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SUSTAINABLE PRODUCT DEVELOPMENT BASED ON AXIOMATIC DESIGN PRINCIPLES: AN INDUSTRIAL APPLICATION

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ABSTRACT

This paper reports an industrial application of framework based on axiomatic design (AD) principles to facilitate sustainable product development. A pedestal fan is used as the main subject of study and the case study was carried out in a household appliance company involving cross-functional collaboration between designer, procurement manager and manufacturing engineer to increase recovery profit of the product, while ensuring the sustainability of the supply chain and manufacturing at the same time. 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, this framework can be employed to provide guideline for companies in designing and developing sustainable products that are less harmful to environment in the subsequent lifecycle stages.

Keywords: axiomatic design, sustainable product realization, design for EOL management, green supplier selection.

INTRODUCTION

As a result of population growth as well as the improvement of quality of life, more products are being manufactured to offer services or to be consumed directly by users (Chertow, 2000). This complicates environmental sustainability challenge and hence, it is important to minimize environmental footprints associated with these products in order to address environmental issues (Ramani *et al.* 2010). Mounting environmental issues, coupled with public pressure and stricter regulations are the main drivers that motivate worldwide firms/companies to change their ways of designing and releasing new products (Choi *et al.* 2008). Firms/companies are being held responsible for producing products in an environmentally friendly way and seamless integration of sustainability into design practices is seen as an area of future importance (Ramani *et al.* 2010).

In this paper, an application of axiomatic design (AD) framework to facilitate sustainable product development process is presented and discussed. The industrial application is done in electrical appliance companies based in South East Asia (SEA). The companies, Dyson Operations Pte. Ltd. and Dyson Manufacturing Sdn. Bhd. are subsidiaries of Dyson Technology Ltd., located at Singapore and Malaysia respectively. Dyson Ltd. is a British technology company that designs and manufactures vacuum cleaners, hand dryers, bladeless fans, and heaters while its SEA facilities focus on developing engineering solutions for product design and manufacturing.

The main focus of this case study is about developing a guided product development process that brings positive impact to the (end-of-life) EOL management, green supply chain as well as the manufacturing sustainability. Readers are directed to previous literature for better understanding of the proposed approach (Lee and Badrul, 2014a), (Lee and Badrul, 2014b), (Lee and Badrul, 2014c). Using a sub-assembly of a tower fan as a subject of study, employees of various departments were requested to involve in a development process that aims to produce a refined solution by collecting data, providing suggestion/alternatives alongside other necessary input, and giving their insight in the area of sustainable development.

METHODOLOGY

Selection of Subject

A subject (e.g. a product) is required to engage the respondents and to demonstrate application of proposed approach in real-life scenario. Ease of access to the product information and relevance to the case study were among the factors considered during the selection of subject. Some products being developed are highly confidential and are not allowed to be disclosed to the public by any means in near future. Therefore, the information concerning the chosen subject must be accessible publicly and/or reachable via published sources. Apart from that, the subject of study must be relevant to the case study and able to simulate real sustainability problem that is related to the proposed approach. The product being used as subject of study is an Air Multiplier™ pedestal fan. Particularly, the respondents were asked to focus on the problems that lie in the sub-assembly of lower casing portion. There are problems observed in this sub-assembly which concern the design for EOL management, green supplier selection and also sustainable manufacturing that can potentially be solved by the proposed approach. Also, information concerning this product (and its sub-assemblies) are accessible via online articles, magazines, and also granted patents.

Selection of Respondents

The respondents were selected based on their job scope relevance, career exposure and understanding on the subject being studied (i.e. the product they were informed with the general workflow and purpose of this exercise, data to be collected individually, as well as the expected outcome after the completion of the case study. The Stakeholder - D.S. Lee is currently an Engineering Manager at Dyson Operations Pte. Ltd., Singapore. Prior to his tenure with this company, Lee has been working with a few other companies that develop home entertainment system and printing solutions which include printer, plotter and photo kiosk. Lee is a very experienced engineer/manager in South East Asia region and has been involved in product design and development for 14 years to date, mostly in Singapore and Penang, Malaysia.

The Designer - Nick Tan is working as a Senior Design Engineer at Dyson Operations Pte. Ltd., Singapore. He is currently managing a group of Design Engineers to complete engineering tasks given (failure analysis, new concept development, etc.) and is also required to provide guidance, engineering solutions and design proposal from time to time. Before joining Dyson, Nick was working with JVC for 12 years, and involved extensively in development of home entertainment and car audio systems. One of his notable projects with the company was to develop a car audio system that was equipped with motorized head unit. He later joined Phillips where he started developing televisions and other products in this category before moving on to his career at Dyson. In total, Nick has been working in the industry of consumer electronics for 19 years. He is very familiar with the product design and development industry in South East Asia region as he has been stationed primarily in Singapore throughout his career and was traveling to some other regional areas for business purpose.

The Procurer - Sharon Lee is a Procurement Manager at Dyson Operations Pte. Ltd., Singapore. She is involved extensively in Dyson's procurement activities for electronic and electro-mechanical components. As a Procurement Manager, Sharon needs to be technically inclined and is equipped with very strong engineering background. Her day-to-day tasks include sourcing of required components as well as auditing and assessing suppliers' capability and competency. Cost benchmarking is also one of her expertise. Her input on current market trend, industrial standard and new technology availability is very valuable to the Dyson's Research, Design and Development (RDD) team. To date, Sharon has 21 years of experience in procurement process. Prior to her current position at Dyson, she has been employed by Hewlett Packard (HP) and Flextronics. Sharon is stationed mainly in Singapore and it is necessary for her to travel frequently to regional countries to visit suppliers for audit process. Therefore, she is very well-verse with the capabilities of the regional suppliers.

The Manufacturing Engineer - W.T. Koh is a Manufacturing Engineer at Dyson Manufacturing Sdn. Bhd., Malaysia. At Dyson, he is required to advise manufacturing equipment specification, manufacturing cycle time and process flow. To date, he has completed a few vacuum cleaner manufacturing projects during his employment at Dyson. Prior to his tenure with Dyson, Koh was working with a company that develops vision inspection system for detecting defects in advanced electronic components. Koh currently has more than 3 years of working experience in product manufacturing industry in Malaysia.

Data Collection and Analysis

Interview sessions (in-depth interviews) were conducted with each of the respondents to collect their understanding and point of view on sustainable product development. Furthermore, these interviews enable better understanding on the respondents' background, work experience and current job scope. The interviewees were also asked to share other 'green' approach they have come across in their previous companies and/or other companies in the industry. Each of the respondents also discussed the work-related activities involved at Dyson and necessary effort given by the company to achieve sustainability. They were also required to share their thoughts on how to implement effective 'green' practice and sustainable product development as a corporate process.

Other than that, the respondents were required to give their input to support the proposed approach. For instance, the stakeholder was required to decided weight factor for analysis of suppliers' environmental performance and selection of sustainable manufacturing process. On the other hand, designer was asked to provide ideas and solutions that can potentially improve the recoverability of the subject being discussed and the procurement manager was responsible for conducting questionnaire survey and provide grading for each of the alternative suppliers identified. Manufacturing engineer was also tasked to provide estimation of cutting conditions, breakdown of costs and other resources required to produce certain parts within the sub-assembly.

After the input from each of the respondents were collected, the information was compiled and tabulated (Boyce and Neale, 2006) before being analysed by means of axiomatic design approach as stated in previous literature. Next, the respondents were briefed again about the outcome of the analysis.

RESULTS

This section presents the details of the information collected from each of the respondents to support the proposed axiomatic design approach with the aim to improve the product development sustainability by tackling the areas EOL management, supply chain and manufacturing. Also, this section shows the result of data analysis that led to the selection of certain design alternatives, manufacturing options and sources of components. Figure-1 shows hierarchy of functional requirements (FR) and design parameters (DP) to achieve

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sustainable product development for the concerned area. Each of the FRs and DPs are listed as follows:

FR_1 : To achieve sustainable product development
FR_{11} : Functional product that enables effective product recovery
FR_{12} : Sustainable supply chain management
FR_{13} : Environmentally conscious manufacturing
FR_{111} : Fan to be safe, durable, acoustically pleasing and user-friendly
FR_{112} : Fewer parts or less material volume used in a product
FR_{121} : To purchase PCBA from green supplier
FR_{131} : To adopt optimized manufacturing solution for metal boss
FR_{1111} : Product should be stable and enough to prevent toppling
FR_{1112} : Main Body to withstand 3 to 5 oscillation cycles per minute for 3-year warranty life
FR_{1113} : Product should have good acoustic performance below or equal to 63 dba (Vacuums & More, 2015)
FR_{1114} : There must be feature on the product to enable the customer to power on/off the product plus control the fan speed
FR_{1121} : Less hardware in a product
FR_{1122} : No unnecessary parts for any phase of product lifecycle in a product
FR_{1211} : Supplier(s) to have adequate quantitative environmental capability
FR_{1212} : Supplier(s) to show satisfactory qualitative environmental capability
FR_{1311} : Manageable cutting conditions
FR_{1312} : Satisfactory manufacturing performance
FR_{1313} : Desired sustainability performance
FR_{12111} : Total pollutant costs should be minimized with the acceptable limit of +50%
FR_{12112} : Total improvement costs should be maximized with the acceptable limit of -50%
FR_{12121} : All sub-criteria of management competencies (MC) must be over 5 (5,20,20)
FR_{12122} : All sub-criteria of green image (GI) must be over 5 (5,20,20)
FR_{12123} : All sub-criteria of design for environment (DE) must be over 5 (5,20,20)
FR_{12124} : All sub-criteria of environmental management (EM) systems must be over 5 (5,20,20)
FR_{12125} : All sub-criteria of environmental competencies (EC) must be over 5 (5,20,20)
FR_{13131} : Machining cost per part must be in the range of MYR 0 to 3.50
FR_{13132} : Energy consumption per part must be in the range of 0 to 6 kWh
FR_{13133} : Part cleaning cost must be in the range of MYR 0 to 5.00
FR_{13134} : Environmental friendliness must be at least 5 (5,20,20)
FR_{13135} : Operational safety must be at least 5 (5,20,20)
FR_{13136} : Personnel health must be at least 5 (5,20,20)

DP_1 : To consider EOL management, green supply chain and sustainable manufacturing during design stage
DP_{11} : Design for EOL management
DP_{12} : Purchase from green supplier(s)
DP_{13} : Adopt optimized manufacturing solution
DP_{111} : Fan to pass toppling test, survive maximum potential oscillation cycles, have acceptable sound power level and built-in physical control
DP_{112} : Reduce the number of parts or material volume used in a product
DP_{121} : PCBA supplier to be assessed based on qualitative and quantitative environmental criteria
DP_{131} : Cutting conditions, sustainability and machining performance to be considered during optimization
DP_{1111} : Base stand with diameter of 200mm to 300mm to be attached to lower casing
DP_{1112} : Main body to have substantial reinforcement at bottom area to prevent fatigue failure due to cyclical bending stress from the oscillation module
DP_{1113} : Acoustic foam to be placed in main body
DP_{1114} : Mechanism such as push-button and/or control knob to be incorporated into product
DP_{1121} : Speed control to be performed by holding on/off button
DP_{1122} : On/off button to be made transparent to allow IR ray from remote control
DP_{1211} : Supplier(s) to meet pollutant and improvement costs requirement
DP_{1212} : Supplier(s) to have acceptable capabilities in terms of management competencies, green image, design for environment, environmental management systems and environmental competencies
DP_{1311} : Cutting condition to be set within realistic/achievable range
DP_{1312} : Employ adequate cooling method
DP_{1313} : All sustainability factors to satisfy respective requirement
DP_{12111} : Select Supplier F and Supplier S
DP_{12112} : Select Supplier F and Supplier S
DP_{12121} : Select Supplier F as green supplier
DP_{12122} : Select Supplier F as green supplier
DP_{12123} : Select Supplier F as green supplier
DP_{12124} : Select Supplier F as green supplier
DP_{12125} : Select Supplier F as green supplier
DP_{13131} : Process III to be employed to produce part
DP_{13132} : Process III to be employed to produce part
DP_{13133} : Process III to be employed to produce part
DP_{13134} : Process III to be employed to produce part
DP_{13135} : Process III to be employed to produce part
DP_{13136} : Process III to be employed to produce part

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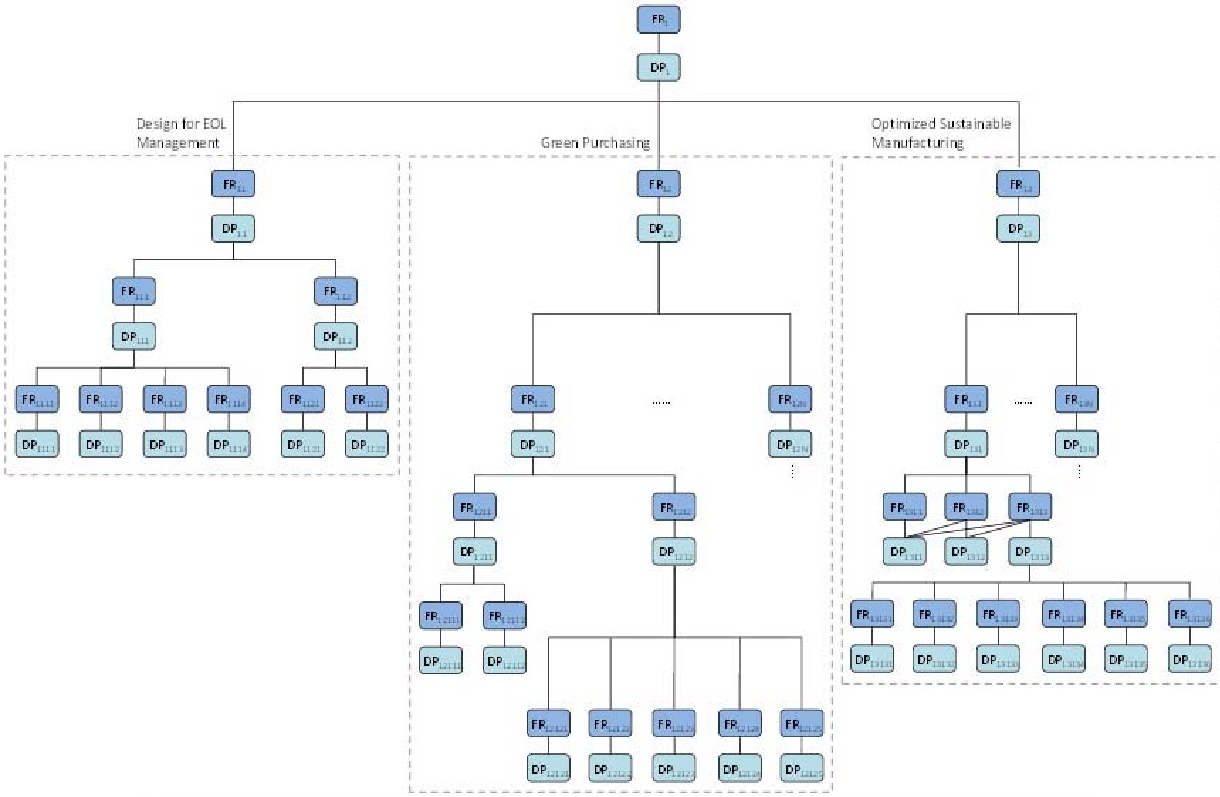

Figure-1. Hierarchy of FRs and DPs to achieve sustainable product development for lower casing portion of pedestal fan.

Stakeholder's Input

The study to improve the pedestal fan in terms of sustainability started with collecting input from project stakeholder (in this case, D.S. Lee). Such input include functional requirement concerning customer needs and product functions as well as design requirement prescribed to facilitate product refurbishment. Lee stated that the product is expected to be safe for users, acoustically pleasing and user-friendly. When asked about the refurbishment-related requirements, Lee mentioned that the product should consist of fewer parts or less material. Regarding the acceptance threshold for quantitative analysis of suppliers environmental capabilities, Lee pointed out that 50% is an acceptable level in this case considering the fact that there were only limited number of suppliers being shortlisted. Lee also decided that criteria weight for qualitative analysis of suppliers' environmental capabilities should be as tabulated in Table-1. He emphasised on management competencies as he assigned the highest weight factor to this particular category. He opined that senior management's support and decision is crucial to the implementation of green policies. Apart from that, Lee was asked to provide his views on selection of manufacturing process, he suggested that the sustainability requirements and their respective weight factors should be as presented in Table-2 and Table-3. Concerned for the workers' safety and well-being, Lee specified heavier weight for the category of 'Safety, Health and Environment'.

Design for EOL Management: Lower Casing Portion

By following the hierarchy of FRs and DPs (depicted in Figure-1) and input from stakeholder, Designer Nick Tan specified the essential sub-FRs and sub-DPs to satisfy customer needs and to ensure that the EOL product is recoverable. Figure-2 shows two different embodiments of lower casing portion of pedestal fan. These embodiments are adopted from recent patents filed by Dyson Technology Limited (Dyson and Brough, 2014), (Smith *et al.* 2014). A base stand (part B) is used to prevent toppling of product. At the same time, to address the concern of fatigue failure due to long hours of fan oscillation, Nick Tan added reinforcement ribs to Main Body C as a countermeasure. Acoustic foam D is added into the product to substantially increase the acoustic performance to meet the desired level. Mechanism such as push-button and/or control knob are incorporated into lower casing A to enable the interaction between users and the product (e.g. allow speed control).

When recovery-related FRs and DPs are incorporated during problem definition stage (denoted FR_{112} and DP_{112}), Embodiment 1 will be ruled out since it requires more parts to be produced and assembled when user interaction (UI) mechanism is to be refurbished.

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Embodiment 1 employs a dial (part H) to adjust fan speed and introduces a transparent window (part I) to allow transmission of infrared (IR) ray. As for Embodiment 2, the need for part H is eliminated by integrating the fan speed adjustment function into the power button E. By holding power button E, the software adjusts the fan speed gradually to the maximum level and then slowly back to the minimum level. By implementing Embodiment 2 in which the power button E is made transparent, transparent window (part I) is also excluded since the IR ray can now be transmitted through the power button.

Additional parts/components in an assembly will eventually lead to a comparatively complicated disassembly and reassembly processes (Lee and Badrul, 2015). One should note that the two embodiments are comparable to each other in terms of fulfilling customer needs if recovery-related FRs and DPs were not taken into consideration. Inclusion of recovery-related FRs and DPs distinguished the two embodiments and ruled out the one that requires lengthier procedure for refurbishing the UI assembly.

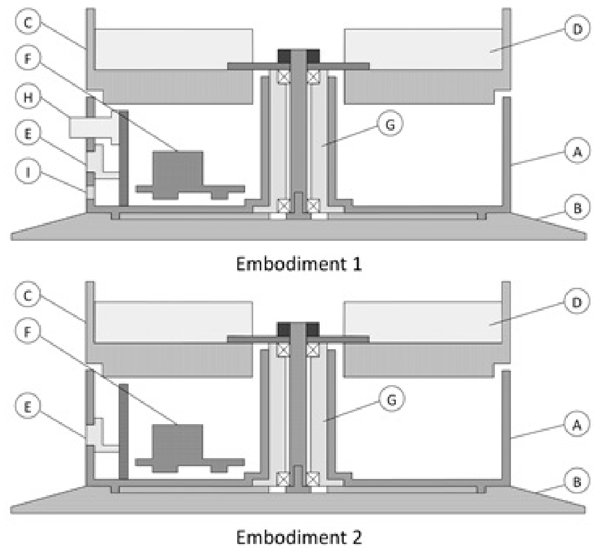

Figure-2. Possible design alternatives for lower casing portion of a pedestal fan.

Table-1. Stakeholder's input on criteria weight for qualitative analysis of suppliers' environmental capabilities (in percentage).

	Management Competencies	'Green Image'	Design for Environment	Environmental Management Systems	Environmental Competencies
Weight	25	20	20	15	20

Table-2. Stakeholder's input on sustainability requirement for manufacturing process.

	Operational Sustainability			Safety, Health and Environment		
	Machining Costs (MYR/part)	Energy Consumption (kWh/part)	Waste Management (MYR/part)	Environmental Friendliness	Operational Safety	Personnel Health
Requirement	0 - 3.5	0 - 6	0 - 5	5 / 20	5 / 20	5 / 20

Table-3. Criteria weight factor for selection of manufacturing process.

	Operational Sustainability	Safety, Health and Environment
Criteria weight	40	60

Table-4. Total pollutant costs and total improvement costs recorded for each of the PCBA suppliers.

Supplier Name	Total Pollutant Costs (MYR)	Total Improvement Costs (MYR)
Supplier E	480,000	183,000
Supplier F	456,427	200,000
Supplier S	307,283	240,154
Supplier V	500,000	200,000

Table-5. Information contents: Suppliers' quantitative environmental capabilities.

Supplier Name	Pollutant Costs	Improvement Costs	Sum
Supplier E	Infinite	1.540	Infinite
Supplier F	4.997	1.323	6.320*
Supplier S	0.930	1.000	1.930*
Supplier V	Infinite	1.323	Infinite

Green Supplier Selection: Printed Circuit Board

In this section, collected data and results of environmental capability analysis on printed circuit board assembly (PCBA) are being presented. Procurement manager Sharon Lee was asked to collect a series of cost-related information from a list of shortlisted alternative suppliers. Incidentally, the available suppliers that produce PCBA for Dyson's products are limited to those tabulated in Table-4. The names and contact information of the alternative suppliers are to be remained confidential. Therefore, they are represented only by the characters of "E", "F", "S" and "V". Table-4 shows the total pollutant costs and improvement costs given by various alternative suppliers. Pollutant costs include solid waste disposal costs, water waste treatment costs, chemical waste disposal costs and so on. On the other hand, improvement costs (expenditure dedicated to improve environmental performance) are such as costs for staff training, spending on new equipments, and recycling costs (Humphreys *et al*. 2003). When information content for each alternative supplier is calculated with respect to quantitative environmental criteria set by the stakeholder, a tabulation as shown in Table-5 can be obtained. The results indicate that only Suppliers F and S (denoted by asterisks) have finite information content and are qualified for qualitative analysis at the next stage.

Using a set of questionnaire forms, procurement manager then investigated the qualitative capabilities of the eligible suppliers and graded them with linguistic terms such as "poor", "good", "excellent" and so on. Table-6 shows the performance grades of each of these categories for each supplier as determined by procurement manager in response to a series of questions. By employing identical system range and calculation procedure as shown in previous literature, calculated unit indexes are shown in Table-8. By having the smallest sum of unit indexes, Supplier F is deemed as the most eligible green supplier, followed by Supplier S.

Selection of Optimized Green Manufacturing Process: Metal Boss

This section presents results and data collected by Manufacturing Engineer for the purpose of sustainability performance analysis with the aim of attaining an optimized process to produce a metal boss (part G in Figure-2) being used in the lower casing portion to hold a central shaft extending from the upper casing portion.

These components are part of the mechanism that enables the oscillation of the pedestal fan about its central axis.

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Table-6. Evaluation results presented by procurement manager in respect of qualitative factors.

	Management Competencies				'Green Image'			Design for Environment					Environmental Management Systems				Environmental Competencies			
	Senior Management Support	Environment Partners	Training	Information Exchange	Customer's Purchasing Retention	Green Market Share	Stakeholders Relationship	Recycle	Reuse	Remanufacture	Disassembly	Disposal	Environmental Policies	Environmental Planning	Implement and Operation	ISO 14001 Certification	Clean technology availability	Use of environmental friendly material	Pollution reduction capability	Returns handling capability
Supplier F	E	V	E	E	V	E	E	V	V	V	V	V	E	E	V	E	V	V	E	G
Supplier S	V	G	V	G	V	V	V	G	G	G	G	G	E	V	V	E	F	V	V	G

Table-7. The weighted results of information content for alternative suppliers.

	Management Competencies				'Green Image'			Design for Environment					Environmental Management Systems				Environmental Competencies			
	Senior Management Support	Environment Partners	Training	Information Exchange	Customer's Purchasing Retention	Green Market Share	Stakeholders Relationship	Recycle	Reuse	Remanufacture	Disassembly	Disposal	Environmental Policies	Environmental Planning	Implement and Operation	ISO 14001 Certification	Clean technology availability	Use of environmental friendly material	Pollution reduction capability	Returns handling capability
Supplier F	0.0000	0.0010	0.0000	0.0000	0.0002	0.0000	0.0000	0.0002	0.0002	0.0002	0.0002	0.0002	0.0000	0.0000	0.0000	0.0000	0.0002	0.0002	0.0000	0.1433
Supplier S	0.0010	0.2113	0.0010	0.2113	0.0002	0.0002	0.0002	0.1433	0.1433	0.1433	0.1433	0.1433	0.0000	0.0000	0.0000	0.0000	1.1612	0.0002	0.0002	0.1433

Table-8. Unit Indexes for weighted information contents.

Supplier Name	Management Competencies	'Green Image'	Design for Environment	Environmental Management Systems	Environmental Competencies	Total Unit Index
Supplier F	0.0002	0.0001	0.0002	0.0000	0.0359	0.0364*
Supplier S	0.1061	0.0002	0.1433	0.0000	0.3262	0.5758

Due to the geometry of the metal boss, the Manufacturing Engineer decided to employ turning technique to produce the component. In this case, the choice of cooling method is limited to conventional machining. Other alternative cooling lubricating fluid (CLF) delivery systems (e.g. high-pressure jet-assisted machining and cryogenic machining) are not available within the facility of Dyson. Machining data were estimated based on different sets of cutting parameters used on conventional lathe turning machine. 3 processes namely Process I, II and III alongside their respective cutting conditions are displayed in Table-9.

Table-9. Cutting condition and processes being considered for metal boss manufacturing.

	Cutting Speed (m/min)	Feed rate (mm)	Depth of cut (mm)
Process I	30	0.25	1.2
Process II	60	0.25	1.2
Process III	90	0.25	1.2

The estimation of sustainability performance for each of the alternative processes (with different cutting conditions) given above are tabulated in Table-10. Weighted information content and calculated unit indexes are shown in Table-11 and Table-12 respectively. It is indicated in Table-12 that Process III is the most viable process among the alternatives due to its affordable machining costs and lower energy consumption which in turn leads to the lowest calculated unit indexes.

CONCLUSIONS

This case study serves a validation of the proposed approach to demonstrate the usage of AD principles to aid the product development process and at the same time, to attain improved sustainability in subsequent stages of product lifecycle. A pedestal fan was selected to be the main subject of the case study. Four participants were chosen to take part in this case study as 'Stakeholder', 'Designer', 'Procurement Manager', and 'Manufacturing Engineer' respectively. Specifically, the stakeholder was required to specify design requirements and design ranges while other roles were supposed to perform data collection, generation of design solutions, short-listing of alternatives and grading of alternatives. The input were then compiled and analysed by means of AD framework and information content calculation to eliminate ineligible alternatives and eventually came out with the most sustainable options for the development of the pedestal fan. In terms of EOL management, it was obligatory to have functional requirement to address EOL management concern and the stakeholder specified that the product must consume lesser material and components. With this in mind, the designer delivered a design solution that can merge multiple functions into a single part. The stakeholder also stated the weight factor and acceptance threshold for analysis of supplier's environmental capabilities. The procurement manager conducted questionnaire survey to obtain necessary information to support the selection of the most eligible green supplier by using AD approach. The manufacturing engineer also contributed by gathering estimated machining data and provided required grading for the purpose of identifying an optimized solution for manufacturing of metal boss.

By having an AD framework, it allows functional requirements to be cascaded and communicated effectively to various departments, from top management to executives attached to design team, procurement department as well as manufacturing division. Each respondent was aware of their respective area of focus and is able to narrow their activities to certain scope, despite having minimal understanding of sustainable product development beforehand. The roles and responsibilities of each job function in the process of sustainable product development is well-defined. The underlying mathematical model of AD approach also enable information content to be calculated and allow each of the alternative solutions to be quantified and ranked. In short, challenges in the three key areas (i.e. EOL management, supply chain and manufacturing) can be addressed effectively by introducing the proposed approach to prescribes the guidance and analytical approach for decision making.

However, to implement this approach successfully across the entire organization, training needs to be provided beforehand to educate employees into using the proposed framework proficiently. To enable effective monitoring and evaluation in the long run, this framework can be integrated into various departments' key performance index (KPI) to enforce periodical review and continuous improvement.

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Table-10. Sustainability performance corresponding to alternative processes.

Machining Process	Machining Costs (MYR/part)	Energy Consumption (kWh/part)	Waste Management (MYR/part)	Environmental Friendliness	Operational Safety	Personnel Health
Process I	4.19 – 4.63	9.22 – 10.19	4.75 – 5.25	Fair	Good	Fair
Process II	3.29 – 3.64	5.96 – 6.59	4.75 – 5.25	Fair	Good	Fair
Process III	3.00 – 3.31	4.87 – 5.38	4.75 – 5.25	Fair	Good	Fair

Table-11. Weighted information contents (sustainability performance for alternative processes to produce metal boss).

Machining Process	S_{OP}			S_{SHE}		
	Machining Costs	Energy Consumption	Waste Management	Environmental Friendliness	Operational Safety	Personnel Health
Process I	Infinite	Infinite	0.8251	1.5656	0.5234	1.5656
Process II	0.3376	1.7231	0.8251	1.5656	0.5234	1.5656
Process III	0.0000	0.0000	0.8251	1.5656	0.5234	1.5656

Table-12. 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
Process I	Infinite	1.2182	Infinite
Process II	0.9619	1.2182	2.1802
Process III	0.2750	1.2182	1.4933*

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