Reducing effects of design uncertainties on product sustainability

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Abstract: Product designers need to consider users’ requirement changes in the product life cycle. Existing practices of product design lack an effective method to quantify uncertainty effects on products. This research proposes a method to evaluate product sustainability under the generational variety uncertainty. An integrated method of agent-based modeling, quality function deployment (QFD), and axiomatic design theory is developed to simulate users’ preference changes. The contribution in this paper is to address all sustainability pillars including the social, environmental, and economy in the proposed solution. The quantified uncertainty is then used to evaluate impacts on product sustainability. The proposed method is validated using an example of the wheelchair design.

1. Introduction
Products are expected to meet varying users’ preferences (Beuren, Gomes Ferreira, & Cauchick Miguel, 2013). Diversified products result in the high cost of product development efforts (Kohtamäki, 2013).
Partanen, Parida, & Wincent, 2013; Reim, Parida, & Örtqvist, 2014). The attention to minimize environmental impacts of products has been increasing (Gremyr, Siva, Raharjo, & Goh, 2014; Masui, Sakao, Kobayashi, & Inaba, 2003). A sustainable product is mainly decided in its design phase. Product design can decide up to 80–90% of sustainability performance in the product life cycle (May, Taisch, & Kerga, 2012). As the uncertainty accompanies in processes of product design, having accurate data of users’ preferences is always a challenge.

In engineering design, the lack of definition, lack of knowledge, and lack of trust in knowledge are considered as the uncertainties (Afshari & Peng, 2014; Wynn, Grebici, & Clarkson, 2011). Uncertainties require the flexibility to maintain the performance of a system. A prerequisite to embed the flexibility in the design is to recognize functions and components of a product that are likely to change under uncertainties. Consequently, with accurate data in the design stage such as future changes of a product, uncertainty effects on sustainable impacts of the product can be reduced.

The variety across the future generations of a product is known as the generational variety (Martin & Ishii, 2002). The change of users’ preferences during the product life cycle is uncertain in the product design stage. Due to the change of user’s preferences, a product may not satisfy requirements anymore in the application stage. Increased product diversity requires the additional cost and development efforts. Another solution, proposed in this research, is to evaluate changes and to adapt the changes in the product design. A design objective is therefore considered to minimize product environmental impacts under users’ requirement changes. For example, if the material in a printer frame is identified as the most pollutant factor, the designer can replace the frame material to minimize environmental impacts of the printer.

The objectives of this research are to quantify the evolution of users’ preference changes, and to investigate effects of the quantified changes in product design. The proposed model is validated using a wheelchair product. In rest parts of the paper, the related research is first reviewed. A proposed method is then described in details, followed by the method implementation and a case study. The paper is concluded by discussions of contributions, deliverables, and future research directions.

2. Literature review

2.1. Methods to study generational variety of products

Most products are developed from generation to generation following users’ requirements, technology progress, market segmentations, and the price competition (AlGeddawy & ElMaraghy, 2011; Chen, Yeh, & Hu, 2011). The product variety increases the complexity of the product development. A review of Engineering Change Management (ECM) highlights a gap in literature to evaluate the engineering changes in quality, manufacturing, and post-manufacturing of a product (Hamraz, Caldwell, & Clarkson, 2013).

Jarratt, Eckert, Caldwell, and Clarkson (2011) reviewed tools and techniques during the engineering change process to classify them into hard technologies (e.g. process and material requirement planning), soft techniques (e.g. QFD and Design for Manufacture and Assembly), academic tools and prototypes (e.g. Change propagation methods). Using change propagation approaches, the effect of changes was investigated in the internal structure and sub-assemblies of a product (Eckert, Clarkson, & Zanker, 2004). Next generations of change propagation approaches provided better solutions to manage complexity of multiple contextual changes. Martin and Ishii (2002) introduced Design for Variety (DFV) to quantify the change. Using Generational Variety Index (GVI), changes of product components were evaluated to meet the future requirements. The internal effect of change propagations into other product components was then measured using Coupling Index (CI). Using Change Propagation Index (CPI), Suh et al. measured the total changes propagation of components (Suh, Weck, & Chang, 2007). Sensitivity design structure matrix (sDSM) identified design variables for the most sensitive to changes; a designer can insert flexibility to these highlighted subsystems or components (Kalligeros, 2006). Giffin et al. (2007) suggested a normalized CPI to compare sensitive
components in design scenarios. The approach is limited in defining the magnitude of changes in the multi-domain analysis. Koh, Caldwell, and Clarkson (2012) presented a model to predict and manage undesired engineering change propagations during the product development. House of quality and change prediction methods (Clarkson, Simons, & Eckert, 2004) were the basis of the proposed methods. The methods were used to assess change options during engineering changes. Bartolomei (2007) extended Engineering System Matrix (ESM) to identify variable components for socio-technical systems. Changing components were identified using the sensitivity analysis, change propagation analysis, and estimated cost of changes. The proposed method lacks in ranking and analyzing multiple contextual changes. The method was later extended to a new framework of Engineering Systems Multiple-Domain Matrix (Bartolomei & Hastings, 2012).

Agent-based models (ABMs) have been proposed to solve problems with the large size of the domain and frequently changing structures (Barbati, Bruno, & Genovese, 2012). Reviewing applications of agent-based modeling, there is a limited contribution made in design fields compared to other areas. Agent-based models have been applied in the modular and collaborative design of products (Liu, Chen, Wang, & Wu, 2014). Multi-agent systems provide a structure to include designers’ ideas in a collaborative fashion. Ostrosi, Fougères, Ferney, and Klein (2012) applied agent-based modeling in product families for the conceptual design. The proposed approach considered the product configuration as a structural and collaborative design problem different actors were used in modeling. Cao, Zhu, Cui, and Tan (2008) proposed an agent-based approach to map behavioral and functional matrices for the conceptual design of mechanical products. A design flow was proposed by Xu, Han, and Ye (2008) for customized products using the similarity evaluation. The method combines the analysis of user’s requirements using QFD and a multi-agent system to optimize decisions. Using a hybrid approach, Wang and Chen (2012) proposed a method in the collaborative product design for the optimal selection of modules. The approach used the fuzzy multi-criteria decision-making, QFD, and linear integer programing. Afshari and Peng (2015) proposed a hybrid method to investigate users’ preferences in a product life cycle. Integrating QFD, data mining and ABM, the changes of requirements during the product life cycle were simulated. The proposed method shows a better convergence in product changes compared to the GVI method. Therefore, it is required to develop an accurate prediction for the future changes of products.

2.2. Methods to investigate environmental impacts of products

Decisions in the early design phase affect the entire product life cycle. Various methods and tools have been developed to consider environmental measures in the design phase. Design for environment (Fiksel & Wapman, 1994), design for life cycle (Alting, 1991), and Life cycle assessment (ISO 14040, 2006) are some of the approaches widely accepted in product design studies. Eco-design tools have been developed to integrate environmental issues in the product development processes (Pigosso & Sousa, 2011), and to assess the entire environmental impact of a product with different design variants (Russo, Rizzi, & Montelisciani, 2014). Different classifications of eco-design tools have been proposed in literature. Ramani et al. (2010) proposed four categories of eco-design tools including checklist-based tools, life cycle assessment (LCA)-based tools, quality function deployment (QFD)-based tools, and integrated tools. In another classification, tools are divided to standards/guidelines, comparative tools, and analytic tools (Chou, 2014; Knight & Jenkins, 2009). We review the advantages and disadvantages of these echo-design tools as follows.

Tools based on LCA analyse product interactions with environments through materials and energy in different stages of the life cycle to investigate potential environment impacts. LCA is known as an objective method to evaluate the environmental profile of a product or process (ISO 14040, 2006). As much information and effort is required in the detail analysis, using LCA-based tools are costly and time-consuming (Koffler, Krinke, Schebek, & Buchgeister, 2008). LCA is considered as a pre-determined tool that is limited in generating environmentally compliant options (Deutz, McGuire, & Neighbour, 2013).
Checklist-based tools evaluate the environmental impact of products through a series of questions to guide the creation of sustainable design concepts in designer’s mind. These tools are qualitative and easily applicable to highlight environmental impacts in even small and medium companies. The challenge of using these tools is their subjective nature and difficulties to provide concrete solutions for different stages in the product life cycle (Ramani et al., 2010).

QFD-based tools embed objective measures in the sustainable product design. Several tools such as QFD for environment, House of ecology, and Green Quality Function Deployment have been introduced in QFD-based tools. The common concept behind these tools is to collect customers’ requirements and environmental needs, and then to correlate these needs with product and process specifications (Masui et al., 2003). Dependence on designer’s knowledge and experience and the likelihood of ignoring the entire product life cycle in the analysis are disadvantages of these tools (Bouchereau & Rowlands, 2000).

The reviewed tools can be categorised as non-integrated tools and integrated tools. The non-integrated tools need some justification for suitable uses in different companies. Knight and Jenkins (2009) claimed that available eco-design tools may not been widely used by industries because the methods are required to be generic and customization before the application. In contrary, the integrated tools are developed to utilize advantages of multiple tools and techniques for eco-design.

Integrated tools try to improve different eco-design tools using a holistic and integrated approach. Some of the tools provide the web-based assessment and education tools to help designers in sustainable design (Lothhouse, 2006). Some of the tools integrate methods and techniques, such as life cycle costing and LCA (Senthil, Ong, Nee, & Tab, 2003), multi-criteria decision-making and LCA (Khan, Sadik, & Veitch, 2004; Wang, Chan, & White, 2014), and optimization and mathematical modeling (Russo & Rizzi, 2014; Thurston & Srinivasan, 2003). Some eco-design tools are developed to evaluate the environmental impacts within specific industries, which indicate the applicability of proposed methods by the quantification of eco-efficiency measures (Bonvoisin, Lelah, Mathieux, & Brissaud, 2014; Taghdisian, Pishvaie, & Farhadi, 2014).

One of the most successful tools to study environmental impacts of products is Function Impact Matrix (FIM) that fills the gap between the introduced tools (Bernstein et al., 2010). The method integrates LCA, benchmarking, and QFD to identify the environmental impact of each product function in overall system performance. The tool highlights opportunities to redesign a product in the early design phase. The strength of the tool is simply integration of qualitative and quantitative techniques to cover the entire product life cycle, and the weakness is its subjectivity. Inoue et al. (2012) proposed a preference set based design (PSD) method for the flexible and robust design solution under uncertainty. The method considers designer’s preference for a multi-objective design problem including the physical performance and environmental impacts of product. A lack of identifying specific sources of uncertainty is witnessed in this research. Also, the method does not consider the social dimension of sustainability in its multi-objective solution. Kim, Kara, and Kayis (2014) proposed a conceptual framework to study the economic and environmental impacts at the product and the market levels. The framework defines an upper environmental impact limit, and then identifies either the allowable volume of product or further environmental improvements to not exceed the impacts of previous generation of the product. The framework helps comparing different technologies in trade-off between product design and market share. The limitation of the proposed framework is observed in ignoring detail design parameters, and the lack of investigating emerging technology uncertainties.

In summary, integrated tools are shown more compatible with real needs of industries for the environmental impact analysis. Due to the proven effectiveness of the FIM method in applying environmental factors in the early design phase, the FIM method is adopted as a part of the integrated method proposed in this research.
2.3. Methods to model uncertainty and reduce its effects

Simulation-based approaches and agent-based models are widely used to reduce uncertainty effects on the product life cycle (Afshari & Peng, 2014). The ability to test different improvement scenarios makes these methods popular. But these methods cannot meet the need of details in design steps and users’ behaviors in the life cycle assessment. Moreover, a mistake-proof solution for product design is not guaranteed. In other words, retroactive improvement scenarios used in these methods may not be effective for unexpected uncertainties.

Another approach is the use of the axiomatic design (AD) (Suh, 2001). Two axioms including independence axiom and information axiom were defined in the AD. Suh (2005) applied the AD to reduce the complexity of designs via satisfying the functional requirements of products, processes, and systems based on design constraints. Complexity was defined as a measure of uncertainty in achieving specified functional requirements (FRs). A solution using the AD was proposed to reduce information uncertainty for each type of complexity. Xiao and Cheng (2008) investigated the relationship of axioms and robust design to conclude an inherent connection between them. Their studies show that the design satisfying independence and information axioms is more robust. This proves the consistency between the AD and robust design. A review of the applications of axiomatic design shows that the AD is flexible in the combination of other methods and tools (Kulak, Cebi, & Kahraman, 2010). None of the reviewed studies provided a solution for the sustainable product development.

Kim et al. (2014) proposed a product assessment approach to find the volume of products based on technology changes and environmental impacts of the products. The approach applied AD as a function of product features to determine drivers of environmental impacts. The strength of the method is the joint study of economic and environmental impacts of each product generation on the product life cycle. But it lacks the study of uncertainty in product life cycle decisions. Beng and Omar (2014) proposed a framework for the sustainable product with less environmental harms. Axiomatic design principles were used in three areas including design for the sustainable end of life (EOL), the green supplier selection, and the optimization for sustainable manufacturing. The environmental effects were minimized by defining a proper relationship between FRs and DPs, and by minimizing information contents of each alternative. A lack of uncertainty studying on environmental impacts during the product life cycle is witnessed.

In summary, the limited research has been found in using the AD theory for uncertainty effects on the product sustainability.

3. Proposed method

Environmental impacts of products are studied in the design stage considering the generational variety of the product. To evaluate the generational variety of a product, changes of users’ preferences are simulated over a product life cycle as illustrated in Figure 1. Steps are shown in the numbered rectangular blocks and outputs are depicted using the dashed rectangular in Figure 1.

The first step is to evaluate changes of functional requirements over a product life cycle. An integrated method is adopted using agent-based modeling (Afshari, Peng, & Gu, 2013) and the diffusion theory (Bass, 1969). The basic Bass diffusion equation is extended as Equation (1) to evaluate effects of mass media and people’s interaction on the changes of product functional requirements.

\[
\frac{dP(t)}{dt} = m \cdot [\bar{P} - P(t)] + n \cdot \frac{P(t)}{\bar{P}} \cdot [\bar{P} - P(t)]
\]  

(1)

In Equation (1), \(P(t)\) is the total number of adopters to new products at time \(t\); \(\bar{P}\) is the total number of potential adopters; \(m\) is the coefficient of innovation, the first item in the equation shows the people who bought new product without the influence of others; \(n\) represents the coefficient of imitation, the second item shows the people who bought new product influenced by others.
Equation (1) is adopted to propose a mathematical model for the uncertainty evaluation. Events such as technology improvements and interactions with other people in society affect users’ preferences, these events are sources of uncertainty in users’ preferences as presented in Figure 2 (Eckert, Clarkson, de Weck, & Keller, 2009). To model the interactions, a time-based view of events affecting users’ preferences is presented in Figure 3.

It is assumed that people’s interactions happen more often than the technology improvement; hence, the period of people interactions ($t$) is shorter than the period of technology improvement ($Pr$). To measure average users’ preferences, the value of individual preferences is formulated in different periods of time. Equation (2) illustrates user’s preferences in duration A where people’s interactions happen.

$$CP_{i,j}(t) = \gamma_{f_{rd}}(i, j, t) \left[ (1 - \omega_{f_{rd}}) CP_{i,j}(t-1) + \omega_{f_{rd}} P_{f_{rd}} \right] \left[ 1 - \gamma_{f_{rd}}(i, j, t) \right] \cdot CP_{i,j}(t-1)$$

The autonomy of users in adopting (updating) their preferences in the interaction with a friend ($f_{rd}(i, j, t)$) is shown as Bernoulli distribution with $p = 0.5$. A set of interaction events affects individual user’s preferences between technology updates ($t < Pr$). Equations (3 and 4) formulate users’ preferences in duration B and point C shown in Figure 3.

$$CP_{i,j}(t_m) = \sum_{t=1}^{t_m} \gamma_{f_{rd}}(i, j, t) \left[ (1 - \omega_{f_{rd}}) CP_{i,j}(t-1) + \omega_{f_{rd}} P_{f_{rd}} \right] + \left( 1 - \gamma_{f_{rd}}(i, j, t) \right) CP_{i,j}(t-1)$$

$$CP_{i,j}(Pr_{1}) = \phi_{tech}(i, j, Pr_{1}) \left[ (1 - \omega_{tech}) CP_{i,j}(t_m) + \omega_{tech} P_{tech} \right] + \left( 1 - \phi_{tech}(i, j, Pr_{1}) \right) CP_{i,j}(t_m)$$

At the end of a product life cycle, the individual preference is calculated and mutual effects of events are evaluated using Equation (5). Users’ preferences for each part are measured at the end of the product life cycle; an average of all users’ preferences is presented in Equation (6).

$$CP_{i,j} = \sum_{t=1}^{T} \phi_{tech}(i, j, Pr_{m}) \left[ (1 - \omega_{tech}) CP_{i,j}(t_m) + \omega_{tech} P_{tech} \right] + \left( 1 - \phi_{tech}(i, j, Pr_{m}) \right) CP_{i,j}(t_m)$$
For industrial applications, a large population is used to follow Equations (2–6). We simulate the process using agent-based modeling. Pseudo code used for agent-based modeling is shown in Figure 4.

Users’ preferences are represented as agents in a multi-agent simulation environment. Each agent has a random number of friends with a contact list in close or far distance from where the agent lives. Some technical and non-technical events such as the technology update, friend’s advices, etc. occur during the interaction with other agents or with the environment. Data mining techniques are used to obtain required rates and parameters (e.g. technology update rate, life cycle time, and number of connections). Due to the independent nature of agents, they have the authority to either update their preferences or ignore received signals. After the acceptance of a new technology, affected agents advertise the new technology to their connections; therefore, users’ preferences are updated accordingly. The simulation continues in a specified product life cycle. The list of changes in users’ preferences over the product life cycle is then mapped into functional requirements using QFD. The output of this step is the amount of changes in functional requirements under uncertainty ($\Delta FR_{\text{uncertainty}}$).

The second step of the method measures environmental impacts of product during the life cycle. Function Impact Method (FIM) is used in the evaluation of environmental impacts for individual
product functionalities to connect next steps of the method (Bernstein et al., 2010). The environmental impacts are evaluated in a deterministic environment that is not affected by any uncertainty over the course of time. In the design stage, knowledge and experience on the product environmental impacts is not as precise as expected. The evaluation begins with decomposing a product into components, and then measures the material, manufacturing, use, and end of life impacts of each component. After defining details of each component based on product functions, environmental impacts of individual components are evaluated as Function Impact (FI).

In the third step, the effect of changes in users’ preferences is measured. This stage will build the link between the environmental impacts analysis and the generational variety of a product. The effect of users’ preference changes over the product life cycle on environmental impacts is evaluated using Equation (7).

\[
\Delta FI = \Delta FRs_{uncertainty} \times FI
\]  

(7)

To verify that effects of the uncertainty on the function impact (FI) is precisely measured, changes of FRs (\(\Delta FRs_{uncertainty}\)) should be normalized before using Equation (7). At the end of this step, a list of the most affected functional requirements over the product life cycle is achieved. But some details are required to use the information in product design.

In the last step, the contribution of each design parameter (DP) on environmental impacts is investigated. A designer can use the results to improve a product design. Among mapping tools, the axiomatic design theory is used in this step. Our focus is on the physical domain where functional requirements (FRs) are mapped into design parameters (DPs). Two axioms including independence axiom and information axiom are evaluated. In the independence axiom, the independence of the FRs is maintained. Here, functional requirements are defined as the minimum set of independent requirements that characterizes the design goal to minimize the environmental impacts. The information axiom aims to minimize design information content; the design with the least information content will be the best solution. The independence axiom is used to ensure the decoupled or uncoupled design. Equation (8) indicates the relationship in a physical domain of the axiomatic design.

\[
FRs = [A] \times DPs
\]  

(8)

To provide an uncoupled or decoupled design, \([A]\) should be diagonal or triangular matrix respectively. The knowledge and experience of designers can be used to investigate appropriate DPs satisfying FRs independence as shown in Equation (9).

\[
\Delta FI = [A] \times \Delta DPs
\]  

(9)
In this step, DPs are to satisfy related functional impacts (FI) to make \([A]\) a diagonal or triangular matrix. A designer may select different sets of DPs or different array values within \([A]\) to satisfy an uncoupled or decoupled design; therefore, the second axiom is used to select the best design.

As the budget limitation will affect revising the product design, DPs should be prioritized according to the budget to optimize the design solution. We use the concept of Rigidity of Design Sustainability (\(r\)) to ensure that the maximum magnitude of environmental impacts are addressed under the available budget. Using a step-wised algorithm, the best DP with the maximum \(K\) value is selected.

\[
K = \frac{EI_i}{RB_i}
\]

(10)

In each iteration (\(t\)), one DP out of \(n\) DPs is selected and \((r)\) index is revised using Equations (11 and 12).

\[
r_t = \sum_{i=1}^{n} EI_i - \sum_{i=1}^{t} EI_i, \quad \forall t \leq n
\]

(11)

\[
\tilde{r} = \frac{r_t}{\sum_{i=1}^{n} EI_i}
\]

(12)

The algorithm to search DPs stops when Equation (13) is satisfied.

\[
\sum_{i=1}^{t} RB_i \leq \text{Total Budget}
\]

(13)

If other constraints such as the minimum magnitude of environmental impacts are considered, the algorithm can be revised accordingly.

4. Case study

The proposed method is applied to a wheelchair design. A sustainable solution is required for the wheelchair design to meet requirements of the product cost, durability and low environmental footprints. The purpose is to verify that the proposed method can help designers to improve environmental impacts of a product under the generational variety uncertainty. All analyses are conducted for a benchmark wheelchair proposed by Hosseinpour (2013).

A recent analytical report shows that the wheelchair manufacturing industries in the USA devoted a significant portion of total funding to the research and development (R&D) activities (Curran, 2016). In the last 5 years, the average industries have spent at least 12% of revenue in the R&D to obtain a competitive advantage. The report highlights that new investors to this industry face high barriers to enter the market in terms of R&D costs or buying existing patents from other industries. Moreover, the environmental compliance costs have raised due to government’s increased scrutiny of manufacturing processes. Thus, providing a cost-effective and environmentally friendly solution will be embraced by wheelchair manufacturing industries to reduce costs.

Initially, a users’ preference survey was conducted. The preferences were then mapped into functional requirements using QFD. A group of experts was contacted to discuss the mapping solution. Parameters related to the product life cycle and technology trends were estimated. If a product exists in the market, its past data are used for estimation; otherwise, similar technologies and products are benchmarked to obtain the parameters. Product behavioral and interactional functions are investigated using data mining and marketing research. The users’ tendency to advertise new technologies is also investigated. Finally, the estimated parameters are used to simulate the product life cycle using agent-based modeling. Agents are defined as users’ preferences to interact each other in an environment (market or city). Technology innovations are updated regularly, and broadcasted.
to all agents. Some pioneer agents may adopt the new technology, and then advertise it thorough a group of connected friends. Through the simulation of the product life cycle, users’ preference changes are investigated over time.

Following steps in Figure 1, the wheelchair life cycle is simulated using ABM. Parameters in Table 1 are used for the life cycle simulation. AnyLogic commercial software package (version 6.8.1) is used to simulate users’ preference change as shown in Figure 5.

After initializing the simulation model, all agents are set in the blue color. In each 90-days simulation (three months), new technology trends are broadcasted to random users. It changes the color of agents from blue to green. Then, those users who follow the technology innovation are informed and they may update their preferences by changing the color to red. The trend of technologies is evaluated using the data of wheelchair parts during the last 20 years.

After the simulation of the wheelchair life cycle, measured changes in users’ preferences are transferred into changes in FRs ($\Delta FRs_{\text{Uncertainty}}$). The output is a list of normalized value of changes in FRs (to remove bias effects of data changeability) for measuring uncertainty effects. In the next step, the environmental impacts of the wheelchair during its life cycle are evaluated using function impact method (FIM) as shown in Figure 6. In this figure, the total environmental impacts index (EI) of each part is measured using the SolidWorks software. The carbon footprint of each part is measured in a unit of kg carbon dioxide equivalent (CO$_2$). The contribution of individual components in each product function is then distributed. The analysis highlights the most contributed functional requirements in environmental impacts of the wheelchair including having a moving system, supporting loads, and holding hip and thigh.

The effect of users’ preference changes on environmental impacts of the wheelchair is quantified using Equation (7). The ranking of FRs is changed when the effect of users’ preference changes is measured using Equation (14).

$$\Delta FI = \begin{bmatrix}
0.6 & \cdots & 0 \\
\vdots & \ddots & \vdots \\
0 & \cdots & 0.28
\end{bmatrix} \times 
\begin{bmatrix}
52.66 \\
\vdots \\
3.91
\end{bmatrix}
= 
\begin{bmatrix}
31.34 \\
\vdots \\
1.10
\end{bmatrix}
$$

(14)

To identify parameters contributing to the environmental impacts of the wheelchair under uncertainty, changes of FI are mapped into DPs. The AD is applied for the uncoupled or decoupled design. The relationship between functional requirements and design parameters is depicted. The mapping illustrated in Figure 7 shows a decoupled design. The mapping area is divided into two main rectangular areas for environmental impacts. In the first rectangular area, DPs are selected for the wheel, seat, main frame, and reclining mechanism. In the second rectangular area, the cost of components, number of components, material properties, and component sizes show the most contributing DPs to wheelchair environmental impacts.

| Table 1. Parameters for the wheelchair life cycle simulation |
|-------------------------------------------------------------|
| **Parameters** | **Value [unit]** |
| Number of agents ($I$) | 10,000 |
| Number of parts ($J$) | 20 |
| Technology update time ($Pr_t$) | 90 [day] |
| Product life cycle duration ($Pr_{lm}$) | 20 [year] |
| Weight of media (innovation), ($\omega_{tech}$) | 0.1 (%) |
| Weight of friends (imitation), ($\omega_{frd}$) | 0.25 (%) |
| Number of FRs | 17 |
| Number of DPs | 17 |
A comprehensive solution would redesign all components to minimize the environmental impacts of the product; however, the proposed algorithm chooses DPs to meet the minimum cost within the FRs based on the budget limitation. To initiate assigning DPs, a list of given budgets is needed considering analyses and resources required for each DP. Because of the lack of data, an estimated budget can be utilized using the degree of coupling between DPs and the probability of changes for each DP. For more accuracy, a measure is used to quantify design efforts for each DP based on the required budget. Table 2 presents a list of criteria for the design activities; the criteria are obtained from experts in the wheelchair design. The criteria include the diversity of potential materials (C1), Variety of parts and details (C2), Coupling with the other parts (C3), Number of technical tests required (C4), Ease of access to developed technologies (C5), and difficulties in prototyping (C6). All criteria are measured between 1 and 10. A higher number reflects more efforts and activities needed to design a DP.

In Figure 8, the sustainability index is used to select DPs according to the design activities required for DPs. The sustainability index is a normalized measure of functional impacts ($\Delta FI$) for DPs in Figure 7. Figure 8 shows that by revising 5 DPs (DP1, DP8, DP9, DP7, and DP3) more than 85% of the product environmental impacts can be reduced. The developed method helps to prioritize the DPs according to the required design activities and available budgets.

The result of proposed methods is also compared to the case of disregarding uncertainty. As presented in Table 3, the ranking of most pollutant FRs (as output of the FIM) is assessed with the ranking of FRs in Equation (14).
Table 3 shows the influence of users' preference changes on the ranking of the most contributing FRs in wheelchair environmental impacts. Traditionally, decisions to revise the design of a product were made only upon life cycle of a product. The proposed method enriches the reliability of previous approaches by considering the effects of uncertainties. Despite the other methods, the developed method is integrated into the selection DPs using the AD as presented in Figure 7.

The established DPs are then used to improve wheelchair’s environmental impacts. The original design of the wheelchair can be revised considering general DPs identified in the small rectangular area (presented in Figure 7). Such improvements include reducing the weight of components and the number of components, using environmentally friendly martial, etc. Several improvements are obtained in the wheelchair design improvement using the proposed method. For example, a designer could use the method to improve the design of “drive wheel” by reducing the weight. In this case, environmental impacts of the drive wheel are reduced from 47.26 kg CO2 into 36.76 kg CO2 by improving the design of the part. Table 4 summarizes the improvements and compares the proposed method with traditional methods.

### Table 2. List of the criteria to estimate design activities for DPs

| No.  | DPs                             | C1 | C2 | C3 | C4 | C5 | C6 | Sum |
|------|---------------------------------|----|----|----|----|----|----|-----|
| DP1  | Wheels specification           | 4  | 4  | 3  | 5  | 5  | 4  | 25  |
| DP2  | Electrical motor power         | 3  | 8  | 6  | 9  | 8  | 6  | 40  |
| DP3  | Reclining mechanism            | 4  | 5  | 5  | 4  | 5  | 4  | 28  |
| DP4  | Arm-rest properties            | 4  | 4  | 4  | 4  | 5  | 4  | 25  |
| DP5  | Back-rest specification         | 5  | 6  | 4  | 4  | 4  | 5  | 28  |
| DP6  | Head-rest adjustability        | 4  | 5  | 4  | 4  | 5  | 4  | 26  |
| DP7  | Leg-rest property              | 4  | 5  | 3  | 5  | 5  | 3  | 25  |
| DP8  | Seat property                  | 3  | 6  | 5  | 6  | 6  | 5  | 31  |
| DP9  | Main frame strength            | 7  | 8  | 8  | 7  | 6  | 6  | 42  |
| DP10 | Anti-tip wheel mechanism       | 3  | 5  | 5  | 4  | 4  | 3  | 24  |
| DP11 | Cushion specification          | 2  | 3  | 5  | 3  | 5  | 4  | 22  |
Therefore, a sustainable solution is obtained using the social (users’ preference mining), environmental (functional impacts analysis), and economic pillars (the budget or design efforts needed as a function of cost).

5. Conclusions
This paper proposed a comprehensive approach to reduce effects of uncertainty on environmental impacts of products. The method considers changes of users’ preferences using an indicator of the generational variety uncertainty in a product life cycle. The method applies the agent-based modeling to quantify users’ preference changes. The design analysis continues with breaking down a product into its components and subassemblies. Based on defined materials and processes in the BOM, environmental impacts of each product function are evaluated using the FIM method. The effect of quantified changes in users’ preferences is measured, and the most effective functions are identified. By adapting the AD theory and QFD methods, the effects of changes on environmental impacts are reduced. The method is validated using the design example of a wheelchair product.

The contribution of this research is a quantitative and qualitative method to measure environmental impacts of a product under its life cycle uncertainty. Instead of end-of-pipe solutions, this research proposes a method to reduce environmental impacts before manufacturing and introducing a product to the market. As presented in Table 4, a traditional analysis would direct us to identify

| Parameters                                           | Proposed method | Without uncertainty |
|------------------------------------------------------|-----------------|---------------------|
| Have a moving system                                  | 1               | 1                   |
| Hold hip and thigh                                    | 2               | 5                   |
| Support all loads without fracture                    | 3               | 4                   |
| Have reclining back-rest, leg-rest                   | 4               | 8                   |
| Hold the legs                                         | 5               | 9                   |
| Operate with electrical energy                        | 6               | 11                  |
| Hold hands                                           | 7               | 6                   |
| Does not tilt                                        | 8               | 3                   |
| Hold back body                                       | 9               | 2                   |
| Decline pressure point                               | 10              | 7                   |
| Hold the head                                        | 11              | 10                  |
the most pollutant components of a product, and improve its design for fewer impacts to the environment. On the contrary, this research measures the potential changes of a product in the future. Design parameters (DPs) are then addressed for detail design improvements.

Due to the qualitative nature of research, a group of experts are solicited to contribute in mapping process. The knowledge and expertise levels of participants would affect the expected quality of the solution. For the future research, the authors plan to extend the model with more factors including time and cost required in the product development under the generational variety uncertainty. A multi-objective method will be developed to optimize design objectives under uncertainty.

**Nomenclature**

| Symbol | Description |
|--------|-------------|
| \(I\)  | set of customers (\(i \in I\)) |
| \(J\)  | set of product parts or components (\(j \in J\)) |
| \(T\)  | set of events time (\(t \in Pr\)) and (\(Pr \in T\)) |
| \(CP_{ij}(t)\) | preference of customer \(i\) for part \(j\) at time \(t\) |
| \(\gamma_{frd}(i,j,t)\) | adoption probability of customer \(i\) for part \(j\) at time \(t\) after interaction with a friend |
| \(\omega_{frd}\) | weight of friends (imitation) in adopting a new technology |
| \(P_{frd}\) | friends technology preference |
| \(\varphi_{tech}(i,j,Pr)\) | adoption probability of customer \(i\) for part \(j\) at time \(t\) after introducing into a new technology |
| \(\omega_{tech}\) | weight of media (innovation) in adopting a new technology |
| \(P_{tech}\) | technology improvement rate |
| \(CP_{j}\) | average customers’ preference for part \(j\) |

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**Table 4. Comparing proposed method with the traditional methods to improve product environmental impacts**

| Used analyses | Traditional approaches | Proposed method |
|---------------|-----------------------|-----------------|
| Components’ environmental impacts | (1) Components’ environmental impacts | (1) Components’ environmental impacts |
| | (2) Users’ preference changes | (2) Users’ preference changes |
| | (3) Requested functional changes | (3) Requested functional changes |
| | (4) Axiomatic design (resilient for changes) | (4) Axiomatic design (resilient for changes) |

| Pollution reduction scope | Traditional approaches | Proposed method |
|---------------------------|-----------------------|-----------------|
| Product end-of-life | Entire product lifecycle including: |
| | (1) Design |
| | (2) Manufacturing |
| | (3) Product end-of-life |

| Benefits | Traditional approaches | Proposed method |
|----------|-----------------------|-----------------|
| Identifies the most pollutant parts of a product | Simulates/measures future functionalities of a product, and hints the design parameters to be improved |
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References
Afshari, H., & Peng, Q. (2014). Modeling evolution of uncertainty in sustainable product design. In Proceedings of the ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2014 (p. V004T06A052). Buffalo, NY.
Afshari, H., & Peng, Q. (2015). Modeling and quantifying uncertainty in the product design phase for effects of user preference changes. Industrial Management & Data Systems, 115, 1637–1665.
Afshari, H., Peng, Q., & Gu, P. (2013). An agent-based method to investigate customers’ preference in product lifecycle. In Proceedings of the ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (p. V004T05A046). Portland, OR.
AlGedawy, T., & ElMaraghy, H. (2011). Product variety management in design and manufacturing: Challenges and strategies. In The 4th International Conference on Changeable, Agile, Reconfigurable and Virtual Production (pp. 518–523). Montreal.
Alting, L. (1991). Life cycle design. Concurrent Engineering, 1, 19–27.
Barbat, M., Bruno, G., & Genovese, A. (2012). Applications of agent-based models for optimization problems: A literature review. Expert Systems with Applications, 39, 6020–6028.
Bartolomei, L., & Hastings, D. (2012). Engineering systems multiple-domain matrix: An organizing framework for modeling large-scale complex systems. Systems Engineering, 15, 41–61.
Bass, F. M. (1969). A new product growth for model consumer durables. Management Science, 15, 215–227.
Beng, L. G., & Omor, B. (2016). Integrating axiomatic design principles into sustainable product development. International Journal of Precision Engineering and Manufacturing-Green Technology, 1, 107–117.
Bernstein, W. Z., Ramanujan, D., Devanathan, S., Zhao, F., Sutherland, J., & Ramani, K. (2010). Function impact matrix for sustainable concept generation: A designer’s perspective. In ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (pp. 377–383). Montreal.
Beuren, F. H., Gomes Ferreira, M. G., & Cauchick Miguel, P. (2013). Product-service systems: A literature review on integrated products and services. Journal of Cleaner Production, 47, 222–231.
Bonvansin, J., Lelah, A., Matheux, F., & Brissaud, D. (2014). An integrated method for environmental assessment and eco-design of ICT-based optimization services. Journal of Cleaner Production, 68, 144–154.
Bouchereau, V., & Rowlands, H. (2000). Methods and techniques to help quality function deployment (QFD). Benchmarking: An International Journal, 7, 8–20.
Cao, D. X., Zhu, N. H., Cui, C. X., & Tan, R. H. (2008). An agent-based framework for guiding conceptual design of mechanical products. International Journal of Production Research, 46, 2381–2396.
Chen, C. M., Yeh, C. Y., & Hu, J. L. (2011). Influence of uncertain demand on product variety: Evidence from the international tourist hotel industry in Taiwan. Tourism Economics, 17, 1275–1285.
Chou, J. R. (2014). An ARIZ-based life cycle engineering model for eco-design. Journal of Cleaner Production, 66, 210–223. http://dx.doi.org/10.1016/j.jclepro.2013.11.037
Clarkson, P. J., Simons, C., & Eckert, C. M. (2004). Predicting change propagation in complex design. Journal of Mechanical Design, 126, 765–779.
Curran, J. (2016). Wheelchair manufacturing in the US. IBISWorld Industry Report ID04098. Retrieved from ibisworld.com.
Deutz, P., McGuire, M., & Neighbour, G. (2013). Eco-design practice in the context of a structured design process: An interdisciplinary empirical study of UK manufacturers. Journal of Cleaner Production, 39, 117–128.
Eckert, C., Clarkson, P. J., & Zanker, W. (2006). Change and customisation in complex engineering domains. Research in Engineering Design, 15, 1–21.
Eckert, C., Clarkson, P. J., de Weck, O., & Keller, R. (2009). Engineering change: Drivers, sources, and approaches in industry. In Proceedings of the 17th International Conference on Engineering Design (ICED 09), 4, 24–27.
Fiksel, J., & Wapman, K. (1994). How to design for environment and minimize life cycle cost. IEEE International Symposium on Electronics & the Environment (pp. 75–80). San Francisco, CA.
Giffin, M., Keller, R., De Weck, O., Eckert, C., Bounova, G., & Clarkson, P. J. (2007). Change Propagation Analysis in Complex Technical Systems. In 2007 Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC2007 (pp. 183–192). Las Vegas, NV.
Greymy, I., Siva, V., Rahajo, H., & Koh, T. N. (2014). Adapting the Robust Design Methodology to support sustainable product development. Journal of Cleaner Production, 79, 231–238.
Hammaz, B., Caldwell, N. H. M., & Clarkson, P. J. (2013). A holistic categorisation framework for literature on engineering change management. Systems Engineering, 16, 473–505.
http://dx.doi.org/10.1080/00207540701737724
http://dx.doi.org/10.1016/j.jclepro.2011.12.015
http://dx.doi.org/10.1016/j.jesw.2011.12.015
http://dx.doi.org/10.1002/sys.20143
http://dx.doi.org/10.1016/j.jclepro.2013.11.037
http://dx.doi.org/10.1016/j.jclepro.2012.08.035
http://dx.doi.org/10.1016/j.jclepro.2012.12.028
http://dx.doi.org/10.1016/j.jclepro.2012.08.035
http://dx.doi.org/10.1016/j.jclepro.2014.01.003
http://dx.doi.org/10.1016/j.jclepro.2014.05.018
http://dx.doi.org/10.1080/23311916.2016.1231388
Hosseinpour, A. (2013). Integration of axiomatic design with quality function deployment for sustainable modular product design. Winnipeg: University of Manitoba.

Inoue, M., Lindow, K., Stark, R., Tanaka, K., Nahm, Y. E., & Ishikawa, H. (2012). Decision-making support for sustainable product creation. Advanced Engineering Informatics, 26, 782–792.

International Standard Organization, (ISO). (2006). ISO 14044: Environmental management—life cycle assessment—requirements and guidelines. Geneva: Author.

Jarratt, T. A. W., Eckert, C. M., Caldwell, N. H. M., & Clarkson, P. J. (2011). Engineering change: An overview and perspective on the literature. Research in Engineering Design, 22, 103–124. http://dx.doi.org/10.1007/s00163-010-0097-y

Kalligeros, K. (2006). Platforms and real options in largescale engineering systems. Cambridge, MA: Massachusetts Institute of Technology.

Khan, F. I., Sadiq, R., & Veltch, B. (2004). Life cycle index (LINDEX): a new indexing procedure for process and product design and decision-making. Journal of Cleaner Production, 12, 59–76. http://dx.doi.org/10.1016/j.jclepro.2008.10.002

Koffler, C., Kinke, S., Schekert, L., & Buchgeister, J. (2008). Volkswagen slim.LCI: A procedure for streamlined inventory modelling within life cycle assessment of vehicles. International Journal of Vehicle Design, 46, 172–188. http://dx.doi.org/10.1504/IJVD.2008.017181

Koh, E. C. Y., Caldwell, N. H. M., & Clarkson, P. J. (2012). A method to assess the effects of engineering change propagation. Research in Engineering Design, 23, 329–351. http://dx.doi.org/10.1007/s00163-012-0131-3

Kohtamäki, M., Partanen, J., Parida, V., & Wincent, J. (2011). Non-linear relationship between industrial service offering and sales growth: The moderating role of network capabilities. Industrial Marketing Management, 42, 1374–1385. http://dx.doi.org/10.1016/j.indmarman.2010.04.018

Kuligowski, M., Partanen, J., Parida, V., & Wincent, J. (2011). Non-linear relationship between industrial service offering and sales growth: The moderating role of network capabilities. Industrial Marketing Management, 42, 1374–1385.

Kulak, O., Cebi, S., & Kahraman, C. (2010). Applications of axiomatic design principles: A literature review. Expert Systems with Applications, 37, 6705–6717. http://dx.doi.org/10.1016/j.eswa.2010.03.061

Liu, J., Chen, M., Wang, L., & Wu, Q. (2014). A task-oriented modular and agent-based collaborative design mechanism for distributed product development. Chinese Journal of Mechanical Engineering, 27, 641–654. http://dx.doi.org/10.3903/CJME.2014.03.641

Lothhouse, V. (2006). Ecodesign tools for designers: Defining the requirements. Journal of Cleaner Production, 14, 1386–1395. http://dx.doi.org/10.1016/j.jclepro.2005.11.013

Martin, M. V., & Ishii, K. (2002). Design for variety: Developing standardized and modularized product platform architectures. Research in Engineering Design, 13, 213–235.

Masui, K., Sakao, T., Kobayashi, M., & Inaba, A. (2003). Applying quality function deployment to environmentally conscious design. International Journal of Quality and Reliability Management, 20, 90–106. http://dx.doi.org/10.1108/02656710310453836

May, G., Taisch, M., & Kerga, E. (2012). Assessment of sustainable practices in new product development. IFIP Advances in Information and Communication Technology (AICT), 384, 437–447. http://dx.doi.org/10.1007/978-3-642-33980-6

Ostrosi, E., Fougères, A. J., Ferney, M., & Klein, D. (2012). A fuzzy configuration multi-agent approach for product family modelling in conceptual design. Journal of Intelligent Manufacturing, 23, 2565–2586. http://dx.doi.org/10.1007/s10845-011-0541-5

Pigasso, D. C. A., & Sousa, S. R. (2013). Life Cycle Assessment (LCA): Discussion on full-scale and simplified assessments to support the product development process. Cleaner Production Initiatives and Challenges for a Sustainable World, 3rd International Workshop advances in cleaner production (pp. 1–10). São Paulo.

Ramani, K., Ramunjan, D., Bernstein, W. Z., Zhao, F., Sutherland, J., Handwerker, C., & Thurston, D. (2010). Integrated sustainable life cycle design: A review. Journal of Mechanical Design, 132, 091004. doi:10.1115/1.4002308

Rein, W., Parida, V., & Örtqvist, D. (2014). Product-Service Systems (PSS) business models and tactics–A systematic literature review. Journal of Cleaner Production, 97, 61–75.

Russo, D., & Ritzi, C. (2014). An eco-design approach based on structural optimization in a CAD framework. Computer-Aided Design and Applications, 11, 579–588. http://dx.doi.org/10.1016/j.cad.2014.05.026

Russo, D., Re, C., & Montelisciani, G. (2014). Inventive guidelines for a TRIZ-based eco-design matrix. Journal of Cleaner Production, 76, 95–105. http://dx.doi.org/10.1016/j.jclepro.2014.04.057

Senthil, K., Ong, S. K., Nee, A. Y. C., & Tab, B. H. (2003). A proposed tool to integrate environmental and economical assessments of products. Environmental Impact Assessment Review, 23, 51–72. http://dx.doi.org/10.1016/S0959-338X(02)00032-X

Suh, E. S., Weck, O. L., & Chang, D. (2007). Flexible product platforms: Framework and case study. Research in Engineering Design, 18, 67–89. http://dx.doi.org/10.1007/s10163-007-0032-z

Suh, N. P. (2001). Axiomatic design: Advances and applications. New York, NY: Oxford University Press.

Suh, N. P. (2005). Complexity in Engineering. CIRP Annals – Manufacturing Technology, 54, 46–63. http://dx.doi.org/10.1016/j.cirp.2005.07.008

Toghdisian, H., Pishvai, M. R., & Farhadi, F. (2014). Multi-objective optimization approach for green design of methanol plant based on CO2-efficiency indicator. Journal of Cleaner Production, 103, 640–650.

Thurston, D. L., & Srinivasan, S. (2003). Constrained optimization for green engineering decision-making. Environment and Resource Technology, 37, 5389–5397. http://dx.doi.org/10.2222/est.0344359

Wang, C.-H., & Chen, J.-N. (2012). Using quality function deployment for collaborative product design and optimal selection of module mix. Computers & Industrial Engineering, 63, 1030–1037. http://dx.doi.org/10.1016/j.cie.2012.06.014

Wang, X., Chen, H. K., & White, L. (2014). A comprehensive decision support model for the evaluation of eco-designs. Journal of the Operational Research Society, 65, 917–934. http://dx.doi.org/10.1057/jors.2013.23

Wynn, D. C., Grebici, K., & Clarkson, P. J. (2011). Modelling the evolution of uncertainty levels during design. International Journal on Interactive Design and Manufacturing (IJIDeM), 5, 187–202. http://dx.doi.org/10.1115/iidem.2010.0131-y

Xiao, R., & Cheng, X. (2008). An analytic approach to the relationship of axiomatic design and robust design. International Journal of Materials and Product Technology, 31, 241–258. http://dx.doi.org/10.1080/16864360.2014.902691

Xu, X., Han, W., & Ye, T. (2008). Design flow of customized products based on similarity evaluation with cubic QFD based on MAS. International Symposiums on Information Processing (pp. 462–468). Moscow.
