and p_i is inversely proportional.

$$I_i = \log_2\left(\frac{1}{p_i}\right) \quad (5)$$

The probability of having a successful design is governed by “design range” and “system range”. Design range is a designer-specified range of tolerance whereas system range means the capability of the system in delivering what the designer desires to achieve. Acceptable design solution exists in the region where design range and system range overlap as depicted in Fig. 2.¹⁹ Hence, p_i (in the case of uniform probability distribution function) can be formulated as

$$p_i = \left(\frac{\text{common range}}{\text{System range}}\right) \quad (6)$$

Considering a design scenario that involves multiple FRs (e.g. bottle-can opener as shown in Fig. 3), information content can be calculated as follows, assuming that the probability of satisfying FR_1 with DP_1 is 0.9 and the one for FR_2 with DP_2 is 0.85.²¹⁻²²

$$\begin{aligned} I_{\text{total}} &= I_1 + I_2 = \log_2\left(\frac{1}{0.9}\right) + \log_2\left(\frac{1}{0.85}\right) \\ &= 0.1520 + 0.2345 \\ &= 0.3865 \end{aligned}$$

The abovementioned crisp AD approach can be used as the solution of decision-making problems where available information is suitable to be modeled by probability theory.²³ However, one needs to be aware

Fig. 2 Design range, system range, common range and probability density function of a FR¹⁹

FR₁ : Design a device that can open bottles.
FR₂ : Design a device that can open cans.

Fig. 3 Bottle-can opener with its essential FRs²¹⁻²²

that expressing qualitative and linguistic decision variables in the form of crisp numbers would be ill defined.²³⁻²⁴ While crisp AD approach cannot be utilized when available information is qualitative and linguistic, fuzzy set theory is particularly useful when dealing with imprecision of language and human thought in decision-making process.²³

As for Fuzzy Information Axiom approach, triangular fuzzy number (TFN, as shown in Fig. 4) can be used to express data in linguistic terms when system and design ranges happen to be stated linguistically. The notation of TFN and information content are formulated by equation (7) and equation (8) respectively. In this case, the common area is the intersection between TFNs of design range and system range as illustrated in Fig. 5.²⁴⁻²⁵

$$\mu(x) = \begin{cases} \frac{x-c}{a-c}, & (c \leq x \leq a) \\ \frac{b-x}{b-a}, & (a \leq x \leq b) \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

$$I_i = \log_2\left(\frac{\text{TFN of system range}}{\text{Common area}}\right) \quad (8)$$

Both crisp and fuzzy AD approaches have been applied extensively for design and decision making purposes. A review of literature indicates that AD principles have been utilized in five major areas of applications namely (1) product design, (2) system design, (3) manufacturing system design, (4) software design and (5) decision-making.²³ For instance, Shin et al. employed the crisp approach in designing a nuclear fuel spacer grid.²⁶ Apart from that, Gumus et al. developed a product development lifecycle model based on the independence axiom and design domains.²⁷ As for fuzzy AD, the approach is utilized in a multi-attribute transportation company selection problem by Kulak and Kahraman.²⁵ Also, it has been used in

Fig. 4 Triangular fuzzy number²³

Fig. 5 The common area of system and design ranges, where α , δ , κ , and λ are parameters that represent the TFNs²⁴⁻²⁵

manufacturing system selection by Kulak et al.²⁴ The authors applied fuzzy AD approach to identify suitable punching machine among a number of alternatives. Besides that, Celik et al. also employed the information axiom to select the best docking facilities of shipyards.²⁸ Nonetheless, the application of AD principles for sustainable product development can be considered being in its infancy stage.

3. An Axiomatic Approach to Achieve Sustainable Product Development

3.1 The Role of Axiomatic Design

This section discusses the potential application of axiomatic design principles in the three key areas (i.e. design for sustainable EOL, green supplier selection and optimization for sustainable manufacturing) as well as its feasibility to address sustainability issues.

3.1.1 Design for Sustainable EOL

Nowadays, disposal can no longer be the primary retirement strategy for products that reach their end-of-life, due to stronger stewardship for product retirement urged by environmental regulations. To reduce waste and save resources, end-of-life (EOL) management can be a useful solution.⁵ In this aspect, additional FRs can be introduced during problem definition stage to differentiate design objectives that address environmental needs from product FRs that are related to customer needs.²⁹ For instance, when a set of FRs and DPs are given as follows to prescribe the design of closed-back housing for a media player (shown in Fig. 6), both Embodiment 1 and Embodiment 2 (see Fig. 7) should be considered acceptable since they are able to meet all three FRs determined previously. Embodiment 3 should be discarded as it does not fulfill FR₃.

FR₁: To provide protection for internal components
 FR₂: To enable viewing of display screen through housing
 FR₃: To maximize volume available to store components without increasing the device size

DP₁: Maintain substantial overall housing thickness
 DP₂: Introduce an opening on housing which is covered by transparent window
 DP₃: An area of reduced thickness around the opening that allows transparent window to abut

However, one should notice that the previous set of FRs and DPs do not specify design requirement from product recovery standpoint.

Fig. 6 Example: media players with closed-back housing

Considering a scenario of replacing defective window during product refurbishment, FR₄ and DP₄ should be taken into account during problem definition stage in order to minimize product recovery cost and in turn lead to higher recovery profit. Note that FR₄ is further decomposed into FR₄₁ and FR₄₂. Lesser parts lead to shorter time to complete disassembly, fewer breakdowns and a smaller amount of labor required to perform disassembly. At the same time, easy disassembly operation means reduction in time, tools, labor and rework needed for product disassembly.³¹

FR₁: To provide protection for internal components

FR₂: To enable viewing of display screen through housing

FR₃: To maximize volume available to store components without increasing the device size

FR₄: Easier or more economical disassembly of the parts in product³¹

FR₄₁: Fewer parts needed for disassembly in a disassembled unit

FR₄₂: Easy disassembly operations for the parts in the disassembled unit

DP₁: Maintain substantial overall housing thickness

DP₂: Introduce an opening on housing which is covered by transparent window

DP₃: An area of reduced thickness around the opening that allows transparent window to abut

DP₄: Defective window to be replaced by minimal recovery operations³¹

DP₄₁: Reduce the number of parts needed for disassembly

DP₄₂: Design the parts with ease of disassembly

If recovery-related FRs and DPs were included during the problem definition stage (denoted by FR₄ and DP₄), Embodiment 1 would be ruled out as well since it requires additional effort to remove and replace the transparent window during recovery process. It involves prying action, removal of bezels and sliding the window out of the housing with other components attached to it.³² In contrast, the transparent window can be removed more easily from the housing if

Fig. 7 Cross-sectional view of each embodiment taken from line A-A across screen area³⁰

Embodiment 2 was adopted. It can be achieved by simply prying the window after heating the adhesive with a blower.³³ This embodiment also facilitates the reassembly process as the transparent window may be adhered directly onto the housing without having to place the window into the housing.

3.1.2 Analysis of Environmental Capabilities for Green Supplier Selection

Selection of supplier is a process of choosing key suppliers based on a set of pre-established criteria. When dealing with green supplier selection, environmental criteria can be divided into two broad groups i.e. quantitative and qualitative criteria. Depending on environmental management strategy practiced by an organization, one or both groups of criteria may be used at the same time for selection of green supplier. Quantitative criteria include pollutant costs (expenditure related to pollution and energy consumption) and improvement costs (investment in improving environmental performance). Only supplier(s) who has satisfactory result in this stage shall proceed further for qualitative analysis.³⁴ Fig. 8 shows a systematic model of the environmental framework. The information axiom can be particularly useful when dealing with such analysis problem. Data collected (either in numerical term or linguistic factor) for each alternative supplier can be converted into quantifiable scores (information content) with the help of equations (5) to (8). From there, ranking of alternatives can be achieved by arranging the suppliers according to their calculated information content. Supplier with the smallest information content should be selected as most eligible green supplier.

As an example, a set of FRs and DPs concerning quantitative capabilities are set by a buyer company as follows and a list of suppliers (together with their improvement and pollutant costs) are given in Table 1.

FR₁: Total pollutant costs should be minimized with the acceptable limit of +25%

FR₂: Total improvement costs should be maximized with the acceptable limit of -25%

According to FR₂, the most eligible green supplier should have the maximum improvement costs and the minimum allowable limit is 25% lesser compared to the maximum amount. Under this circumstance, information content for improvement costs of Supplier F should be calculated in this manner (refer to Fig. 9):

$$\begin{aligned} \text{Area of system range} &= (1,837,500 - 0) \times 1 \\ &= 1,837,500 \end{aligned}$$

$$\begin{aligned} \text{Area of common range} &= [1,837,500 - 0.75(2,000,000)] \times 1 \\ &= 337,500 \end{aligned}$$

$$\begin{aligned} I_2 &= \log_2 \left(\frac{\text{System range}}{\text{Common range}} \right) \\ &= \log_2 \left(\frac{1,837,500}{337,500} \right) \\ &= 2.445 \end{aligned}$$

Table 1 Total pollutant costs and total improvement costs recorded for each of the legal suppliers

Supplier Name	Total Pollutant Costs (USD)	Total Improvement Costs (USD)
Supplier A	1,137,850	2,000,000
Supplier B	1,503,700	1,900,000
Supplier C	1,018,000	1,630,000
Supplier D	1,877,000	1,370,000
Supplier E	968,900	1,435,650
Supplier F	1,145,000	1,837,500
Supplier G	1,673,800	1,243,600

Fig. 8 Environmental framework for incorporating environmental criteria into the supplier selection process³⁴

When information content for each alternative supplier is calculated with respect to quantitative environmental criteria, a similar tabulation as shown in Table 2 can be obtained. The results indicate that only Suppliers A, C and F have finite information content and are qualified for qualitative analysis at the next stage.

Previously, a case study has been presented to apply fuzzy AD approach to evaluate suppliers qualitatively.³⁵ The proposed approach is able to translate qualitative terms such as “good”, “fair” and “excellent” into weighted score and thus lead to indicative results that rank alternative suppliers according to qualitative environmental capabilities. Utilizing similar approach, qualitative environmental criteria of Suppliers A, C, and F can be analyzed and ranked according to their calculated weighted information content. Smaller information content signifies higher eligibility. This information can be useful to procurement team in order to incorporate company’s environmental policy into purchasing activities.

3.1.3 Optimization for Sustainable Manufacturing

Machining processes constitute a major manufacturing activity that contributes to the development of the worldwide economy.³⁶ In the developed world, it is estimated that machining processes contribute about 5% of the total GDP. Furthermore, the importance of machining is anticipated to increase even further due to shorter product cycle and more flexible manufacturing systems induced by economic factors.³⁷ Owing to the aforementioned reasoning, machining is chosen to be the focus of discussion in this section.

Optimization problem of sustainable machining involves a few types of parameters including the functionality/performance, cutting

condition and sustainability level.¹⁸ The following FRs and DPs can be used for easier visualization on the cause-effect relationship:³⁸

FR₁: To maintain cutting condition within manageable range

FR₂: To attain satisfactory machining performance

FR₃: To achieve process sustainability at desired level

DP₁: Parameters of cutting condition must be set within constraints

DP₂: Employ adequate cooling method

DP₃: All sustainability factors to satisfy respective requirement

The relationship between the FRs and DPs can be stated in terms of design equation (see equation (9)). Note that both DP₁ and DP₂ have to be considered in order to achieve FR₂. Previous research has proven that machining performance (e.g. surface roughness and material removal rate) differs with cooling methods and cutting conditions utilized for the machining process.^{18,36} Besides that, it can be seen that all three DPs are involved when it comes to satisfying FR₃. This is due to the dependency of sustainability parameters on cutting condition and cooling method set by the user as experiments have shown that machining cost and energy consumption vary with cutting speed and coolant delivery systems.³⁶ In this case, the design matrix obtained is a triangular matrix which signifies that the design being considered is a decoupled design. Under this circumstance, with the purpose of satisfying the independence axiom, DPs should be adjusted in a particular sequence. DP₁ should be varied first to meet FR₁, followed by adjusting DP₂ to fulfill FR₂. Lastly, DP₃ can be determined to achieve FR₃.¹⁹ In this case, parameters of cutting condition such as feed rate and cutting speed must first be determined within constraint before selecting cooling method to fulfill desired machining performance. After that, for each selected cooling method (with given cutting conditions), sustainability parameters can be analyzed and compared against the requirement.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \quad (9)$$

To analyze the sustainability level of machining processes, a hybrid model (consists of crisp and fuzzy AD approaches) can be employed to yield performance score (in terms of information content) for each process. Following the information axiom, process sustainability can be identified by their respective information content. The smallest information content signifies the most sustainable process. Table 3 shows an example of sustainability performance consists of operational sustainability (S_{OP}) as well as environmental friendliness, health and safety (S_{SHE}) for a list of alternative processes. For demonstration purpose, fuzzy AD approach is used to convert performance of HPJAM (environmental friendliness) into information content using system range subjectively set by decision maker as in Fig. 10, together with a set of pre-determined design range as follows, with the application of equations (5) to (8).

FR₃₁: Machining cost per part must be in the range of \$0 to \$1.85.

FR₃₂: Energy consumption per part must be in the range of 0 to 0.15 kWh.

FR₃₃: Part cleaning cost must be in the range of \$0 to \$0.08.

FR₃₄: Environmental friendliness must be at least 5 (5,20,20).

Fig. 9 Improvement costs of Supplier F: Crosshatched area denotes common range

Table 2 Information contents: Suppliers’ quantitative environmental capabilities

Supplier Name	Pollutant Costs	Improvement Costs	Sum
Supplier A	3.927	2.000	5.927*
Supplier B	Infinite	2.248	Infinite
Supplier C	2.676	3.648	6.324*
Supplier D	Infinite	Infinite	Infinite
Supplier E	2.406	Infinite	Infinite
Supplier F	4.066	2.445	6.511*
Supplier G	Infinite	Infinite	Infinite

FR₃₅: Operational safety must be at least 5 (5,20,20).

FR₃₆: Personnel health must be at least 5 (5,20,20).

With the aid of Fig. 11, a detailed calculation of information content for environmental friendliness of HPJAM is given below. Note that respective weighting factors can be imposed on S_{SHE} and S_{OP} ³⁷ and it can be done by applying equation (10).^{24,25} In this case, equal weight of 0.5 is used for both S_{SHE} and S_{OP} .

$$\begin{aligned} \text{Area of system range} &= 0.5(10 - 4)(1) \\ &= 3 \end{aligned}$$

Fig. 10 TFNs for intangible factors²⁵

Fig. 11 Environmental friendliness of HPJAM: crosshatched area denotes intersection of design range and system range

$$\begin{aligned} \text{Area of common range} &= 0.5(10 - 5)(0.2778) \\ &= 0.6945 \end{aligned}$$

$$\begin{aligned} I_{34} &= \log_2 \left(\frac{\text{System range}}{\text{Common range}} \right) \\ &= \log_2 \left(\frac{3}{0.6945} \right) \end{aligned}$$

$$\begin{aligned} I_{34}(\text{weighted}) &= 2.111^{0.5} \\ &= 1.4529 \end{aligned}$$

$$I_{ij} = \begin{cases} \left[\log_2 \left(\frac{1}{p_{ij}} \right) \right]^{1/w_j}, & (0 \leq I_{ij} < 1) \\ \left[\log_2 \left(\frac{1}{p_{ij}} \right) \right]^{w_j}, & (I_{ij} > 1) \\ w_j, & I_{ij} = 1 \end{cases} \quad (10)$$

When weighted information content for each alternative process is calculated based on sustainability criteria (using crisp and fuzzy AD approaches), tabulation as shown in Table 4 can be obtained. After that, unit index of each category are calculated by dividing the total information contents in Table 4 by the number of sub-criteria of category. For example, the category of operational sustainability factor has three sub-criteria namely machining costs, energy consumption and waste management. The total information content for these factors should be divided by three in order to obtain the unit index for operational sustainability. This step is essential because each criterion consists of different numbers of sub-criteria which may affect the sum of information content.²⁴ Calculated unit indexes are organized and shown in Table 5. Table 5 indicates that conventional machining is the

Table 5 Unit indexes for weighted information content (* denotes viable process that satisfies all FRs with minimum information content)

Manufacturing Process	Operational Sustainability	Safety, Health and Environment	Sum
Conventional Machining	1.8288	2.6415	4.4702*
Cryogenic machining	Infinite	0.0000	Infinite
HPJAM	Infinite	0.7909	Infinite

Table 3 Sustainability performance corresponding to cutting condition.

Machining Process	S_{OP}			S_{SHE}		
	Machining Costs	Energy Consumption	Waste Management	Environmental Friendliness	Operational Safety	Personnel Health
	(\$/part)	(kWh/part)	(\$/part)			
Conventional machining	1.811	0.148	0.078	Poor	Poor	Poor
Cryogenic machining	2.016	0.147	0.004	Excellent	Excellent	Excellent
HPJAM	1.794	0.202	0.074	Fair	Good	Good

Table 4 Weighted information contents

Machining Process	S_{OP}			S_{SHE}		
	Machining Costs	Energy Consumption	Waste Management	Environmental Friendliness	Operational Safety	Personnel Health
	(\$/part)	(kWh/part)	(\$/part)			
Conventional machining	1.7931	1.9717	1.7215	2.6415	2.6415	2.6415
Cryogenic machining	Infinite	1.8146	0.0000	0.0000	0.0000	0.0000
HPJAM	1.6370	Infinite	1.1413	1.4529	0.4598	0.4598

only viable process that satisfies all required sustainability performance. Both cryogenic machining and HPJAM have infinite information content due to unsatisfying machining costs and energy consumption respectively.

3.1.4 Summary

From EOL standpoint, AD principles can potentially guide designers/engineers to produce enhanced product architecture that simplifies product recovery procedure when refurbishment-related requirement is involved during problem definition stage. This advantage will in turn lead to a substantial cost-saving and bring higher recovery profit.

When dealing with green supplier selection, the information axiom can be utilized as multi-criteria analysis approach that translates suppliers' environmental capabilities (either in cost-based numbers or linguistic factors) into information content. Calculated information content can eventually serve as indicator for ranking of alternative suppliers.

Design equation (9) provides a visualization of optimization problem concerning sustainable machining. An optimized manufacturing solution can possibly be obtained by following a step-by-step procedure namely (1) setting the cutting condition within manageable range, (2) selecting adequate cooling method and (3) analysis of sustainability performance. Furthermore, a hybrid model (comprises of crisp and fuzzy AD approach) can facilitate analysis of process sustainability that involves criteria weight for both S_{OP} and S_{SHE} .

3.2 Proposed Sustainability Framework

A sustainable product development framework (see Fig. 12) is proposed by rearranging the FRs and DPs used throughout the previous

section in hierarchical manner. Note that the chart is constructed by using machining as example of major manufacturing process. One should be aware that this framework is applicable to but not limited to products manufactured by means of machining. FRs and DPs being considered in Fig. 12 are listed as follows:

- FR₁: To achieve sustainable product development
- FR₁₁: Functional product that enables effective product recovery
- FR₁₂: Sustainable supply chain management
- FR₁₃: Environmentally conscious manufacturing
- FR₁₁₁: Media player to have small-sized body and simplistic appearance (example)
- FR₁₁₂: Product to have high recovery potential
- FR₁₂₁: To purchase raw material for closed-back housing from green supplier (example)
- FR₁₃₁: To adopt optimized manufacturing solution for closed-back housing (example)
- FR₁₁₁₁: Closed-back housing to provide protection for internal components (example)
- FR₁₁₂₁: Easier or more economical disassembly of the parts in the product (example)
- FR₁₂₁₁: Supplier(s) to have adequate qualitative environmental capability
- FR₁₂₁₂: Supplier(s) to show satisfactory qualitative environmental capability
- FR₁₃₁₁: Manageable cutting conditions
- FR₁₃₁₂: Satisfactory manufacturing performance
- FR₁₃₁₃: Desired sustainability performance

Fig. 12 Hierarchy of FRs and DPs to achieve sustainable product development

- DP₁: To consider EOL management, green supply chain and sustainable manufacturing during design stage
- DP₁₁: Design for EOL management
- DP₁₂: Purchase from green supplier(s)
- DP₁₃: Adopt optimized manufacturing solution
- DP₁₁₁: To use closed-back housing with overall dimensions of 50 mm×30 mm×7 mm and button-less control (example)
- DP₁₁₂: Fewer parts (or less material volume) in product and more economical replacement of parts in discarded product (example)
- DP₁₂₁: Raw material supplier to be assessed based on qualitative and quantitative environmental criteria (example)
- DP₁₃₁: Cutting conditions, sustainability and machining performance to be considered during optimization (example)
- DP₁₁₁₁: Maintain substantial housing wall thickness (example)
- DP₁₁₂₁: Defective window to be replaced by minimal recovery operations (example)
- DP₁₂₁₁: Supplier(s) to meet pollutant and improvement costs requirement
- DP₁₂₁₂: Supplier(s) to have acceptable capabilities in terms of management competencies, green image, design for environment, environmental management systems and environmental competencies
- DP₁₃₁₁: Cutting condition to be set within realistic/achievable range
- DP₁₃₁₂: Employ adequate cooling method
- DP₁₃₁₃: All sustainability factors to satisfy respective requirement

The top-level requirement for firms/companies to fulfill is to achieve sustainable product development (FR₁). This can potentially be attained by considering EOL management, green supply chain and sustainable manufacturing process (DP₁). Hence, FR₁ is further decomposed to yield FR₁₁, FR₁₂ and FR₁₃ which dictate requirements for the three key areas. To increase productivity and thus the profit of a product recovery process, the product must be designed to accommodate simple refurbishment process (DP₁₁) and in order to practice green supply chain strategy, parts/raw material must be purchased from green supplier(s) (DP₁₂). Finally, an optimized manufacturing solution is required with the purpose of meeting process sustainability (DP₁₃).

FR₁₁ can be strategically decomposed to properly address requirements regarding product function, customer needs and most importantly, requirements that concern product refurbishment (FR₁₁₁ and FR₁₁₂). Ideally, all parts should be purchased from green suppliers in order to properly address environmental issues. Therefore, FR₁₂ is further decomposed to specifically impose such requirement on each item (FR₁₂₁ - FR_{12N}). Then, suppliers of each item should meet the respective quantitative and qualitative environmental criteria (FR₁₂₁₁ and FR₁₂₁₂). Likewise, all parts/components of a product must be manufactured by means of environmentally conscious process so as to maximize the product's overall sustainability. Consequently, FR₁₃ is decomposed to another level to particularly state requirements related to sustainable process for each part (FR₁₃₁). As mentioned beforehand, this study uses machining process as illustrative example and should therefore involve requirements related to cutting conditions and machining performance only (FR₁₃₁₁ - FR₁₃₁₃). Other factors (e.g. molding parameters) shall be included should the product calls for additional types of manufacturing techniques.

The chart serves as a general guideline for FRs and DPs related to sustainable product development and therefore, the hierarchy can be expanded by further decomposing the FRs to involve more detailed, assembly-specific requirements. By performing the procedure presented in the previous section, with the aid of the set of proposed FR and DP hierarchy, an environmentally friendly product that considers the recovery procedure, green supply chain and sustainable manufacturing can potentially be developed.

4. Conclusions

With its wide range of application and significant potential in formalizing design and development process, the integration of axiomatic design principles into sustainable product development has been the main focus of this paper. Particularly, application of axiomatic design principles into the areas of design for EOL management, green supplier selection and sustainable manufacturing have been demonstrated by using illustrative examples with the aim of emphasizing the feasibility of using such approach in reducing impact to the environment due to product development activities.

It is advisable to include FRs relevant to product recovery during problem definition stage as it is likely to lead to design alternative that can contribute to higher recovery profit with the help of AD principles. Also, information axiom can be used for multi-criteria analysis problems as seen in green supplier selection and evaluation of sustainability performance of manufacturing process. Data collected in terms of numerical form or linguistic factor are able to be converted into indicative performance scores (information content) that can subsequently facilitate selection/decision making process. Such decisions (concerning design for EOL management, green supplier selection and sustainable manufacturing) made during early design/development stage are expected to benefit subsequent lifecycle phases as design/development stage usually involves decisions that brings most significant impact to other stages.³⁹

In the last section of the paper, a proposed framework for sustainable product development has been constructed by means of decomposition. The framework prescribes the general rules for decision making in the three key areas namely EOL management, green supplier selection and sustainable manufacturing with a vision of realizing sustainable product development.

ACKNOWLEDGEMENT

This research was funded by the Ministry of Higher Education, Malaysia under grant no. ERGS Vot E024. The authors would like to acknowledge the entire organization of Universiti Tun Hussein Onn Malaysia for its continuous support and contribution that lead to the success of this research.

REFERENCES

1. Ayres, R. U. and Ayres, L. W., "A Handbook of Industrial Ecology," Edward Elgar, 2002.

2. BEA, "Annual Industry Accounts," http://www.bea.gov/about/pdf/IED_Annual.pdf (Accessed 20 Sep. 2010)
3. EIA, "2002 Manufacturing Energy Consumption Survey," 2006.
4. Chertow, M. R., "The IPAT Equation and Its Variants: Changing Views of Technology and Environmental Impact," *J. Ind. Ecol.*, Vol. 4, No. 4, pp. 13-29, 2000.
5. Zhao, F., Sutherland, J., Handwerker, C., Choi, J. -K., Kim, H., and et al., "Integrated Sustainable Life Cycle Design: A Review," *Journal of Mechanical Design*, Vol. 132, No. 9, Paper No. 091004, 2010.
6. Choi, J. K., Nies, L. F., and Ramani, K., "A Framework for the Integration of Environmental and Business Aspects Toward Sustainable Product Development," *Journal of Engineering Design*, Vol. 19, No. 5, pp. 431-446, 2008.
7. Miheclic, J. R., Paterson, K. G., Phillips, L. D., Zhang, Q., Watkins, D. W., and et al., "Educating Engineers in the Sustainable Futures Model With a Global Perspective," *Civil Engineering and Environmental Systems*, Vol. 25, No. 4, pp. 255-263, 2008.
8. Duda, J. W., "A Decomposition-Based Approach to Linking Strategy, Performance Measurement, and Manufacturing Systems Design," Ph.D Thesis, Massachusetts Institute of Tech. Dept. of Mechanical Engineering, Cambridge, pp. 235-239, 2000.
9. Kwak, M. and Kim, H. M., "Evaluating End-of-Life Recovery Profit by a Simultaneous Consideration of Product Design and Recovery Network Design," *Journal of Mechanical Design*, Vol. 132, No. 7, pp. 1-17, 2010.
10. Min, H. and Galle, W. P., "Green Purchasing Practices of US Firms," *Int. J. Oper. Prod. Manage.*, Vol. 21, No. 9/10, pp. 1222-1238, 2001.
11. Webster, F. J., "The Changing Role of Marketing in the Corporation," *J. Marketing*, Vol. 56, No. 4, pp. 1-17, 1992.
12. Leenders, M. R. and Fearon, H. E., "Purchasing and Materials Management," Richard D. Irwin, 1993.
13. Williams, A. J., Guinipero, L. C., and Henthorne, T. L., "The Cross-Functional Imperative: the Case of Marketing and Purchasing," *Int. J. Purchasing Mater. Manage.*, Vol. 30, No. 3, pp. 29-33, 1994.
14. Preuss, L., "In Dirty Chains? Purchasing and Greener Manufacturing," *Journal of Business Ethics*, Vol. 34, No. 3-4, pp. 345-359, 2001.
15. Green, K., Morton, B., and New, S., "Green Purchasing and Supply Policies: Do They Improve Companies' Environmental Performance?" *Supply Chain Management: An International Journal*, Vol. 3, No. 2, pp. 89-95, 1998.
16. Min, H. and Galle, W. P., "Green Purchasing Strategies: Trends and Implications," *International Journal of Purchasing and Materials Management*, Vol. 33, No. 3, pp. 10-17, 1997.
17. Gutowski, T., "Design and Manufacturing for the Environment," *Handbook of Mechanical Engineering*, Springer-Verlag, 2004.
18. Jawahir, I. S., Wanigarathne, P. C., and Wang, X., "Product Design and Manufacturing Processes for Sustainability," Chapter 12 *Mechanical Engineers' Handbook: Manufacturing and Management*, John Wiley & Sons, 2006.
19. Suh, N. P., "The Principles of Design," Oxford University Press, pp. 3-54, 1990.
20. Finger, S. and Dixon, J. R., "A Review of Research in Mechanical Engineering Design. Part I: Descriptive, Prescriptive, and Computer-Based Models of Design Processes," *Research in Engineering Design*, Vol. 1, No. 1, pp. 51-67, 1989.
21. Suh, N. P., "A Theory of Complexity, Periodicity and the Design Axioms," *Research in Engineering Design*, Vol. 11, pp. 116-131, 1999.
22. Park, G. J., "Analytic Methods for Design Practice," Springer, pp. 17-105, 2007.
23. Kulak, O., Cebi, S., and Kahraman, C., "Applications of Axiomatic Design Principles: A Literature Review," *Expert Systems with Applications*, Vol. 37, No. 9, pp. 6705-6717, 2010.
24. Kulak, O., Durmuolu, M. B., and Kahraman, C., "Fuzzy Multi-Attribute Equipment Selection Based on Information Axiom," *Journal of Materials Processing Technology*, Vol. 169, No. 3, pp. 337-345, 2005.
25. Kulak, O. and Kahraman, C., "Fuzzy Multi-Attribute Selection Among Transportation Companies using Axiomatic Design and Analytic Hierarchy Process," *Information Sciences*, Vol. 170, No. 2, pp. 191-210, 2005.
26. Shin, M. K., Lee, H. A., Lee, J. J., Song, K. N., and Park, G. J., "Optimization of a Nuclear Fuel Spacer Grid Spring using Homology Constraints," *Nuclear Engineering and Design*, Vol. 238, No. 10, pp. 2624-2634, 2008.
27. Gumus, B., Ertas, A., Tate, D., and Cicek, I., "The Transdisciplinary Product Development Lifecycle Model," *Journal of Engineering Design*, Vol. 19, No. 3, pp. 185-200, 2008.
28. Celik, M., Kahraman, C., Cebi, S., and Er, I. D., "Fuzzy Axiomatic Design-Based Performance Evaluation Model for Docking Facilities in Shipbuilding Industry: The Case of Turkish Shipyards," *Expert Systems with Applications*, Vol. 36, No. 1, pp. 599-615, 2009.
29. Lee, G. B. and Badrul, O., "An Axiomatic Approach to Design for Sustainable End-of-life: A Review of Literature," *Applied Mechanics and Materials*, Vol. 315, pp. 705-709, 2013.
30. Weber, D. J., Moolsintong, P. J., and Zadesky, S. P., "Media Player with Machined Window Undercut and Transparent Wall Disposed Therein," US Patent, No. 20120281344A1, 2012.
31. Chen, K. Z., "Development of Integrated Design for Disassembly and Recycling in Concurrent Engineering," *Integrated Manufacturing Systems*, Vol. 12, No. 1, pp. 67-79, 2001.

32. iFixit.com, "iPod Nano 2nd Generation Teardown," <http://www.ifixit.com/Teardown/iPod+Nano+2nd+Generation+Teardown/592/1> (Accessed 25 Aug. 2013)
33. Detwiler, B., "Apple iPod Nano 6th Generation (2010) Teardown," <http://www.techrepublic.com/pictures/apple-ipod-nano-6th-generation-2010-teardown/> (Accessed 25 Aug. 2013)
34. Humphreys, P. K., Wong, Y. K., and Chan, F. T. S., "Integrating Environmental Criteria into the Supplier Selection Process," *Journal of Materials Processing Technology*, Vol. 138, No. 1, pp. 349-356, 2003.
35. Lee, G. B. and Badrul, O., "Green Supplier Selection: Analysis of Qualitative Environmental Criteria using Fuzzy Axiomatic Approach," *Applied Mechanics and Materials*, Vol. 465, pp. 1054-1059, 2014.
36. Pusavec, F., Kramar, D., Krajnik, P., and Kopac, J., "Transitioning to Sustainable Production - Part II: Evaluation of Sustainable Machining Technologies," *Journal of Cleaner Production*, Vol. 18, No. 12, pp. 1211-1221, 2010.
37. Jayal, A. D., Badurdeen, F., Dillon Jr, O., and Jawahir, I. S., "Sustainable Manufacturing: Modeling and Optimization Challenges at the Product, Process and System Levels," *CIRP Journal of Manufacturing Science and Technology*, Vol. 2, No. 3, pp. 144-152, 2010.
38. Lee, G. B. and Badrul, O., "Optimization for Sustainable Manufacturing Based on Axiomatic Design Principles: a Case Study of Machining Processes," *Advances in Production Engineering & Management*, Vol. 9, No. 1, pp. 31-43, 2014.
39. Rebitzer, G., "Integrating Life Cycle Costing and Life Cycle Assessment for Managing Costs and Environmental Impacts in Supply Chains," *Cost management in supply chains*, Springer, pp. 127-146, 2002.