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Theme-Based Comprehensive Evaluation in New Product Development Using Fuzzy Hierarchical Criteria Group Decision-Making Method

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Abstract

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Keywords

criteria, hierarchical, fuzzy, development, product, evaluation, comprehensive, method, theme-based, decision-making, group

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***Abstract*—One of the features of the digital ecosystem is the integration of human cognition and socio-economic themes into the process of new product development (NPD). In a socio-economic theme-based NPD, ranking a set of product prototypes that have been designed always requires the participation of multiple evaluators and consideration of multiple evaluation criteria. Using the well-being theme-based garment NPD as a background, this paper first presents a fuzzy hierarchical criteria group decision-making (FHCGDM) method which can effectively calculate final ranking results through fusing all assessment data from human beings and machines. It then presents a garment NPD comprehensive evaluation model with hierarchical criteria under the well-being theme through identifying a set of marketing tactics from a consumer acceptance survey. It further provides an establishment process for an NPD evaluation model under the digital ecosystem framework. Finally, a garment NPD case study further demonstrates the proposed well-being NPD comprehensive evaluation model and the FHCGDM method. The advantages of the proposed evaluation method include successfully handling criteria in a hierarchical structure, automatically processing both objective measurements from machines and subjective assessments from human evaluators, and using the most suitable type of fuzzy numbers to describe linguistic terms.**

***Index Terms*—Decision support systems, digital ecosystems, fuzzy sets, multicriteria decision making (MCDM), new product development (NPD), product evaluation.**

I. Introduction

THE digital ecosystem is defined as an open, loosely coupled, domain clustered, demand-driven, and self-organizing agents' environment, in which each species is proactive and responsive for its own benefit or profit [8], [11]. The underlying technology for digital ecosystems is composed of web services architecture, self-organizing intelligent agents, ontology-based knowledge sharing and intelligence-based decision support, and recommendation and evaluation systems. It is at the intersection of industry, business, human endeavors, social science, and cutting edge Internet technologies, and is an application-driven research.

According to the social and technical requirements presented in the privilege technical report of the European Commission for FP7 Framework Program [10], future research activities on digital ecosystem development will deal with multidisciplinary subjects, pay more attention to the integration of information with socio-economic systems, and improve the user-centered design of products and services through integration with human actions and cognition. The enhancement of interactions between human actions, socio-economic concepts, and technical structures has become an important trend for the development of new digital ecosystems. The implementation of these systems in different industrial sectors can effectively change traditional methods of design, management, and production.

In this context, we aim to integrate human actions and complex socio-economic themes, such as well-being and sustainable development, into the process of new product development (NPD) in order to adapt its design to various competitive markets. Under the digital ecosystem framework, this process of NPD consists of four main phases: theme generation, product design and detail engineering, product and process development and evaluation/testing, and production and market launch [1], [12], [30]. This process becomes more and more digitalized in current digital ecosystems. In a garment NPD process, theme-related evaluation/testing can be directly linked with marketing analysis through a set of digital processes. The evaluation/testing aims to identify which features must be incorporated into the product, what benefits the product will provide, and how consumers will react to the product [1], [17]. This phase includes choosing and ranking prototype products by a set of criteria under a design theme. It will test the theme through asking a sample of prospective consumers and relevant designers on what they think of the idea, as well as by obtaining measuring data from particular machines. With the support of digital ecosystems, more NPDs will start using advanced techniques to optimize the evaluation process and analyze the evaluation results.

Literatures and practices indicate that NPD evaluation is a kind of preference-based dynamic decision, and many human

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cognition, technical standard, and complex socio-economic factors need to be considered [20], [29]. Therefore, the first is to determine the evaluation criteria and their relevance to the implementation of a design theme. A garment NPD comprehensive evaluation always involves multiple criteria in a hierarchical structure. These criteria have different roles and relevance to a design theme. In this paper, the design theme for a garment NPD is "well-being"—i.e., to assess which garment product best matches the features of a well-being design and owns the well-being experience in wearing. This design theme needs to assess the criteria which include factors not only related to garment function properties but also to fashion styles and marketing demands.

Well-being of garment product quality is a complex concept relating consumer preference to product design; in particular, it takes the idea of quality as a philosophical and sociological notion which is evaluated through the senses and perception. A well-being-based garment NPD evaluation is often organized in groups, such as a set of garment designers and/or salespersons, because an individual may not have sufficient knowledge to appropriately assess a product. Moreover, it often requires gathering, processing, and assessing data from manufacturing devices. In practice, human evaluators often express their assessment in subjective expressions, in particular, the linguistic terms [19], [24]; for example, to express the relevance of a criterion to a design theme, the terms "*relevant* (or *important*)" and "*very relevant* (or *very important*)" can be used, while related machines provide data in objective data in which 10 m^2 and $-20\,^{\circ}$C could be used. Therefore, a challenge here is how to effectively fuse both subjective assessments and objective data.

Since a garment NPD evaluation exhibits typical features of multicriteria decision making (MCDM) and group decision-making (GDM) problems, the aforementioned issues require extending MCDM and combining it with GDM methods with the capability to deal with the following: 1) hierarchical criteria (for example, a product can be evaluated by multiple aspects, in which each aspect can be evaluated by multiple criteria, and each criterion can be evaluated by multiple subcriteria); 2) objective and subjective data fusion; and 3) linguistic information processing to the well-being design theme.

This paper first explores what constitutes a well-being product and what features represent the concept of a well-being design from the consumer's point of view. A marketing survey was conducted to discover consumers' perceptions and requirements on the well-being theme. The collected data were used to determine product evaluation criteria and identify their relevance grades (weights). This paper proposes a garment NPD comprehensive evaluation model which has a hierarchical structure of evaluation factors under the well-being theme. In order to handle linguistic terms used in the NPD evaluation model, a fuzzy hierarchical criteria group decision-making (FHCGDM) method is developed. The method combines MCDM with GDM methods and proposes hierarchical operators to fuse the data obtained from both human evaluators and machines. It applies fuzzy set techniques to handle three kinds of linguistic terms in evaluating garment products. A fuzzy hierarchical criteria group decision-support system (FHCGDSS) implements the proposed method and is used to support real garment NPD evaluations. Furthermore, through analyzing the evaluation data obtained from evaluators and machines under each criterion, we establish a relationship between human senses and machine measurement values. This relationship is very important, as it can be directly used in the detailed engineering step of future product design.

The main contributions of this paper include the following: 1) the proposal of a garment NPD evaluation model under the theme of well-being design; 2) the proposal of an establishment process for an NPD evaluation model, which can be used in many kinds of other products and/or with other themes; 3) the development of an FHCGDM method and a specialized software tool for garment NPD evaluation; and 4) the development of an application to directly support garment NPD evaluations and the establishment of a corresponding relation between human-sense and machine measurements.

Following the introduction, preliminaries and related work are presented in Section II. Section III describes the FHCGDM method for NPD evaluation. Section IV discusses the concept of well-being design and presents a garment NPD comprehensive evaluation model under the concept and its establishment process. An application of garment NPD using the proposed model and method is illustrated in Section V. Conclusions are highlighted in Section VI.

II. Preliminaries and Related Work

A. Related Work

Multicriteria decision making is widely used in the evaluation of a finite number of predetermined alternatives, which are associated with a level of achievement of the criteria. Based on the criteria, a selection or ranking of the alternatives is made [21]. GDM, including group decision-making models [20] and aggregation approaches [1], [18], has been extensively studied in the literature. Since it was proposed by Zadeh [33], fuzzy set theory has been widely used to deal with linguistic variables in various decision and evaluation applications, particularly in MCDM and GDM [2], [21], [28], [34]. For example, Chang and Chen [9] developed a fuzzy MCDM method for technology transfer strategy selection in biotechnology. Furthermore, Carlsson and Fuller [7] reviewed the developments in fuzzy MCDM methods and identified some important applications. Dubois *et al.* [13] proposed two uncertainty modeling frameworks, namely, the transferable belief model and the qualitative possibility theory, to deal with multiexperts multicriteria assessment problems. Stover and Hall [25] further provided an overview of the fuzzy-logic architecture and discussed its application in data fusion, indicating that highly complex systems with a large number of inputs will benefit from the use of qualitative linguistic rules if the control task is properly partitioned. Goodridge and Kay [16] presented a modular fuzzy control architecture and an inference engine that can be used to multilayer fuzzy behavior fusion for real-time reactive control systems. A more recent result by Sun *et al.* [26] reports the fuzzy-logic-based control of an induction motor for a dc grid power-leveling system. Bouafia, Krim, and Gaubert [3] particularly presented their results on the evaluation and selection of a fuzzy-logic-based switching state. Yu and Kaynak [32] further reported their survey on how to use soft computing-based intelligent systems to provide alternative means for engineering and product development. Our recent developments on fuzzy MCDM proposed a fuzzy multicriteria group decision method [21], [22] and a software tool called Decider [23]. However, theme-based product evaluation in NPD with fuzzy hierarchical criteria in a group is a new exploration.

B. Preliminaries

For the convenience of describing the proposed FHCGDM method, we first introduce some basic notions and related theorems of fuzzy sets and fuzzy numbers.

Definition 1: A fuzzy set $\widetilde{A}$ in a universe of discourse X is characterized by a membership function $\mu_{\widetilde{A}}(x)$ from X to the interval [0, 1]. The function value $\mu_{\widetilde{A}}(x)$ is termed the membership degree of x belonging to $\widetilde{A}$.

Definition 2: The λ-cut of a fuzzy set $\widetilde{a}$ is defined as

$$a_\lambda = \left\{x; \mu_{\widetilde{a}}(x) \geq \lambda, x \in X\right\}. \tag{1}$$

If $a\lambda$ is a nonempty-bounded closed interval in X, it can be denoted by $a\lambda = [a_\lambda^L, a_\lambda^R]$; a_λ^L and a_λ^R are the lower and upper endpoints of the closed interval, respectively.

Definition 3: A fuzzy number is a convex and normalized fuzzy set on R if, for any $\lambda \in [0, 1]$, $a\lambda$ is a finite closed interval.

Definition 4: A triangular fuzzy number $\widetilde{a}$ is defined by a triplet (a_0^L, a, a_0^R), and the membership function $\mu_{\widetilde{a}}(x)$ is defined as

$$\mu_{\widetilde{a}}(x) = \begin{cases} 0 & x < a_0^L \\ \frac{x - a_0^L}{a - a_0^L} & a_0^L \leq x < a \\ \frac{a_0^R - x}{a_0^R - a} & a \leq x \leq a_0^R \\ 0 & a_0^R < x \end{cases} \tag{2}$$

where $a = a_1^L = a_1^R$.

Definition 5: If $\widetilde{a}$ is a fuzzy number and $0 < a_\lambda^L \leq a_\lambda^R \leq 1$ for any $\lambda \in (0, 1]$, then $\widetilde{a}$ is called a normalized positive fuzzy number; if a triangular fuzzy number $\widetilde{a}$ is a normalized positive fuzzy number, then $\widetilde{a}$ is called a normalized positive triangular fuzzy number [31].

Let $F^*(R)$ and $F_T^*(R)$ be the sets of all normalized positive fuzzy number and all normalized positive triangular fuzzy numbers on R, respectively.

Definition 6: If $\widetilde{a}$ is a fuzzy number and $a_\lambda^L > 0$ for any $\lambda \in (0, 1]$, then $\widetilde{a}$ is called a positive fuzzy number. Let $F_+^*(R)$ be the set of all finite positive fuzzy numbers on R.

For any $\widetilde{a}, \widetilde{b} \in F_+^*(R)$ and $0 < \alpha \in R$

$$\widetilde{a} + \widetilde{b} = \bigcup_{\lambda \in (0,1]} \lambda \left[a_\lambda^L + b_\lambda^L, a_\lambda^R + b_\lambda^R\right]$$

$$\alpha\widetilde{a} = \bigcup_{\lambda \in (0,1]} \lambda \left[\alpha a_\lambda^L, \alpha a_\lambda^R\right]$$

$$\widetilde{a} \times \widetilde{b} = \bigcup_{\lambda \in (0,1]} \lambda \left[a_\lambda^L \times b_\lambda^L, a_\lambda^R \times b_\lambda^R\right].$$

Definition 7: Let $\widetilde{a}$, $\widetilde{b} \in F_+^*(R)$, then the quasi-distance function of $\widetilde{a}$ and $\widetilde{b}$ is defined as

$$d(\widetilde{a}, \widetilde{b}) = \left(\int_0^1 \frac{1}{2}\left[\left(a_\lambda^L - b_\lambda^L\right)^2 + \left(a_\lambda^R - b_\lambda^R\right)^2\right] d\lambda\right)^{\frac{1}{2}}. \tag{3}$$

III. FHCGDM Method

This section illustrates the proposed FHCGDM method for the garment NPD evaluation problem.

A. Overview

Evaluating a set of new products under the well-being theme needs to embrace both subjective assessments from human evaluators (such as designers) as well as objective measurements from machines. As the well-being concept is an intrinsic element of a human being's psychological feelings, the machine measurements need to be converted to subjective assessments to reflect human experiences in a qualitative way. To implement the conversion, designers and engineers should identify an acceptable range for each kind of machine measurement and define a preference value. The ranges are determined by the well-being theme, and the preference value is determined by the nature of the criterion relevant to the well-being theme.

After establishing the conversion from machine objective measurements to subjective assessments, the method uses normalized positive fuzzy numbers to express linguistic terms used for subjective assessments on evaluation criteria, relevance grades of criteria, and impacts of evaluators.

The evaluation result for each aspect of the well-being theme is obtained by aggregating assessments on its related criteria and indicators. The obtained results for new designs are used for two purposes. One is to compare different designs to select the one which best matches the features of the well-being theme; the other is to guide the manufacturing procedure to produce a better well-being product. In order to determine which design is better suited to meet the demand of the well-being concept, the results obtained will be compared with two predefined well-being acceptance grades, i.e., the best and the worst acceptance grades. The nearer an evaluation result is to the best acceptance grade, the more satisfactorily the design meets the requirements of the well-being theme.

In summary, the presented evaluation method includes three stages: 1) converting the machine measurements into subjective assessments; 2) evaluating new designs following the hierarchy of criteria; and 3) calculating the acceptance grades of new designs based on the evaluation results. In the following sections, we will provide more detail of these three stages.

B. Symbol Notations

For convenience, this section lists the symbols used in the method illustrations.

Let C_n $(n = 1, 2, 3)$ be the sets of aspects, criteria, and the indicators defined in the garment NPD evaluation model in Fig. 1, respectively. From Fig. 1, we can see that C_1 includes

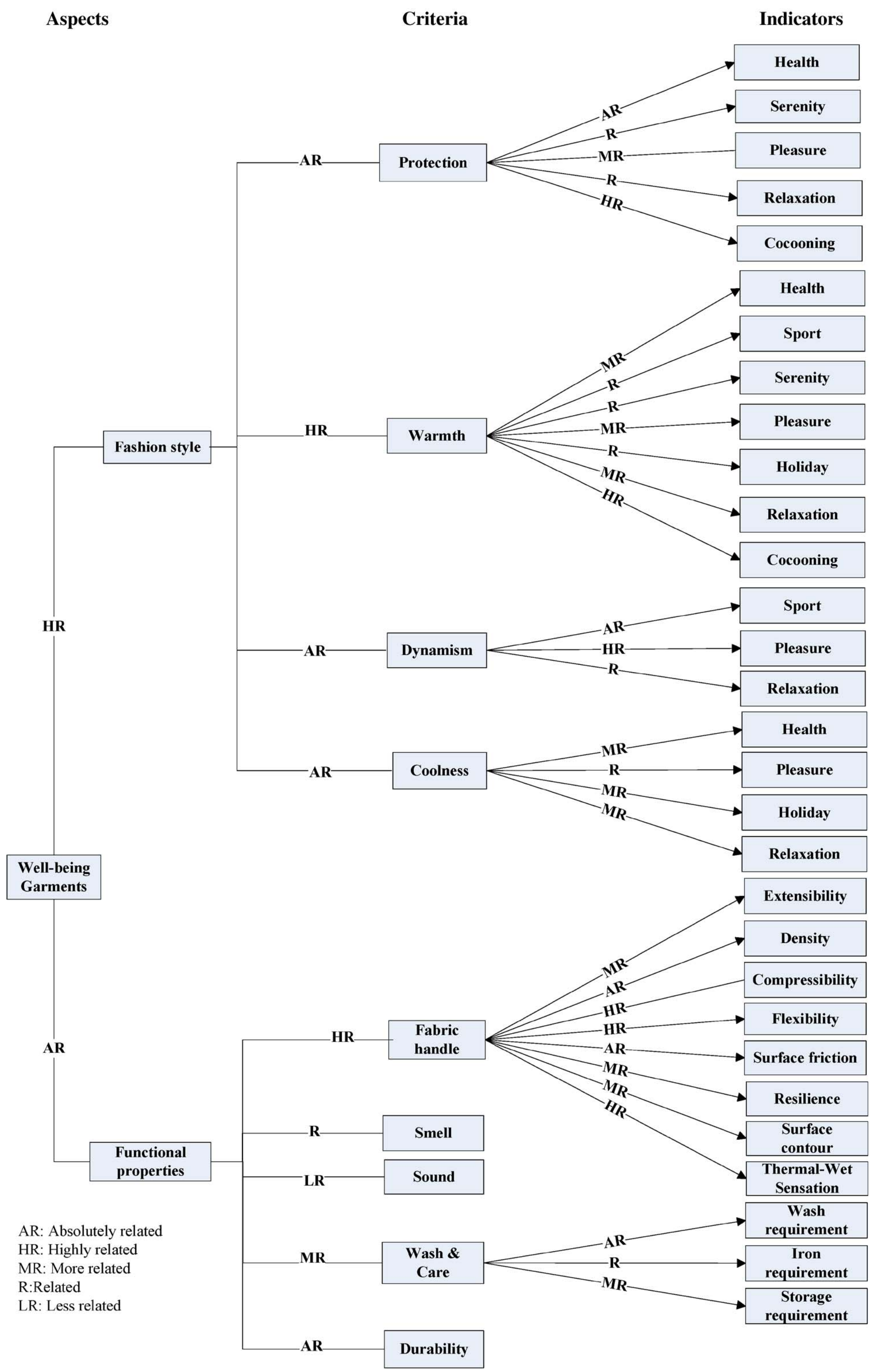

Fig. 1. Hierarchical garment NPD evaluation model under the well-being theme.

two aspects, i.e., "fashion style" and "functional properties"; C_2 includes nine criteria, i.e., "protection," "warmth," "dynamic," "coolness," "fabric hand," "smell," "sound," "wash and care," and "durability"; and C_3 includes 30 indicators. (Note: duplicated occurring indicators in C_3 are used for clarifying the hierarchy structure.) An aspect (or criterion) is supported by some criteria (or indicators). The supporting relationship is displayed by the connection lines. If a factor (i.e., an aspect, a criterion, or an indicator) is not supported by other factors, the factor is called a leaf node; otherwise, it is called a nonleaf node. For instance, the criterion "smell" is a leaf node, and all indicators are leaf nodes.

Based on consumer survey and development practices, each evaluation factor/criterion is given a relevance grade which is

TABLE I
LINGUISTIC TERMS FOR RELEVANCE GRADES

Relevance grades	Fuzzy number label
Absolutely unrelated (AUR)	a_1
Unrelated (UR)	a_2
Less related (LR)	a_3
Related (R)	a_4
More related (MR)	a_5
Highly related (HR)	a_6
Absolutely related (AR)	a_7

TABLE II
LINGUISTIC TERMS FOR IMPACT FACTORS

Impacts (weights)	Fuzzy number label
Absolutely unimportant	s_1
Unimportant	s_2
Less important	s_3
Important	s_4
More important	s_5
Strongly important	s_6
Absolutely important	s_7

TABLE III
LINGUISTIC TERMS FOR SUBJECTIVE ASSESSMENTS

Linguistic terms	Fuzzy number label
Very low	b_1
Low	b_2
Slightly low	b_3
Medium	b_4
Slightly high	b_5
High	b_6
Very high	b_7

chosen from the linguistic term set shown in Table I, where a_i is a normalized positive fuzzy number, $i = 1, 2, \ldots, 7$.

Let $P = \{P_1, P_2, \ldots, P_m\} (m \geq 2)$ be the set of human evaluators, and $M = \{M_1, M_2, \ldots, M_k\}$ $(k \geq 2)$ be the set of machines. Each P_i (or M_j) is associated with an impact factor w_i which indicates its influence on the evaluation result. The impact factors are linguistic terms taken from Table II, where s_i is a normalized positive fuzzy number, $i = 1, 2, \ldots, 7$.

Let $T_s \subseteq F^*(R)$ be the linguistic terms used for expressing subjective assessments as shown in Table III.

C. Machine Measurement Conversions

Machine measurements as evaluations of some factors of the well-being theme must be converted into subjective assessments before being used in the evaluation method. Based on the different natures of these factors, a preference value is first defined for each reasonable measurement range. The preference value has three possible meanings. The first represents the value having the most enhancements for the features of the well-being theme. The second meaning indicates the opposite situation to the first. The third meaning emphasizes that the preference value is the intermediate state between the previous two.

According to the definition of the preference value in a given measurement range, the feedback of consumer surveys, and previous development practices, a conversion function is determined. Without loss of generality, this paper uses f_c for the conversion function with respect to factor c, which is defined from the range $U_c = [a, b]$ to T_S. For any $x \in U_c$, $f_c(x)$ is the obtained subjective assessment from the measurement x.

Machine measurements are often obtained from real manufacturing procedures. These objective measurements do not provide information on consumer experiences. The aforementioned conversion functions attempt to establish links between them.

D. New Design Evaluation

After obtaining subjective assessments from the machine measurements, the evaluation method combines and extends the conventional GDM and MCDM techniques to evaluate new designs under a hierarchy of factors with subjective assessments (linguistic terms). Multiple-source information fusion is a main component of the presented evaluation method for new designs. The implemented aggregation for factors in the hierarchy is illustrated as follows.

Suppose that c is a leaf node which is evaluated by human being evaluators only. Let $P_c = \{e_1, e_2, \ldots, e_l\} \subseteq P$ be the set of human evaluators, and their assessments on c are $v_1, v_2, \ldots, v_l$, respectively. v_i is taken from Table III. Then, the evaluation result v on c is obtained by

$$v = \frac{\sum_{i=1}^{l} w_i v_i}{\sum_{i=1}^{l} (w_i)_0^R} \tag{4}$$

where $(w_i)_0^R$ is the right end of the 0-cut of w_i and w_i is the impact factor of e_i and is taken from Table II. If c is evaluated by both a machine and human being evaluators, let $P_c = \{e_1, e_2, \ldots, e_l\} \subseteq P$ be the set of human being evaluators, and their assessments on c are $v_1, v_2, \ldots, v_l$, respectively, and the machine measurement value is x, then the evaluation result v on c is given by

$$v = \frac{\sum_{i=1}^{l} w_i v_i + w f_c(x)}{\sum_{i=1}^{l} (w_i)_0^R + (w)_0^R} \tag{5}$$

where w is the impact factor of the machine and $f_c(x)$ is the subjective assessment derived from x.

Suppose that c is a nonleaf node, $\{c_1, c_2, \ldots, c_q\}$ is the set of factors supporting c, and $v_1, v_2, \ldots, v_q$ are the obtained evaluations on $c_1, c_2, \ldots, c_q$, respectively. Then, the evaluation result v on c is calculated by

$$v = \frac{\sum_{i=1}^{q} r_i v_i}{\sum_{i=1}^{l} (r_i)_0^R} \tag{6}$$

where r_i is the relevance grade of c_i with respect to the well-being theme and $(r_i)_0^R$ is the right end of the 0-cut of r_i.

Based on the evaluations on all aspects in C_1, the final evaluation for a new design is

$$v = \frac{\sum_{i=1}^{t} r_i v_i}{\sum_{i=1}^{t} (r_i)_0^R} \tag{7}$$

where v_i is the evaluation on an aspect c_i.

E. Acceptance Grade Calculation

The evaluation result of a new design given in (7) is a primary parameter to calculate the acceptance grade of the design. An acceptance grade is a real number which is calculated by (8), where $v^{(0)}$ and $v^{(1)}$ represent the worst and the best evaluation expectations and d is the distance between two fuzzy numbers defined in (3)

$$a_v = \frac{1}{2}\left(d\left(v, v^{(0)}\right) + \left(1 - d\left(v, v^{(1)}\right)\right)\right). \tag{8}$$

$v^{(0)}$ and $v^{(1)}$ are given by the following: $v^{(0)}, v^{(1)} \in F^*(\mathrm{R})$, and

$$v^{(0)}(x) = \begin{cases} 1, & x = 0 \\ 0, & \text{otherwise.} \end{cases}$$

$$v^{(1)}(x) = \begin{cases} 1, & x = 1 \\ 0, & \text{otherwise.} \end{cases}$$

The acceptance grade a_v is then used to rank new designs. If a new design has a higher acceptance grade, the design is said to better match the features of the well-being theme.

F. Further Discussions

The presented NPD comprehensive evaluation method under the well-being theme is not only used to rank new designs but also used to adjust new designs. Real manufacturing of a product can only be based on machine settings. A small difference in the machine settings may lead to a completely different consumer experience. If there are no links between machine settings and consumer experiences, it is hard to know whether a product is really following the design theme and fulfilling consumer demand or not. This job will be completed automatically in the current digital ecosystem. The presented method provides an alternative approach to narrow the gap by converting machine measurements into subjective assessments and fusing information from human beings and machines. The evaluation result that is obtained for each new design is a subjective assessment representing the experiences of human beings. Through adjusting the machine settings and observing the obtained evaluation result, engineers can find the settings that most satisfy the requirements of a product theme and, in turn, can adjust machine settings to produce a product which can best enhance the consumer's experience.

Many other NPD evaluation problems have similar features to the well-being garment NPD, which include the following: 1) evaluation criteria are within a hierarchy; 2) there is a group of evaluators and/or a set of machines or both; 3) there is a set of products (can be any); and 4) evaluators can use any linguistic terms and/or numbers to express their evaluation values. Consequently, the presented FHCGDM method can be directly applied to those problems after necessary modifications in related parameters: n, m, k, and so on. The determination of parameters is dependent on a particular NPD evaluation model. In fact, the presented method can also be used on other MCDM and GDM problems because it is based on and combines MCDM and GDM methods.

The presented method is implemented as a component in our FHCGDSS software. Section V will give a real example of using the presented method to evaluate a set of garment designs under the well-being theme.

IV. Garment NPD Evaluation Model Under the Well-Being Theme

This section presents a garment NPD comprehensive evaluation model under the well-being theme in detail. The establishment process of this model is also presented in this section which can help bridge the communication gap between consumers and designers.

A. Well-Being Theme in Garment Development

Well-being as a theme is a many-sided and complex concept. In broad terms, well-being refers to a well-lived life, a life rich in meaning and personal growth, a life that reflects the fact of one's humanness and one's membership of a community, and, finally, a life built from some sort of conscious thought and reflection as to its content and purpose [5]. A failed product can mean a potential risk to human life and well-being, the loss of public confidence and funding, or the potential loss of market share and competitive advantage [4]. Every engineer, in turn, expects that each new product or service will, in some way, add to our health, comfort, and material well-being [6]. The well-being that individuals derive from clothing will depend to an overwhelming extent on the social norms governing fashion. The expense of purchasing sufficient material for body warmth is trivial compared with the expense of buying clothes that conform to accepted standards within society [14].

In almost all European textile companies, garment NPD focuses on innovative products with modern concepts and advantage techniques, which is a new trade in the current digital ecosystem. A highly innovative product is defined as a product that offers new or unique benefits or solutions for market needs and involves great designs and production challenges. Well-being is one of the solutions. In general, an NPD cycle consists of four stages: development of new product concept and test, simulation of product design and analysis of the production process, product and process development and evaluation/testing, and production and market launch [1], [12], [15]. Except for technical feasibility, strategic fit, financial performance and market opportunity, consumer acceptance, including market requirement, consumer satisfaction and product quality have become the most important issues considered in the NPD process [27].

Well-being of garment product quality is a complex concept, particularly since it takes the idea of quality as a psychological

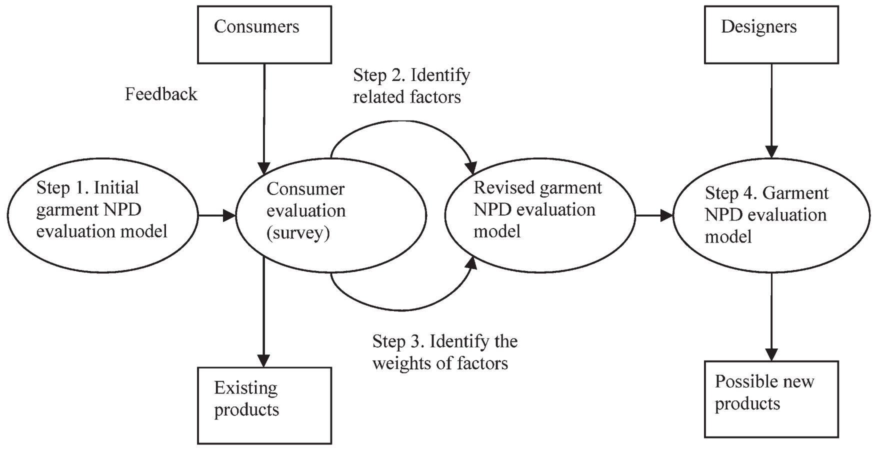

Fig. 2. Establishment process for a garment NPD evaluation model.

notion and is evaluated through the senses; its perception is not usually expressed quantitatively [15], [27]. The design of a well-being garment product has to satisfy the requirements of individuality. These requirements include functional properties such as fulfilling high standards of comfort in wearing and fashion style requirements, such as the feeling of being very relaxed as if on a holiday. To meet these requirements, it is necessary to pay special attention to obtaining high-quality expression and description of influencing factors and criteria to both fashion themes and functional properties. The concept of well-being is described by a set of theme words, which form the criteria to evaluate a product's well-being features. However, some theme words are more relevant to the concept of well-being than others; therefore, a well-being concept will be described by these theme words and their relevance grades (weights). We have to consider the difference between garment designers and consumers in understanding well-being products. An effective way is to combine both viewpoints for evaluating the fashion themes and functional property features of a product under the well-being concept. As machines provide a technical means to assist garment designers in the evaluation to improve engineering standards and accuracy, some features of the products will also be measured by some machines. For example, machines can measure the flexibility and surface friction of a product.

B. Establishment Process of a Garment Product Evaluation Model Under the Well-Being Theme

A garment NPD comprehensive evaluation should be a formative activity, aimed at improving consumer satisfaction and marketing acceptance and enhancing product quality. It usually employs survey results from garment experts and consumers simultaneously. The main difference between the two groups of evaluators is that the experts will assess new prototype products, and consumers can normally only give feedback on products already in the market.

It is presumed to take place at the stage in the NPD cycle where a major resource commitment is required to "prove" the product. This occurs when the product concept moves from preliminary development and testing to scale-up, where piloting/ prototyping or small-scale manufacturing needs to be evaluated. We developed the following process/steps to establish a garment NPD evaluation model for this task, as shown in Fig. 2.

1) To establish an initial garment NPD evaluation model with a hierarchical structure of factors under the theme of well-being.

   Through the literature review and garment expert interviews, an initial garment NPD evaluation model was first established which has two sets of criteria: one relating to *fashion styles* and the other to *functional properties*. Fig. 1 shows all the details.

2) To identify the factors and their relevance grades to the well-being design theme under the proposed garment NPD evaluation model.

   A questionnaire was developed to include all questions related to the factors and indicators identified in the initial evaluation model. Consumer surveys were conducted in selected shops using this questionnaire. The survey results were then used to further identify these factors and their relationships. The finalized factors well-reflect the consumers' viewpoints for all identified features of well-being garment products.

3) To determine the relevance grade (weight) of each factor with respect to both fashion styles and functional properties in NPD evaluation under the well-being concept from the consumer's viewpoint.

   The consumer survey results also identify the weights of factors to the two aspects and indicators to these factors. These weights reflect the importance grade, influence grade, and closeness of each subfactor to its superior factor. They are described by linguistic terms.

4) To finalize the garment NPD evaluation model.

   Through the above steps, the initial evaluation model is revised by adding weights of factors, and a well-being theme-based garment NPD evaluation model is finalized. It has two main aspects (fashion style and function property), each of which has multiple evaluation criteria; each criterion has also a set of indicators (subcriteria). All these factors have the weights shown in Fig. 1. The garment NPD evaluation model can be used to evaluate new products. It can also be used to support the comparison of evaluation results between consumers and designers.

C. Garment NPD Comprehensive Evaluation Model Under the Well-Being Theme

Fig. 1 shows a garment NPD comprehensive evaluation model under the theme of well-being. It has two sets of criteria relating to *fashion styles* and *functional properties* within three levels, namely, aspects, criteria, and indicators. The fashion styles are described by terms such as "protection," "dynamism," "warmth," or "coolness." Each has a number of subfactors, such as "health," "sport," "serenity," "pleasure," "holiday," and so on. The functional properties include "fabric hand," "smell," "sound," "wash and care," and "durability." Some properties also include detailed criteria and have multiple values. For example, *fabric hand* has subfactors of "extensibility," "density," "compressibility," "flexibility," "surface friction," "resilience," "surface contour," and "thermal-wet sensation."

We give the following explanations for some important concepts and criteria used in this model.

1) *Protection* means the condition of being protected.
2) *Dynamism* means sportive or active feeling and image in social and personal life.
3) *Warmth* concerns the state, sensation, or quality of producing or having a moderate grade of heat, friendliness, kindness, or affection.
4) *Coolness* is the feeling of being comfortable or moderately cold.
5) *Fabric handle* is a consumer's instinct to use the sense of touch when choosing a garment, which is to describe and assess the fabric quality and its suitability for a specific end use. The way that the fabric feels is described as *fabric handle*. Some of these indicators can also be tested by machines.
6) *Smell* is about the odor of the garments containing a substance or preparation intended for long-term release onto various surfaces of the human body, notably the skin, claiming one or more specific properties such as fragrance, maintenance in good condition, or control of body odor.
7) *Sound* refers to the noise of the garment, which is made by body movement.
8) *Wash and care label* is the instruction for washing and caring for the garment.
9) *Durability* is the capability of being able to wear the clothing for a long time.

In the model, each criterion presents a concept of well-being and is described by a set of indicators.

For example, dynamism is described by three indicators: sport, pleasure, and relaxation. Different evaluators may have different feelings of well-being and different preferences for its features. Fig. 1 also shows the weights of these aspects, criteria, and indicators. These weights come from the average values of consumer feedback. We can see that *protection*, *dynamism*, and *coolness* are all marked "absolutely related (AR)," and the average value of *warmth*'s weight from consumers is "highly related (HR)." We also find that some indicators have relevance to more than one criterion but with different relevance grades. For example, *relaxation* is an indicator relevant to protection, warmth, dynamism, and coolness but with weights R, MR, R, MR, respectively. These relevance grades can be changed when a product emphasizes a particular theme or style.

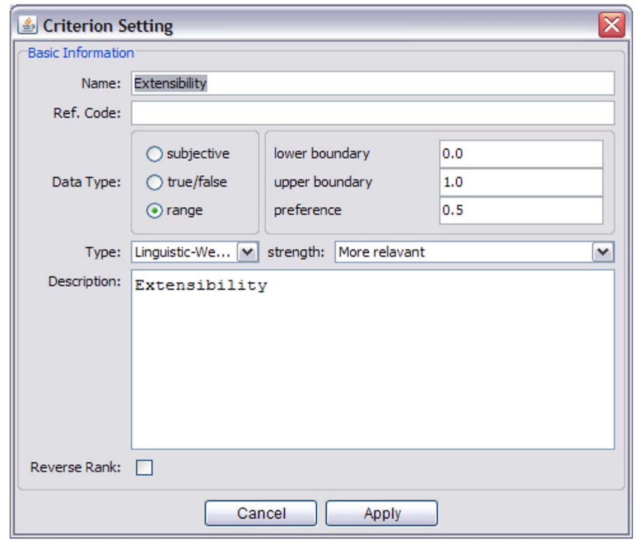

Fig. 3. Objective measure settings for machine measurement.

V. EXPERIMENTAL STUDY

This section illustrates the presented evaluation method through a real application. A garment company has eight new product designs to be evaluated by five human evaluators under the well-being theme-based garment NPD evaluation model shown in Fig. 1. Evaluators are asked to give their assessments of each question (factor) in the form of agreement in the questionnaires. For example, if an evaluator agrees with the statement that the product looks very relaxed, he/she can answer "Very High" to the question (statement). The company will summarize all the evaluators' answers for all questions. The summarized results are described by linguistic terms in Table III. Moreover, 11 devices are used to measure the criteria such as "smell," "sound," "durability," and indicators of the criterion "fabric handle." Based on the hierarchy of factors in Fig. 1 and the evaluators' answers, the company is able to evaluate these new garment products. The relevance grade of each factor is obtained from the consumer survey and is expressed by a linguistic term in Table I.

According to the aforementioned settings, the garment NPD evaluation problem is solved in the FHCGDSS software [23]. In the real experiment, we designed a virtual device to substitute those 11 real devices for simplifying inputs. This will not affect the final evaluation result. An example of settings for machine measurement is given in Fig. 3. Figs. 4 and 5 compare the evaluation results by a human evaluator and by a machine. The comparison indicates that the new product E is the one which most satisfies the consumer and designer experience under the well-being theme; therefore, the machine's current settings for product C is not good enough to match this consumer's experience. However, by comparing Figs. 6 and 7, we know that product C is the most accepted product by all five human evaluators. Hence, the current settings for product C need not

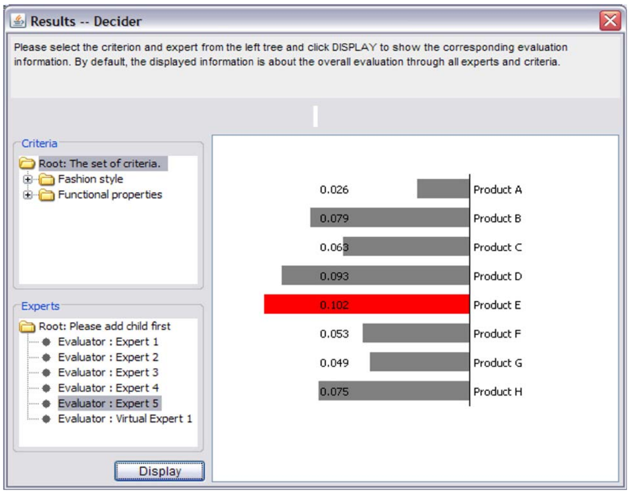

Fig. 4. Final evaluation result for indicator "pleasure" under criterion "warmth."

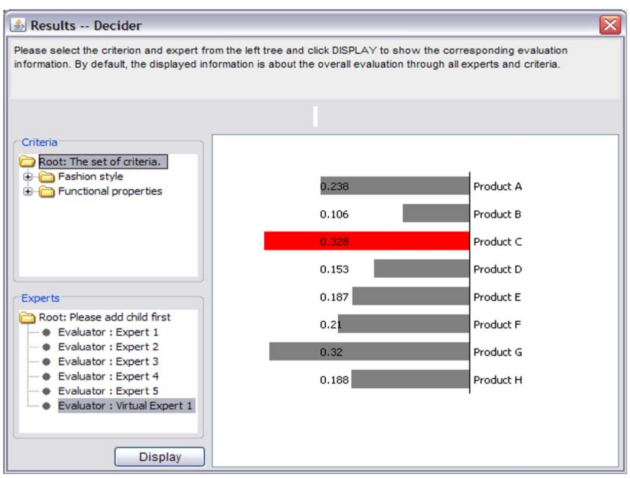

Fig. 5. Machine evaluation result for the eight product designs.

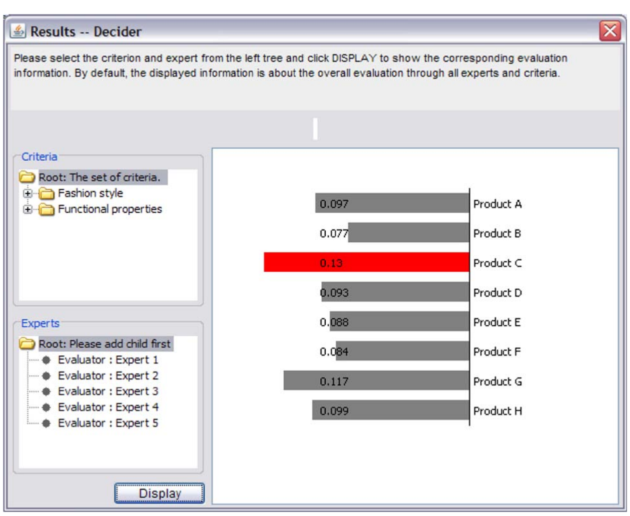

Fig. 6. Evaluation result by all evaluators.

be adjusted too much because it is already the best one in most evaluators' experience.

Compared with other MCDM and GDM methods, the presented method can deal with both subjective and objective information simultaneously, which is more suitable to NPD evaluation. The presented method can deal with criteria in a multilevel hierarchy, which can help decision makers to observe interesting aspect related to NPD evaluation and adjust manufacturing technologies as necessary.

Based on human and machine evaluation results for each product or material on the related criteria, we can establish a set of relationships between human senses and machine measurement values. Therefore, for example, a satisfactory level of "flexibility" by fabric hand can be expressed and described by a set of machine measurement values. These relationships can be directly used in the detailed engineering step of future product design, which is an important part of digital ecosystem development. Through these efforts, the product evaluation process becomes more and more digitalized in current digital ecosystems.

VI. Conclusion and Further Study

With the development of digital ecosystems, optimized NPD integrating human cognition and socio-economic concepts becomes more important in practice and technically implementable. Success in human-centered NPD can be critical for a company to maintain its competitive advantage. The comprehensive evaluation of proposed products is an important step in the NPD process. It involves a complex situation in which some qualitative criteria are within a hierarchy, multiple members have different opinions, and the judgments from evaluators are often in vague rather than crisp numbers, and the data from machines have different ranges. An FHCGDM method has been presented in this paper and applied to evaluate garment products under the theme of well-being. Based on this method, an FHCGDSS is developed to solve hierarchical criteria NPD evaluation problems in practice. Both the developed FHCGDM method and FHCGDSS tool can be easily applied to NPD of different products and with different themes. The contribution of this paper includes the following: 1) the proposal of a garment NPD evaluation model under the theme of well-being design and its establishment means; 2) the development of an FHCGDM method for garment NPD evaluation; and 3) the development of an application to directly support garment NPD evaluation in practice.

Our further study includes establishing ontologies for well-being-related concepts to support automatic evaluation system establishment. We will particularly work on matching experiments for human evaluation with machine assessment. Based on the method proposed in this paper, a web-based online human-centered NPD evaluation system will be also developed.

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