A utility theory-based approach to reducing raw material usage in non-adjustable artifacts, tasks, and environments

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Abstract. In order to accommodate the desired percentage of the target users of a product, decisions must be made to ensure that the design satisfies performance requirements such as user safety, comfort, and ease of use. The marketing concept of "utility theory" is one approach to quantifying the effects of design decisions. It is leveraged in this study to develop a design evaluation approach that considers: a) factors that may be either design-related (design specifications) or user-related (relevant body dimensions) and b) the raw material investment in the design. Based on data collected during a usage behavior study involving doorways of numerous sizes, a conditional logit model was developed to predict the utility of a doorway as a function of its size and the user's stature and shoulder breadth. Next, an eco-design parameter was incorporated into the model as a penalty based on raw material usage. This approach was found to be useful in studying frequently encountered tradeoffs in decisions that could potentially increase product sustainability but could also reduce the utility of the product to the user.

Keywords: design for human variability, discrete choice analysis, design for sustainability, product sizing, anthropometry.

1. Introduction

This paper presents an application of anthropometry-driven and discrete choice-based design decision-making. A conditional logistic regression model is formulated based on data gathered during a behavioral study involving doorways of multiple sizes. The introduction of an eco-design parameter allows the model to penalize design decisions for raw material consumption.

The proposed approach is meant for use in the design of products that are non-adjustable. Examples of such products range from doorways, stairs, office desks, tables, couches, and beds to the relative positioning of different controls in industrial workstations.

Concepts and tools such as just noticeable difference [7, 17] and virtual fitting [3, 6] can be applied to understand the impact of incremental changes in design specifications on the usage experience. In the marketing domain, *utility* is the quantification of a user's preference when assessing a number of product alternatives [4]. This paper proposes an approach to evaluate the utilities of multiple sizes of non-adjustable products (artifacts, tasks, and environments), and to then identify the sizes that help achieve the most efficient ways of allocating raw materials in the design.

Utility theory is based on the principle of rational choice, according to which users always select the product alternative to which they assign the highest utility [2]. The user's process of

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making choice decisions begins with the formation of initial perceptions about each of the available product alternatives. This is followed by the development of preferences, which involves consciously and subconsciously comparing the alternatives and liking one alternative more than another. The user then quantifies these preferences by assessing the utility of each alternative, and finally makes a choice decision [9].

In reality, users' actual choices may not be the one calculated as having the highest utility, thus violating the principle of rational choice [11]. This notwithstanding, the rational choice principle is often used as a simplifying assumption in utility theory-based studies.

Discrete choice analysis (DCA) is a broad category of marketing methodologies aimed at understanding, quantifying, and modeling user choice and the main factors that influence these choice decisions. In DCA, utility is modeled as consisting of two components:

$$\mathbf{U}_{nj} = \mathbf{V}_{nj} + \boldsymbol{\varepsilon}_{nj} \qquad (1)$$

where $\mathbf{U}_{nj}$ is the utility of product alternative j to user n, $\mathbf{V}$ is the quantifiable component of utility, and $\boldsymbol{\varepsilon}$ is the component of utility that is unrelated to the product- and user-related factors considered in the analysis. Accordingly, $\boldsymbol{\varepsilon}$ is modeled as an appropriate distribution. The distribution chosen for this purpose is one of the ways in which DCA methods are classified into logit, generalized extreme value, probit, and mixed logit models [20].

The term $\mathbf{V}$ in Equation (1) is modeled as a function of attributes that are product-specific ($\mathbf{x}$) and user-specific ($\mathbf{s}$):

$$\mathbf{V}_{nj} = \mathbf{V}\left(\mathbf{x}_{nj}, \mathbf{s}_{nj}\right). \qquad (2)$$

Commonly used user-specific predictors of choice include income level, educational qualifications, and family size, while product-related predictors could be design specifications, advertizing expenditure, etc.

A simple DCA modeling technique is conditional logistic regression analysis, which results in a model in the form of Equation (3):

$$\mathbf{U}_{j} = \ln[\mathbf{Pr}(choice = j)] = \Sigma_{k}\,[\mathbf{p}_{jk}\cdot\mathbf{X}_{pk}] \\ + \Sigma_{l}\,[\mathbf{q}_{jl}\cdot\mathbf{X}_{ql}] \quad (3)$$

where k is the number of product-specific factors, l is the number of user-specific factors, and $\mathbf{p}$ and $\mathbf{q}$ are the coefficients of the product- and user-specific factors $\mathbf{X}_{p}$ and $\mathbf{X}_{q}$, respectively.

DCA-influenced methodologies have been applied to the broad area of engineering design in a number of research efforts. Examples of these efforts include a multinomial logit-based universal motor design problem [21], a linear logit-based game theoretical analysis of market structures [19], and a discrete choice survey to demonstrate the construction of user preferences [12]. Thanks to such contributions, DCA is being increasingly accepted in engineering design as a valuable component of decision-making methods.

In the field of ergonomics, relevant anthropometry (body dimensions) are used to assess the "fit" of users into different designs of the product [10]. In design for human variability (DfHV) research, relevant body measures are also known to be good predictors of users' preferred ways of physically interacting with the product [5]. Data about these body measures for the target user populations are therefore used to assess the ability of designs to *accommodate* the desired percentage of the population by satisfying performance criteria such comfort, safety of the user and of other individuals in the usage vicinity, and ease of use.

Recent research has demonstrated the value of anthropometry in DCA-based engineering design decision-making [15]. In addition to its ability to predict user-product interactions, anthropometry enables models to be extrapolated to any target population for which the designer has information about the body measures [14]. This capability, in conjunction with techniques to accurately synthesize anthropometric data for populations [6, 18], allows for the use of models based on a sample population (participants in a survey or experiment) to estimate choice decisions for other populations also.

In this paper, a methodology is proposed for incorporating an eco-design parameter into a model formulated through conditional logistic regression analysis of data from a discrete choice experiment. The eco-design parameter acts as a penalty factor that is dependent on the amount of raw material consumed by the design. The extrapolation of this model to the target population at hand yields estimates of the *raw material minimization-utility* (RMM-utility) across

a range of product specifications. These data help identify the design that maximizes user utility while minimizing raw material consumption.

2. Methodology

The proposed method involves conducting a discrete choice experiment, analyzing the data to formulate a conditional logistic regression model, introducing the eco-design parameter into the model, extrapolating the model to the target user population, and finally examining the utility variation across a range of product specifications. This helps identify the most suitable design for the target population.

In a discrete choice experiment, each participant must be required to evaluate multiple sets of product alternatives, with each set consisting of the same number of alternatives. In every set, the participant should physically interact with all the alternatives and then choose the one they prefer the most. Furthermore, the objective of the experiment is to have the participant evaluate designs with which they can interact safely. Therefore, relevant anthropometry can be used to limit the range of design specifications for each participant to only those sizes that are likely to fit the participant. The implementation of this concept is explained in Section 3. The data collected throughout this experiment are the relevant body measures of every participant, the product sizes presented to the participant in each set, and the choice decision made.

Conditional logistic regression analysis of the discrete choice data from the experiment will yield a model similar to Equation (3):

$$\mathbf{U}_J = \beta_1.(\mathbf{D}_1 \ / \ \mathbf{P}_{J,1}) + \beta_2.(\mathbf{D}_2 \ / \ \mathbf{P}_{J,2}) \qquad (3)$$

where $\mathbf{U}_J$ is the utility of the product alternative to participant J, $\mathbf{D}_1$ and $\mathbf{D}_2$ are the two design attributes of the product, $\mathbf{P}_{J,1}$ and $\mathbf{P}_{J,2}$ are two relevant body dimensions of the participant, and β_1 and β_2 are coefficients of regression.

Many design scenarios entail tradeoffs between user accommodation and resource efficiency. For example, a product can be sized and/or be embedded with enough adjustability to fit the entire target population. However, satisfying the needs of users at the very ends of the

upper and lower tails of anthropometric distributions can be inefficient, since at this point, any increase in size or allocated adjustability will only yield incremental increases in accommodation levels. Accordingly, in order to achieve a balance between accommodation and resource consumption, the objective usually is to accommodate 90% or 95% of the population.

The proposed method helps achieve similar balance between resource efficiency and user comfort and satisfaction through the inclusion of an eco-design parameter in Equation (3). The parameter contains a penalty factor γ, which represents the importance to the designer of the goal of raw material reduction. The greater the importance of the goal, the higher will be the value assigned to γ. The actual value should depend on the designer's own assessment of the importance of minimizing raw material consumption in the design process. The model now takes the form of Equation (4):

$$\mathbf{U}_J = \beta_1.(\mathbf{D}_1 \ / \ \mathbf{P}_{J,1}) + \beta_2.(\mathbf{D}_2 \ / \ \mathbf{P}_{J,2}) - \gamma.f(\mathbf{D}_1, \mathbf{D}_2) \quad (4)$$

where $f(\mathbf{D}_1, \mathbf{D}_2)$ is some measure of raw material consumption. The utility calculated using Equation (4) is now termed raw material minimization-utility (RMM-utility), since it incorporates the sustainable design concern of raw material consumption.

The model can now be extrapolated to the target population. This is done by driving the equation using anthropometric data for that population. The RMM-utility data thus generated can be analyzed to identify the design that best achieves the twin goals of minimizing raw material consumption and providing the target users with the required levels of safety, comfort, and satisfaction.

3. Case study

Interactions with apertures are a way to study users' assessments of the spatial relationship between themselves and the environment. This includes their comfort associated with apertures of different sizes [8]. Doorways are an example of apertures that people interact with multiple times on a daily basis. The combination of influential factors in a doorway-based experiment

(e.g., spatial constraints, aesthetics, physical and cognitive capabilities of the participants) make for a simple yet effective study into usage behaviors. Also, the simplicity of such an experiment notwithstanding, doorways are examples of multi-dimensional design problems that entail tradeoffs between different criteria; a more complex example of such tradeoffs is headroom vs. legroom in automotive seating. Furthermore, the body dimensions relevant to the design of doorways---stature and shoulder width---are easy to measure. For all these reasons, doorways were selected as the subjects of the case study.

The experimental procedure was reviewed and approved by the institutional review board at Penn State University. Participants were 47 in number, and were all student volunteers and the university.

The procedure commenced with the measuring of the participant's stature, biacromial breadth (a measure of shoulder width), and weight. The total range of possible doorway sizes was height 68-84 inches (1727-2134 mm) and width 24-44 inches (610-1118 mm). However, the range of possible doorway sizes for each participant was constrained to be higher than their stature and wider than their biacromial breadth. This was done so that participants would only interact with doorways in which they could physically fit.

The participant then walked through 8 sets of doorways, with each set consisting of 3 doorways. The sizes of all these doorways were randomly drawn from the set of allowable sizes for that participant. With every set, the participant was asked to evaluate the doorways and select their preferred one.

Following the conclusion of the experiment, the data were analyzed using the conditional logistic regression method described in Section 2. This resulted in a model in the form of Equation (3). The predictors in this model were doorway height (D_1), doorway width (D_2), stature (P_1), and biacromial breadth (P_2). Table 1 contains more details about this model. The Pr ($>= |t|$) values for both predictor ratios ($D_1/P_{J,1}$ and $D_2/P_{J,2}$) show significant contributions towards the fit of the model to the underlying data. The log-likelihood value also serves to confirm the reliability of the model.

The model was now extrapolated to two target user populations: female civilian users in Japan and the U.S. Anthropometric data for these populations were obtained from the AIST anthropometric database [1] for the Japanese users, most of who are in the age range of 18-30 years, and NHANES [16] for the U.S. users above 18 years of age. Stature and biacromial breadth data for each population were used as the predictors P_1 and P_2 in the model. The possible doorway sizes for either population were restricted to only those that would fit at least 95% of the users, since this was the accommodation goal. This extrapolation process produced estimates of the utilities of different doorway sizes for each user. The utility values were averaged across all the users in either population, and were used to generate the contour plots in Part **I** of Figure 1.

The Japanese and U.S. users have different ranges of allowable door heights, a direct result of the difference in the variation of stature across the two populations. This aside, the two contour plots are similar. Expectedly, the utility is highest for the largest doorway size (84 inches height and 68 inches width), since this doorway is easiest to walk through and therefore provides the users with the highest level of comfort. However, the average utility value for this doorway is higher for the Japanese population. This is another indicator of the anthropometric differences between the two populations. Based on the contours in Part **I** of Figure 1, the largest doorway sizes were found to be the most suitable design option for both populations.

Next, the eco-design parameter was introduced into the model to result in an RMM- utility estimation model in the form of Equation (4). In order to consider raw material consump-

Table 1

Details about Equation (3), the utility estimation model formulated in Section 3.

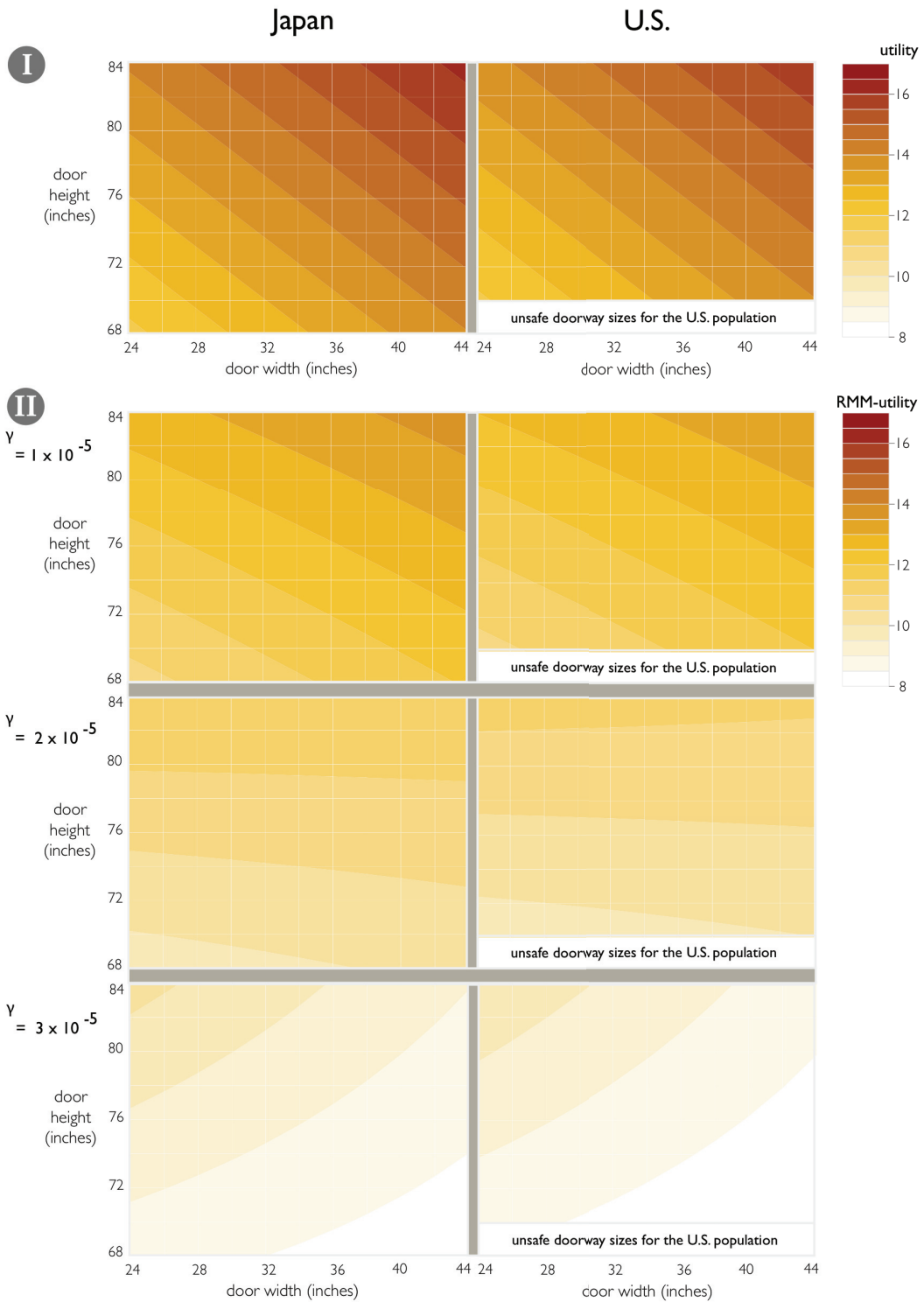|	Coefficient	Std. Error	t-value	Pr ($>= |t|$)
$D_1 / P_{J,1}$	6.09	1.12	5.43	5.7e-8
$D_2 / P_{J,2}$	0.99	0.17	5.86	4.6e-9
Log-likelihood	*-382.06*			

Figure 1: Contour plots of average utility for a range of safe doorway sizes for Japanese and U.S. female civilians. Part **I** shows utility calculated using Equation (3), which does not incorporate the raw material minimization objective. The plots in Part **II** are of raw material minimization-utility (RMM-utility) calculated using Equation (4), with increasing values of the penalty factor (γ) indicating greater emphasis on the objective of reducing raw material consumption.

tion, the function $f(\mathbf{D}_1, \mathbf{D}_2)$ was calculated as $\mathbf{D}_1 \times \mathbf{D}_2$, i.e., the product of doorway height and width. Assuming the same depth and thickness of every doorway frame, $\mathbf{D}_1 \times \mathbf{D}_2$ would be a good predictor of the raw material consumed in the construction of each doorway frame.

The range of possible values for the penalty factor (γ) was estimated keeping in mind the expected range of values of the β coefficients and the $\mathbf{D}/\mathbf{P}$ terms in Equation (4). The $\mathbf{D}/\mathbf{P}$ terms are ratios of doorway specifications to relevant anthropometry. Since the former are chosen to be greater than the latter for 95% of the population, the ratios can be expected to usually be greater than 1, but not more than 3. On the other hand, the $f(\mathbf{D}_1, \mathbf{D}_2)$ term in the penalty factor calculation is a multiple of two variables, one in the 1727-2134 range (height, $\mathbf{D}_1$) and the other in the 610-1118 range (width, $\mathbf{D}_2$). Therefore, in order for the eco-design parameter to assume appropriate values, γ could vary between 0 and 5×10^{-5}. A value of 0 implied no relevance of raw material consumption to the design effort, while a value of 5×10^{-5} meant that raw material minimization was very important. Figure 2 shows plots of average RMM-utilities across the range of allowed doorway sizes and with a few different values of the penalty factor (γ) for the two target populations.

A comparison of Parts **I** and **II** in Figure 1 highlights the impact of the inclusion of the eco-design parameter into the utility estimation model. The average RMM-utility values estimated for either population are lower across the range of allowed doorway sizes. Furthermore, as the penalty factor (γ) is increased, the shape of the contour begins to deviate more markedly from the original shape in Part **I** of Figure 1. In the plots with a γ value of 3×10^{-5}, for constant doorway height, RMM-utility is *negatively* impacted by increase in doorway width. The contours in these plots are also more curved than before.

The design decisions based on the contours in Part **II** of Figure 1 depend on the value assigned by the designer to γ. When γ is 1×10^{-5}, the largest doorway is still the most suitable design for both populations. In contrast, for a γ value of 2×10^{-5}, doorway height 84 inches and width 24 inches are the better design decision for the U.S. population. In these contour plots, width has almost no influence on utility for doorway heights approaching 84 inches. Finally, when γ

is 3×10^{-5}, the most suitable design is clearly 84 inches height and 24 inches width.

The implications of these results and observations are discussed in Section 4.

4. Discussion

4.1. Proposed methodology

The proposed technique involves running a usage behavior experiment, formulating a conditional logistic regression model to predict utility based on product dimensions and user anthropometry, introducing an eco-design parameter into the model to penalize net utility based on the amount of raw material consumed by the design, extrapolating this model to the target population, and analyzing the resulting estimates of RMM-utility to identify the most suitable design. This process was demonstrated through a case study involving doorway design selection.

Following the usage experiment stage of the study, the construction of a utility estimation model in the form of Equations (3) or (4) was found to be a relatively simple task. The utilization of predictor ratios, each consisting of ratios of a design dimension and its relevant body measure, yielded a model that was a good fit to the underlying data (Table 1). Using anthropometric data for the intended users of the product, the model was also easily extrapolated to the target population. The entire process was therefore sufficiently simple to apply and broadranging in its scope. It could be adapted to the design of other non-adjustable artifacts, tasks, and environments.

The eco-design parameter incorporated the sustainability concern of raw material reduction into the model. The penalty factor allowed the designer to assess the importance of this sustainable concern, and to assign an appropriate weight to the raw material consumption-based penalty. The resulting model made for a detailed study of the tradeoff between user comfort (in terms of utilities derived from different doorway sizes) and product sustainability (in terms of raw material consumption). The contour plots shown in Figure 1 were a useful visual aid in decision-making to resolve this tradeoff.

Part **II** of Figure 1 allows for some interesting observations on the effect of increased values of

γ on the RMM-utility contours. The plots with γ equal to $3x10^{-5}$ show that doorway height wields greater influence on RMM-utility than doorway width. The slopes of the other contour plots in Parts **I** and **II** of Figure 1 reiterate this observation. An awareness of this fact allows the designer to allocate sufficient raw material to satisfy the height requirement while minimizing the raw material allocated to satisfy the width requirement. This may not be useful in the design of doorways for settings such as houses, educational establishments, restaurants, etc., where aesthetics are an important concern. However, information from a study like this can be valuable in the design of doorways for industrial installations, emergency exits at public locations, etc., where the goal may be to minimize the dimensions of the exit while ensuring its efficiency and safety. Furthermore, the general methodology proposed in this work can be applied in the design of other non-adjustable artifacts, tasks, and environments, including stairs, office desks, tables, couches, beds, and the controls in industrial workstations.

4.2. Limitations and future work

A common procedure used in the development of experiment-based preference models is selection of the sample population to closely represent the actual target population, and the oversampling of participants in the tails of the population. This is because design decisions are more likely to affect users in the tails of the anthropometric distributions. Not implementing this procedure is a limitation of this study.

The extrapolation of the same model to the target populations implied the assumption that the U.S. and Japanese users have similar assessments of preference to the sample population of students who participated in the discrete choice experiment. This assumption may not always be valid. Factors such as age, economic levels, family sizes, and even cultural differences could play a role in the development of unique preferences across users in any target population.

Developing a procedure for calculating an appropriate value for the penalty factor (γ) is an important objective for future research. In this study, different γ values were used to demonstrate the role of the eco-design parameter on the utility model, with higher values of γ indicating a greater emphasis on raw material reduction in the design process. However, when dealing with a design problem, numerous other considerations will also have to be taken into account in calculating the penalty factor. The most important of these considerations is the relative importance of raw material reduction in comparison to other sustainability concerns such as minimizing emissions of greenhouse gases and particulate matter, minimizing energy consumption, etc.; in some cases, these other concerns may be far more influential in determining product sustainability. The penalty factor calculation process must account for such considerations so that a suitable value of γ is used in the RMM-utility estimation model. The procedures implemented in more comprehensive design for sustainability techniques such as lifecycle analysis and activity-based costing may be useful in this regard.

The doorway design case study in itself has a major limitation: any reduction of doorway size may also be accompanied by an increase in the raw material consumed by the surrounding wall. The validity of this limitation is diminished in the design of entry/exit apertures for industrial or emergency exit applications, among others. Also, for the many reasons mentioned in Section 3, doorways are a good design scenario for the purposes of this case study, which served the purpose of demonstrating the proposed methodology. However, future research could look to apply this methodology in the context of a diverse set of products, including office desks, tables, couches, beds, etc. Doing so would help demonstrate the usefulness of this approach.

4.3. Conclusion

The aim of the proposed methodology is to assist in making more raw material-efficient decisions in the design of non-adjustable artifacts, tasks, and environments. Basic utility theory in the form of conditional logistic regression is leveraged for this purpose. Its current limitations notwithstanding, the resulting RMM-utility modeling technique is a valuable addition to the design for sustainability toolkit. Future research will help incorporate this technique into existing methodologies such as lifecycle analysis and activity-based costing, where it can play a useful role in resolving tradeoffs between user comfort and raw material consumption.

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