Modeling for sustainable product development strategies with general morphological analysis

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Abstract: Sustainable product development is currently of concern by scientists within both academia and engineering. Despite existing literature proposed related to detailed aspects for design for sustainability (D4S), the modeling of life cycle driving forces for D4S in different levels remains insufficient. A morphological analysis (MA) approach was applied to explore the strategies in sustainable product development in this work. With the experts' brainstorming and MA framework, the results for solutions to D4S were obtained under the support program from the Swedish Morphological Society. The specific factors and states for six sustainable development scenarios were acquired and compared. Platform-based innovation, flexible manufacturing system, multi-material lightweight design, energy efficiency priority, disassemble to reuse, remanufacturing, recycling (3R), LCA and CAX software are identified as key strategies for D4S. The sustainability-improving strategies for companies with an eco-design basis, small to medium enterprises (SME), and governments are also briefly discussed respectively.

Keywords: Design for sustainability, D4S, Eco-friendly product, product development strategy, morphological analysis

1 Introduction

Product design for sustainability (D4S) [CD09] is currently highlighted by scientists and industrial engineers to obtain ecological (eco-) friendly products. The sustainable products can be defined as products that provide environmental, social, and economic benefits, while protecting health and welfare as well as maintaining the environment over their full life cycle from raw materials extraction and use, to eventual disposal and reuse [GW15]. D4S is a general destination for electromechanical product design. To achieving this, several detailed aspects including design for environment (DFE) [IG10], design for life cycle (DFLC) [RR10], design for disassembly (DFD) [BO07], design for recycling (DFR) [UF13], and material selection (MS) in eco-design [ST13], have been researched in academia. In this study, focus is placed on physical products, such as automobiles, engineering machinery, and household electronics. The goal of this focus is to explore the main factors and important states related to sustainable product development. The findings will help to improve government policy and enterprise practice to promote the research and development of eco-friendly products.

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Limited studies have been published about the criteria, policy, or factors for sustainable product design. For instance, Maxwell *et al*. [MV03] obtained the criteria for optimising sustainability through process research of sustainable products and services development (SPSD). The criteria included functionality, environmental impacts, social impacts, economic impacts, quality, market demand, customer requirements, technical feasibility, and compliance with legislation and industry/technical specifications. However, the volume of criteria poses a challenge and a trade-off might be needed in specific SPSD environments. Zhang *et al.* [ZX12] presented a theoretical model for new product development by investigating the interactions among customers' preference, firms' product strategies, and government subsidy policies. They found to motivate firms to choose eco-friendly product design strategies, government should put forward effective subsidy policies. Tu *et al.* [TC13] used the survey and data analysis method to analyze the impact factors and strategy of sustainable product development under Corporate Social Responsibility (CSR) in Taiwan. Results from questionnaire interviews were analyzed by using frequency distribution, factor analysis and content analysis approaches. The internal and external major factors were then obtained to guide further sustainable product development. One common feature of the above three studies is that they identified the parameters to evaluate or assist product sustainability. A shortcoming of these pioneering studies lies in the fact that the product lifecycle phases are overlooked.

Morphological analysis (MA) and box method is applied in this work to model the reasons and results for product D4S. General morphological analysis (GMA, briefly named as MA) [RS02] is a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem spaces. MA was initially proposed by Fritz Zwicky – the Swiss astro-physicist and aerospace scientist based at the California Institute of Technology [ZW69]. MA was later further developed by Tom Ritchey in the Swedish Morphological Society. MA is suitable for mapping the relationships within multiple factors and related distinct states according to expert experience. An alternate definition suggests that MA is a computational framework to transform the consistent data within elements given by experts into a visualized model showing reasons and results. The MA acquired model serves as an experimental platform to analyze and compare different operational strategies. A computer-aided MA system was developed by the Swedish MA society and over one hundred projects have been implemented under its instructions. Examples that apply this technique using this software include modeling complex socio-technical systems [RI02], modeling multi-hazard disaster reduction strategies [RI06], and threat analysis for the transport of radioactive material [RI07].

Considering the product conception, raw material, production process, distribution, consumption, and end-of-life phases within a product life cycle, eight factors are selected and multiple distinct states for each factor are defined. The factors cover the design, manufacturing, material selection, energy efficiency, EOL recycling, eco-impact analysis, software tools, and design scenarios with their different states as much as possible. Through the assessment data from experts in different disciplines and computer-aided

MA, drivers for different levels of sustainable product design were discovered. Comparisons for multiple scenarios and analysis for promoting sustainable design within specific scenarios are also discussed.

Section 2 of this paper describes the MA approach and definition data by experts brainstorming. Section 3 outlines the findings from the model via MA. Section 4 discusses the results and compares several sustainability improving strategies. Section 5 provides conclusions of the research.

2 Methodology

The computer-aided MA approach to analyze the reasons for different sustainable development scenarios has been used. The framework of MA and definition data for sustainable product development strategies are described as follows.

2.1 Framework for MA

MA is an easy-to-use computational framework to find many compatible results within multiple reasons. The function of MA is to explore solutions for qualitative, uncertain, and complex problems without mathematical models. Thus, MA is a typical human-computer interaction process with several iterations. As showed in Fig. 1, the internal MA process and the external support from human experts and software tools are illustrated. MA contains three main steps [RS02] as the bold numbers represented in this figure:

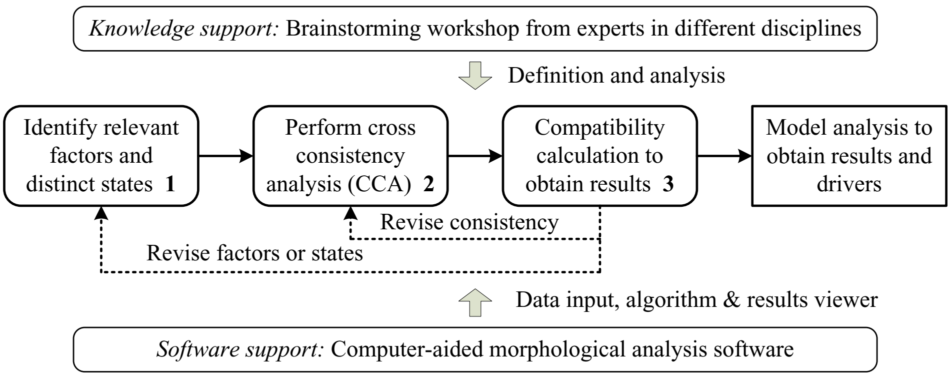


Fig. 1: Framework and external support for MA

Step 1: Setting the factors and distinct states for the problem. In another word, setting the parameters and different values for the strategic analysis problem. The factors are desired to cover different aspects of the problem as completely as possible with a maximum of eight. The states within one factor are better to be mutually independent, namely, only one may be selected. An average of five to six states per factor were defined.

Step 2: Input the cross-consistency analysis (CCA) matrix to reduce the feasible solution space. This step is to represent the inherent relations between pairs of states within different factors. Three values such as total consistency, paritcal consistency, and no consistency can be represented with “ -”, “ K”, and “ X”, respectively.

Step 3: Analyzing the strategies with the obtained model under the environment of MA software. The concerned results and reasons can be acquired and compared to find interesting points.

Note that the experts are better to be in different disciplines to involve multiple knowledge backgrounds. The second step is most time-consuming because of the large amount of assessment data via the brain-storming workshop of experts. Note that the interation process within the three steps is completely normal, and designers are learning more about the nature of their problem space. This article doesn’t discuss the detailed MA algorithm, and the focus lies in findings on product ecological development strategies. Under the research support program from the Swedish Morphological Society [SW15], the CCA matrix was supplied in order to obtain the visualized results by MA software also with several iterations.

2.2 Problem definitions

Since the aim of the research is to explore the drivers for different levels of product development scenarios, eight factors are selected as showed in Table 1. The table contains seven kinds of drivers and one kind of result. Considering design for life cycle principles, the *design innovation types*, *manufacturing modes in enterprise*, *material selection approaches*, *energy efficiency levels in usage*, *recycling levels in end-of-life (EOL)*, *eco-impact analysis modes*, and *computer-aided software tools* are selected as the main factors for the scenarios in D4S. Furthermore, five to six distinct states are provided under each factor according to the state-of-the-art techniques in enterprises with different levels. The detailed states in each factor are also listed in Table 1. To ease the presentation in context, each factor and states are named with letters and numbers.

Table 1: Factors and related states for product development scenarios

Factors	States
A. Design innovation type	A1. Totally innovative design
	A2. Platform-based innovation
	A3. Appearance innovation
	A4. Design for individualized order
	A5. No innovation
B. Manufacturing mode	B1. Flexible manufacturing system
	B2. Multiple manufacturing cell
	B3. Mass production line

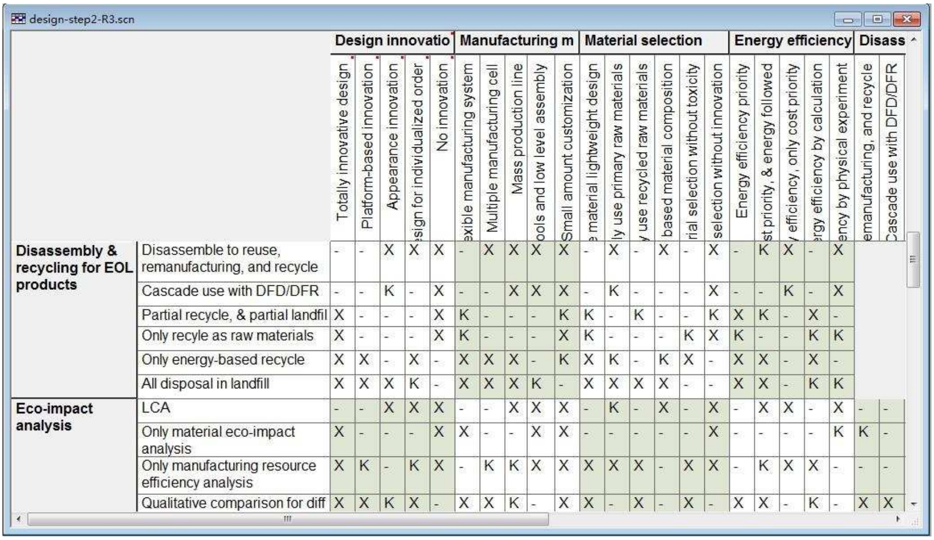
	B4. Distributed machine tools and low level assembly
	B5. Small amount customization
C. Material selection	C1. Multiple material lightweight design
	C2. Only use primary raw materials
	C3. Partially use recycled raw materials
	C4. Cost and safety priority based material composition
	C5. Material selection without toxicity
	C6. Case-based material selection without innovation
D. Energy efficiency in service	D1. Energy efficiency priority
	D2. Cost priority, & energy followed
	D3. Without considering energy efficiency, only cost priority
	D4. Acquiring energy efficiency by calculation
	D5. Acquiring energy efficiency by physical experiment
E. Disassembly & recycling for EOL products	E1. Disassemble to reuse, remanufacturing, and recycle
	E2. Cascade use with DFD/DFR
	E3. Partial recycle, & partial landfill
	E4. Only recycle as raw materials
	E5. Only energy based recycle
	E6. All disposal in landfill
F. Eco-impact analysis	F1. LCA
	F2. Only material eco-impact analysis
	F3. Only manufacturing resource efficiency analysis
	F4. Qualitative comparison for different products
	F5. Multi-attribute decision making by experts
	F6. No eco-impact analysis
G. Software tools	G1. 2D CAD drawing
	G2. 3D CAD modeling and drawing
	G3. CAD/CAM/PLM
	G4. CAD, CAE and analysis tools without LCA
	G5. CAX/LCA
S. Scenarios in design for sustainability	S1. Eco-products with good sustainability
	S2. Products with extrem complexity and high reliability
	S3. Products with cost priority and satisfying eco-regulations
	S4. Products with cost priority and functional satisfaction with little eco-involved
	S5. Low cost and low quality products without eco-involved
	S6. Only functional prototypes

Six scenarios in D4S were defined with the highest one as eco-products with good sustainability to the lowest one as only functional prototypes. The sustainability level from S1 to S6 is decreases in priority. Note that the A1 - totally innovative design means there has principle innovation and little reference case. E2 – cascade use with DFD/DFR represents the EOL products are disassembled and recycled as other kinds of secondary products, with little reuse or remanufacture to original ones. F3 – only manufacturing resource efficiency analysis is to calculate the ratio of material output and input during processes, which likes the financial cost analysis under Enterprise Resource Planning (ERP) system. Most of the states within factors are independent. Although we tried to keep the states within one factor to be independent as much as possible, it cannot be guaranteed that all states are distinct because of the coupling in design process. For instance, the D1 and D4 can be coexisted because with plenty of design data and model, the energy efficiency can be calculated (D4) within an energy efficiency priority design scenario (D1).

The cross-consistency of the elements are defined by the experts brainstorming workshop. Because of the limit of the context, a partial CCA matrix is shown in Fig. 2. The following key to annotate the assessments is used:

- "-" (hyphen) = Good fit, or best fit, or optimal pair.
- "K" = Possible, could work, but not optimal.
- "X" = Impossible or unrecommended idea.

Because the CCA is a two-dimensional and undirectional matrix, it is defined that the columns of the CCA do not contain the last factor, and the first factor is also deleted from the rows in CCA. Note that one must not have a full column or a full row of only "X"s in a parameter-block. There should be at least one "- " in each column and row for each parameter-block. An assessment for any of the cells in the CCA matrix is required.



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		Design innovatio					Manufacturing m					Material selection						Energy efficiency					Disass	
		Totally innovative design	Platform-based innovation	Appearance innovation	esign for individualized order	No innovation	exible manufacturing system	Multiple manufacturing cell	Mass production line	ools and low level assembly	Small amount customization	e material lightweight design	ly use primary raw materials	y use recycled raw materials	based material composition	rial selection without toxicity	selection without innovation	Energy efficiency priority	st priority, & energy followed	y efficiency, only cost priority	ergy efficiency by calculation	ency by physical experiment	emanufacturing, and recycle	Cascade use with DFD/DFR
Disassembly & recycling for EOL products	Disassemble to reuse, remanufacturing, and recycle	-	-	X	X	X	-	X	X	X	X	-	X	-	X	-	X	-	K	X	-	X		
	Cascade use with DFD/DFR	-	-	K	-	X	-	-	X	X	X	-	K	-	-	-	X	-	-	K	-	X		
	Partial recycle, & partial landfil	X	-	-	-	X	K	-	-	-	K	K	-	K	-	-	K	X	K	-	X	-		
	Only recyle as raw materials	X	-	-	-	X	K	-	-	-	X	K	-	-	-	K	X	K	-	-	K	K		
	Only energy-based recycle	X	X	-	X	-	X	X	X	-	K	X	K	-	K	X	-	X	X	-	X	-		
	All disposal in landfill	X	X	X	K	-	X	X	X	K	-	X	X	X	X	-	-	X	X	-	K	K		
Eco-impact analysis	LCA	-	-	X	X	X	-	-	X	X	X	-	K	-	X	-	X	-	X	X	-	X	-	-
	Only material eco-impact analysis	X	-	-	-	X	X	-	-	X	X	-	-	-	-	-	X	-	-	-	-	K	K	-
	Only manufacturing resource efficiency analysis	X	K	-	K	X	-	K	K	X	X	X	X	X	-	X	X	-	K	X	X	-	-	-
	Qualitative comparison for diff	X	X	K	X	-	X	X	K	-	X	X	-	X	-	X	-	X	X	-	K	-	X	X

Fig. 2: Partial cross consistency matrix inputed in morphological analysis software

3 Findings

With the predefined data, the model for sustainable product development scenarios is obtained and visualized by MA software. The model is regarded as an input-output device. As showed in Fig. 3, if one element in the matrix is clicked to be shown in red color, related reasons for this scenario will be highlighted in blue to form a mapping between drivers and results. If one element can not find any drivers in blue, there are no reasons for this scenario under the current problem definitions.

For achieving eco-products with good sustainability (S1), totally innovative design (A1) or platform-based innovation (A2) can be used. Also, flexible manufacturing system (B1) with multi-function robotics and advanced numerical control machine tools will support the eco-manufacturing process. In material selection, the multiple material lightweight design (C1), paritially use recycled raw materials (C3), and material selection without toxicity (C5) are all preferred. The products are desired to be energy efficiency priority (D1) and acquiring efficiency rate be calculation (D4). Further, the products should be designed with ease of disassemble to reuse, remanufacturing, and recycle (3R), or they can be easily cascade use with DFD/DFR. Moreover, CAX/LCA software tools (G5) should be implemented in the development process to support quantitative life cycle analysis (F1) for effective eco-impact assessment.

Design innovation type	Manufacturing mode	Material selection	Energy efficiency in service	Disassembly & recycling for EOL products	Eco-impact analysis	Software tools	Scenarios in design for sustainability
Totally innovative design (A1)	Flexible manufacturing system (B1)	Multiple material lightweight design (C1)	Energy efficiency priority (D1)	Disassemble to reuse, remanufacturing and recycle (E1)	LCA (F1)	2D CAD drawing	Eco-products with good sustainability (S1)
Platform-based innovation (A2)	Multiple manufacturing cell	Only use primary raw materials	Cost priority, & energy followed	Cascade use with DFD/DFR (E2)	Only material eco-impact analysis	3D CAD modeling and drawing	Products with extrem complexity and high reliability
Appearance innovation	Mass production line	Partially use recycled raw materials (C3)	Without considering energy efficiency, only cost priority	Partial recycle, & partial landfill	Only manufacturing resource efficiency analysis	CAD/CAM/PLM	Products with cost priority and satisfying eco-regulations
Design for individualized order	Distributed machine tools and low level assembly	Cost and safety priority based material composition	Acquiring energy efficiency by calculation (D4)	Only recyle as raw materials	Qualitative comparison for different products	CAD, CAE and analysis tools without LCA	Products with cost priority and functional satisfaction with little eco-involved
No innovation	Small amount customization	Material selection without toxicity (C5)	Acquiring energy efficiency by physical experiment	Only energy-based recycle	Multi-attribute decision making by experts	CAX/LCA (G5)	Low cost and low quality products without eco-involved
		Case-based material selection without innovation		All disposal in landfill	No eco-impact analysis		Only functional prototypes

Fig. 3: Drivers for eco-products with good sustainability

Table 2: Reasons for different sustainable product development scenarios

Scenarios	A	B	C	D	E	F	G
S1	A1; A2	B1	C1; C3; C5	D1; D4	E1; E2	F1	G5
S2	A2; A4	B1; B2	C1; C3; C5	D1; D4	E2	F2; F5	G3; G4
S3	A2; A3; A4	B2; B3	C2; C3; C5	D2; D5	E3; E4	F2	G2; G3
S4	A3	B3; B4	C2; C4	D3; D5	E4	F4; F5	G2; G4
S5	A3; A5	B4	C4; C6	D3	E5	F4; F6	G1; G2
S6	A4; A5	B4; B5	C6	D3	E6	F6	G1

For ease of showing and comparison, the reasons for different design scenarios are listed in Table 2. The products with extreme complexity and high reliability (S2) are special for complex electromechanical equipment. Because of its high reliability and specilized requirements, the drivers for it are platform-based innovation (A2) or design for order (A4) with flexible manufacturing system (B1) or multiple manufacturing cells (B2). The states in material selection and energy efficiency are same as S1. Moreover, it desires cascade use with DFD/DFR (E2) with only material eco-impact analysis (F2) or multi-attribute decision making by experts (F5). The suitable softwares are CAD/CAM/PLM (G3) or CAD, CAE and analysis tools without LCA (G4).

For products with cost priority and satisfying eco-regulations (S3), the drivers in design modes are platform-based innovation (A2), appearance innovation (A3), or design for individualized order (A4). The multiple manufacturing cell (B2) or mass production line (B3) are both allowed with only use primary raw materials (C2), partially use recycled raw materials (C3), and to select material without toxicity (C5). Other preferred drivers for this scenario are cost priority & energy followed (D2) or acquiring energy efficiency by physical experiment (D5). EOL strategies are paritial recyle & paritial landfill (E3) or only recycle as raw materials (E4). Only material eco-impact analysis (F2) with 3D CAD modeling (G2) or CAD/CAM/PLM integration (G3) are also driving forces.

The above three scenarios with good product sustainability are our most preferred ones. The following three results from S4 to S6 only exhibit the product development conditions for some lower level enterprises or plants. Products with cost priority and functional satisfaction with little eco-involved (S4) is stilled applied by large number of companies. Their common points are appearance innovation (A3) with mass production line (B3) or distributed machine tools & low level assembly (B4). They perform cost and safety priority based material composition (C4) or only use primary raw materials (C2). They are just considering cost priority (D3) and acquiring energy efficiency by physical experiment (D5). The EOL products can only be recycled as raw materials (E4). Also, lower level eco-impact such as qualitative comparison for different products (F4) or multi-attribute decision making by experts (F5) are still applied. The 3D CAD (G2) or CAD, CAE and analysis tools without LCA (G5) are implemented. The drivers for S5 and S6 can also be found in Table 2 and but not further discussed.

4 Discussion

Several key states in multiple factors are found for sustainable product development. We obtain that the platform-based innovation (A2), flexible manufacturing system (B1), multi-material lightweight design (C1), energy efficiency priority (D1), disassemble to 3R (E1), CAX (G5), and LCA (F1) are all important strategies for achieving eco-friendly products with sustainability. Though totally innovative design (A1) can involve principle innovations in some degree. But it is extremely difficult to develop totally new products "without former cases" successfully. Moreover, design for individualized order (A4) is always done by reconfiguring from an original kernel product. Thus, platform-based innovation (A2) should be carefully focussed by R&D managers to develop eco-friendly and customized products.

Increasing products' sustainability level from the current eco-design level is concerned. Revising the energy efficiency or materials are now widely utilized by companies to reduce the eco-impacts of their outcomes. For example, a household washing machine is redesigned to be better in energy efficiency and use lightweight materials with modularization in structure to ease maintenance and EOL recycling. But the resource efficiency in manufacturing and quantitative LCA are still lacking behind because of their large financial investment. Thus, the LCA and flexible manufacturing system are desired to be concentrated by groups with a degree of basis on eco-design.

There are still suggestions for design scenarios which mainly considering cost priority and functional satisfaction with little or none eco-involved. It is recognized that only providing low level products will be not benefit for the sustainable development of the SMEs. To improve product design in materials, energy efficiency, and to update the manufacturing facilities with flexible multi-functional cells are suitable strategies for SMEs. Further, the market access standard, producer responsibility, and recycling network for EOL products should be more focussed by governments and society.

5 Conclusions

Through the sustainable product development strategy analysis by MA, six key strategies within multiple lifecycle phases are identified for providing eco-friendly products. Specific drivers are found for different sustainable design scenarios. These drivers are regarded as strategies that can be considered by enterprises or governments to promote eco-development, rather than some detailed techniques that can be directly utilized. The platform-based design innovation, flexible manufacturing system, energy efficiency priority, design for recycling, and LCA, CAX software are desired to be focused and integrated. They will be benefit to achieve sustainable product development in higher level. Future work lies in the software architecture research for promoting product D4S.

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