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A new interactive design approach for concept selection based on expert opinion

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Abstract
Effective identification of the optimal design in the early stages of product development is critical in order to obtain the best chances of eventual customer satisfaction. Currently, the advancements in prototyping techniques offer unique chances to evaluate the features of different design candidates by means of product experts acting as assessors and/or customers enrolled as testers. In this paper, the candidate identification using virtual and physical prototypes is described and a practical fuzzy approach toward the evaluation of the optimal design is presented. The proposed methodology is tested on a full case study, namely the choice of optimal design for the traditional Neapolitan coffeemaker, inspired by the prototypes of the Italian designer Riccardo Dalisi. Several concepts are developed in a virtual environment and four alternatives among them are realized using Additive Manufacturing. By allowing experts to interact with virtual and physical prototypes, they were able to express their opinion on a custom fuzzy evaluation scale (i.e. they were freely choosing more or less coarse linguistic scales as well as the related shapes of fuzzy sets to adequately represent the level of fuzziness of their judgments). Once the opinions are collected, the set of best candidate(s) is easily identified and useful suggestion can be obtained for further developing the product.

Keywords Design method · Concept design · Concept selection · Virtual prototyping · Additive manufacturing · Fuzzy set

1 Introduction

Virtual and Physical Prototypes allow testing concepts during the development of new products and enable to explore design candidates more timely and better than in the past, improving their quality and their chances of success. Virtual Prototypes (VPs) help to evaluate and optimize the product and process performances by means of virtual tests, since the very beginning of the life cycle, when nothing is created yet [1,2]. So, in the last two decades, the VPs are more and more used in the main production fields (Mechanics, Aerospace, Architecture, Naval engineering) making easier the selection of the best among different (virtual) design alternatives [3–7]. On the other hand, Physical Prototypes (PPs) are at least used for verification and validation phase at the end of the development cycle as they allow the identification of design errors and confirm the expected performances of optimal concepts. Physical Prototypes are real objects created for testing purposes and to check the final product performances considering user variability and real environment of use. Thus, they are models that look and feel like the final product and they are used to realistically test various alternatives since can dramatically help to assess the level of fulfilment of the user requirements and select the best concept. Usually, they are built to validate the functionality and the usability of the product. A great advantage of the PPs is that they could be characterized by real materials or real properties, which allows to provide real results for specific performances. Moreover, they often can show unexpected (e.g. not previously considered) phenomena fully unrelated to the original target, allowing the further (additional) improvement of the prototype [8] On the other hand, one of the main disadvantages is that usually the PPs have to be outsourced, implying delays in time scheduling and so risks for the production planning. This drawback can be encompassed by the wider use of Additive Manufacturing (AM) as rapid prototyping technology using three-dimensional printers [9]. Thanks to AM, the prototypes can be manufactured, tested

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and modified in a closed loop that contributes to improve reliability and quality [10]. Summarizing, PPs provide both tactile and visual evaluation of the features of real objects such as shape, feel, surface finish, and so on. This tactile advantage should be seen as highly desirable, particularly when interacting with customers. Hence, PPs usually have advantages in addressing ergonomic issues. On the contrary, VPs are mostly used when Physical Prototyping is impracticable, impossible or inefficient. Virtual Prototyping allows the product to be simulated and tested in a digital environment to obtain the best and optimized results. Virtual Prototypes have more benefits in testing aesthetics and predicting performance, related to Fluid Dynamics, Kinematic Analysis and even Visual Evaluation [11,12]. The challenging trend of VPs is to develop Mixed Prototypes (MPs) to give a force feedback to the potential users. Haptic devices can better and better simulate the interaction with the real object furnishing an intuitive experience to the users. This is one of the reasons why, at present, there is a growing interest also on the use of wearable devices that simulate sensorial feedbacks (tactile, visual and auditory) to express basic emotions. The main target is to define methodologies grounded on the interaction between the consumer and the virtual prototypes, in order to enhance the realism of the simulations [13,14] and to improve the design phase and so the final products.

Therefore, the concept selection phase is now possible by means of mixed prototypes that allow to evaluate in many ways the interaction between users and concepts, as well as to stream an interactive process for concept selection. In the aim of defining and operationalizing such a process, one of the main drawbacks occurs when the data referring to the users evaluation are gathered. As a matter of fact, sometimes data collection and data analysis are hindered by the difficulty to define partial attributes and by the impossibility to measure the subjective data by means of the same scale, units and tools. Different approaches and tools based on fuzzy logic and/or genetic algorithms have been proposed to override these issues and get useful results [15–17].

In this paper a novel interactive design approach for concept selection based on experts' opinion is proposed. The method builds upon the generation of a discrete set of virtual and physical prototypes, which are then evaluated using a multi-granular information fusion approach. The method is then tested on a case study from the Italian designer Riccardo Dalisi, the concept selection of the optimal artistic Neapolitan coffee-maker.

2 An interactive design approach for concept selection

In this section an overview of the first phase of the methodology, i.e. the generation of the virtual and physical prototypes, along with a brief review of the related works in the field of concept generation is presented. The proposed approach aims at enhancing the interaction at the interface between designers ideas and technical features of the product, by means of the useful feedback that the designer can gather once some product experts interact with his/her concept through virtual and physical prototypes.

The process originates from the phase of conceptual design, in which the designer, moving from his/her vision and values and the knowledge of consumers' needs, produces a set of plausible conceptual design alternatives among which to choose the best design candidate for the development of the project by means of a formal decision model. Using an interactive design approach, the designer could capture the users' desires, even the unspoken ones, and elaborate to embody them into features through an iterative process of refinement of the concept.

Therefore, there is the need to identify at this very early stage which design candidate(s) among the alternatives could potentially maximize the satisfaction of the users. Once identified the optimal one(s), by the further development phases (engineering design) the design is refined, the compatibility with the design ties checked and then issued the final detailed project and the required documentation. The approach presented in this paper uses virtual and physical prototypes to take the advantages, from a user perspective, of both typologies of prototypes. As a matter of fact, the interaction with the virtual prototypes allows an early evaluation of the product, based on digital models before that the product is built and available for testing. Indeed, the interaction with physical prototypes allows the test user to better feel and perceive the object.

The subsequent evaluation of any design candidate stemming from this phase has to face a twofold difficulty, including the enumeration of the design dimensions to cope with and the distinction among them. Therefore, an approach toward design evaluation based on aggregated categories is preferred. This is needed to select appropriate criteria to evaluate the alternatives. Several researchers have suggested various segmentation of design. These taxonomies, which are summarized in Table 1, have a great deal in common [18].

Subdividing design between functional and aesthetic aspects is necessary to investigate its important role as a link between technical innovation and market opportunities. From a historical point of view about design, it is useful to mind that already Vitruvius, in his ancient Roman writings, argues that a structure must have three qualities: *firmitas*, *utilitas* and *venustas*, namely strength and duration, utility and beauty. These concepts are born on even older models of Plato's theory of beauty, as recalled by Candi [18]. A modern broad definition of design, which at the same time imposes some constraints on the concept, is based upon a three-dimensional segmentation [20] which is used as a basis

Table 1 Segmentation of design, adapted from [18]

Vitruvius	Dreyfuss [19]	Ulrich and Eppinger [8]	Pahl and Beitz [21]	Kotler and Rath [22]	Norman [20]	Di Gironimo et al. [3]
				Durability		
Firmitas	Maintainability	Maintainability				Must be
			Safety			
	Utility					
Utilitas		User interfaces	Clarity	Performance	Behavioral design	One dimensional
	Resources	Resources		(Cost)		
				Quality		
	Communication		Simplicity			
Venustas	Appearance	Emotional appeal			Visceral design	Attractive
		Product differentiation		Appearance		
					Reflective design	

for measuring the emphasis and the focus of design. The three dimensions identified by Norman are visceral, behavioral and reflective, respectively. The visceral design emphasizes the relevance of the aspect, that is the integration of a product into a satisfactory whole through the use of the shape, the lines, the proportion and the color used, with the main purpose of the product distinction [8,19,20,22]. Usability and performance are the cornerstones of the second dimension: behavioral design. Currently for any new product, which increasingly use graphic interfaces, this dimension is often stressed [19], and the importance of the usefulness or intuitiveness of the user interfaces assumes more importance. All these concepts can be combined with the Vitruvian *utilitas*. Low costs, together with environmental impacts [8,22], along with a simplified design enabling easy maintenance, influence the way products are to be produced, maintained and repaired [19] and are all concepts related to behavioral design too. Other concepts included in this dimension are linked to the design method, intended as an interaction of tools, processes and materials aimed at a functional objective and to quality, durability and performance regarded as main elements of every design [22]. Reflective design refers to the message, the culture and the meaning of a product or service. Product design should communicate the philosophy and mission of corporate design [19]. The emotional appeal of a product includes factors such as attractiveness, pride of ownership and impression of quality [8]. Reflective design addresses the economic, psychological, spiritual, social, technological and intellectual needs of human beings.

The last column in Table 1 shows how the dimension of design can be related to the features of the product, once these are segmented according to the Kano's classification of quality elements [3].

Following a well based paradigm of product development [8,21], the dimensions singled out for the candidate selection process are the ones in the work of Dreyfuss, hence adapted as five evaluation categories which are directly linked to the critical targets of the product design.

1. Appearance (i.e. pleasant aesthetic properties);
2. Usability (i.e. convenience of use and safety);
3. Maintainability (i.e. ease of maintenance);
4. Communication (i.e. capability of communicating the brand and his philosophy);
5. Resources (i.e. optimal cost).

Since each of these categories is a complex predicate, not easily referred to objective features, it could be the subject of the evaluation by an expert who is fully aware of its link with the degree of fulfillment of the design target. Nevertheless, for this kind of task too, as originally claimed in [23,24], even experts feel more comfortable providing their knowledge by using terms close to human beings cognitive model than expressing quantitative ratings. Specifically, since experts have to be involved in a very personal evaluation process, it is expected to gather their different judgments about design candidates as ratings expressed with regard to specific semantic scales of linguistic values, which could not share a unique lexicon nor the same formal quantitative representation.

3 A fuzzy-based approach for concept evaluation

The evaluation phase of the concepts can be treated as a Multi-Expert Multi-Criteria Decision Making (ME-MCDM) problem which is not driven by a formal set of judgments. This phase will involve a group of experts sharing their opinions on the alternatives, according to the selected evaluation criteria.

In the ME-MCDM framework, some issues asking for specific approaches arises when [25]

(a) Data are not full available;
(b) Experts deal with the same problem with different opinions;
(c) Experts are not fully confident in their own opinions;
(d) Experts and criteria are considered with different relevance.

It is expected that all of them are simultaneously affecting the case at hand: the (b) and (d) issues are certainly present because of the very same kind of candidate identification problem and, since the experts can only interact with the prototypes in a VE or by means of limited feature AM physical prototypes, it is likely to have to cope with (a) and (c) too.

It is worth noting that the unavoidable uncertainty involved into the evaluation process of a design candidate among a set of alternatives for a new product is not of stochastic nature. Neverthless, fuzzy logic provides tools to model and manage such kind of uncertainty by means of linguistic variables, guaranteeing flexibility and effectiveness to the decision models. This use of fuzzy logic in concept design evaluation has been actually demonstrated useful for application in different fields [26].

Since the experts opinion includes ratings, it is intrinsically vague and hard to be captured by means of exact numerical values. For this reason, a fuzzy approach, where each expert is allowed to express his/her judgments with words on a scale shaped via natural language, is particularly appealing. The use of linguistic values and the choice of an effective methodology to cope with them would make expert ratings more informative and reliable for the ME-MCDM.

The approach presented in this paper aims to tackle the mentioned issues by means of a combination of the Ordered Weighted Average operator—OWA [27] used to combine the ratings of the different experts, and a fuzzy linguistic approach [28]—adopted to make smoother the phase of collection of the ratings by assuring a higher degree of freedom to the experts.

Specifically, the proposed approach allows each expert to choose his/her own scale of evaluation expressed through linguistic terms and also with different granularity, i.e. the scale could be more or less coarse depending on the experts confidence with the evaluation process. This configures what it is referred to as *multi-granular linguistic framework*, since the assessments of the alternatives are represented in multiple linguistic scales.

Finally, the expert evaluations, pooled via the OWA operator, produce a resulting soft ranking of candidate prototypes that can be exploited to select the optimal design or the set of optimal choices, along with useful clues on the features that contributed the most to the achievement of design targets.

4 Case study: the artistic Neapolitan coffee-makers by Riccardo Dalisi

About four decades ago, a passionate and unusal study on the traditional Neapolitan coffee-maker allowed the Italian designer Riccardo Dalisi to conceive several prototypes and finally design an Alessi branded product that gained him the "*Compasso d'Oro*" award in 1981. The worshipped *Napoletana* coffee-maker, celebrated by the reckoned dramatist Eduardo de Filippo for the ritual preparing of coffee, represents the myth of slowness, manual skill and full enjoyment of its aroma. Differently from the newer moka coffee-maker, the traditional Neapolitan one produces the drink by letting the water fall by gravity trough the ground coffee powder as a consequence of its overturning. Figure 1 illustrates how the Neapolitan coffee-maker works: the coffee filter (1) with ground coffee, once capped (2), is placed on the bottom vessel (4) filled by water (3); once the coffeemaker is closed by the top compartment (5) one put it on fire until water boils (6); then set the coffee maker aside and overturn it (7) so that the boiling water falls through the coffee (8). Finally, one can pour the coffee in the cup and drink it (9). The coffee-maker, in summary, consists of two overlapping vessels separated by a full coffee filter. When the water in the bottom vessel boils, the coffee-maker has to be turned upside down (see e.g. Fig. 1, step 7). Hence, the pressure of a few centimeters high column of water causes the filtering phase (ΔP on the filter lower than 103 Pa). This preparing process is slower than the one based on the use of the common Moka coffee-maker. The coffee lovers say that the Neapolitan coffee is better than the Moka one, because of the slow filtering and in addition

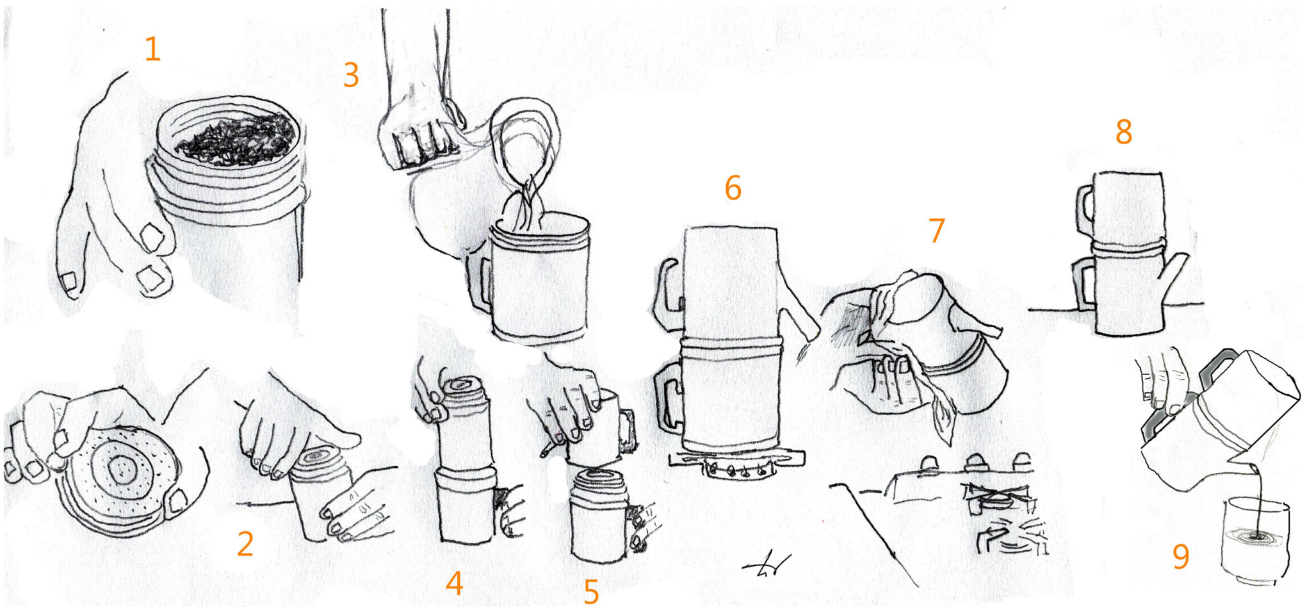


Fig. 1 Sequence of operations for preparing the coffee using the Neapolitan coffee-maker

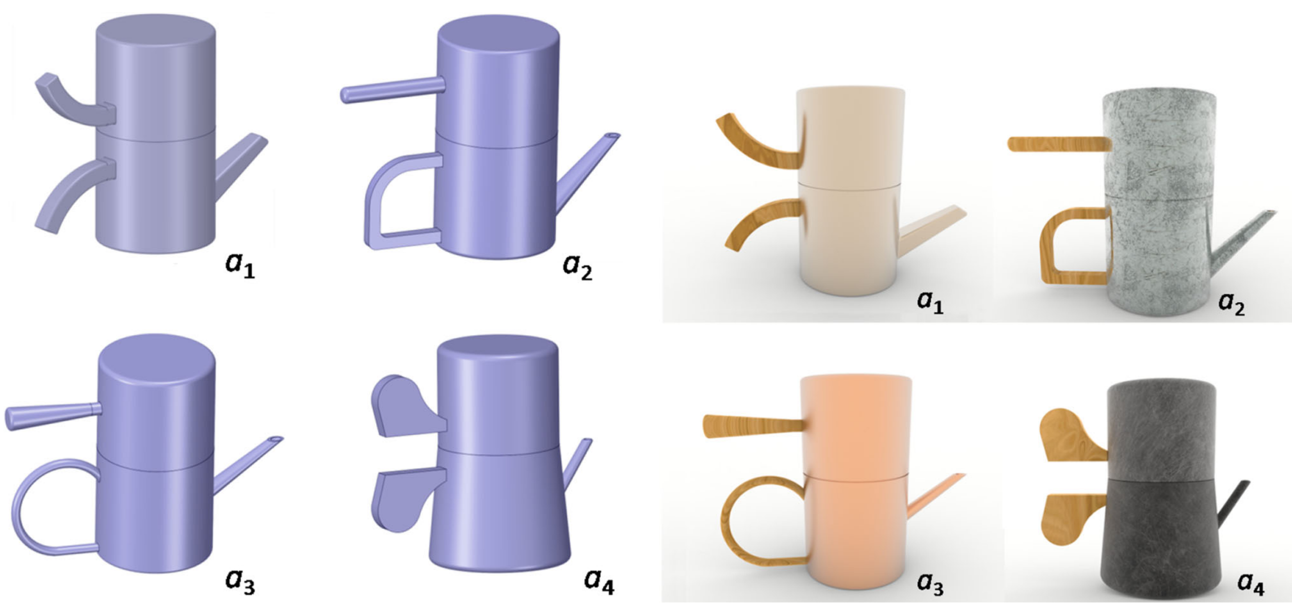


Fig. 2 Virtual prototypes and 3D printed prototypes of the coffee-makers alternatives

the aroma of the coffee is not spoilt by the contact with the overheated water.

4.1 The virtual and physical prototypes

The virtual prototypes of the coffee maker used as case studies are generated to show the customer the product. With the same objective, forthy years ago the Italian designer Riccardo Dalisi asked some artisans to realize the Alessi design in order to produce the Neapolitan coffeemaker on an industrial scale:

> The 300 tin prototypes that Dalisi realized were the most impressive thing of that project… (A. Alessi).

For the case study considered here, four prototypes have been generated: snapshots of their VPs are shown in Fig. 2. The first prototype (a_1) is the classic model of the Neapolitan coffee maker with its "styled arms". The second prototype (a_2) is characterized by the decorative use of the material and the color and by the classical features of the Neapolitan coffee maker with an emphasized shape of its arms. The third prototype (a_3) highlights the peculiar feature of the Neapoli-

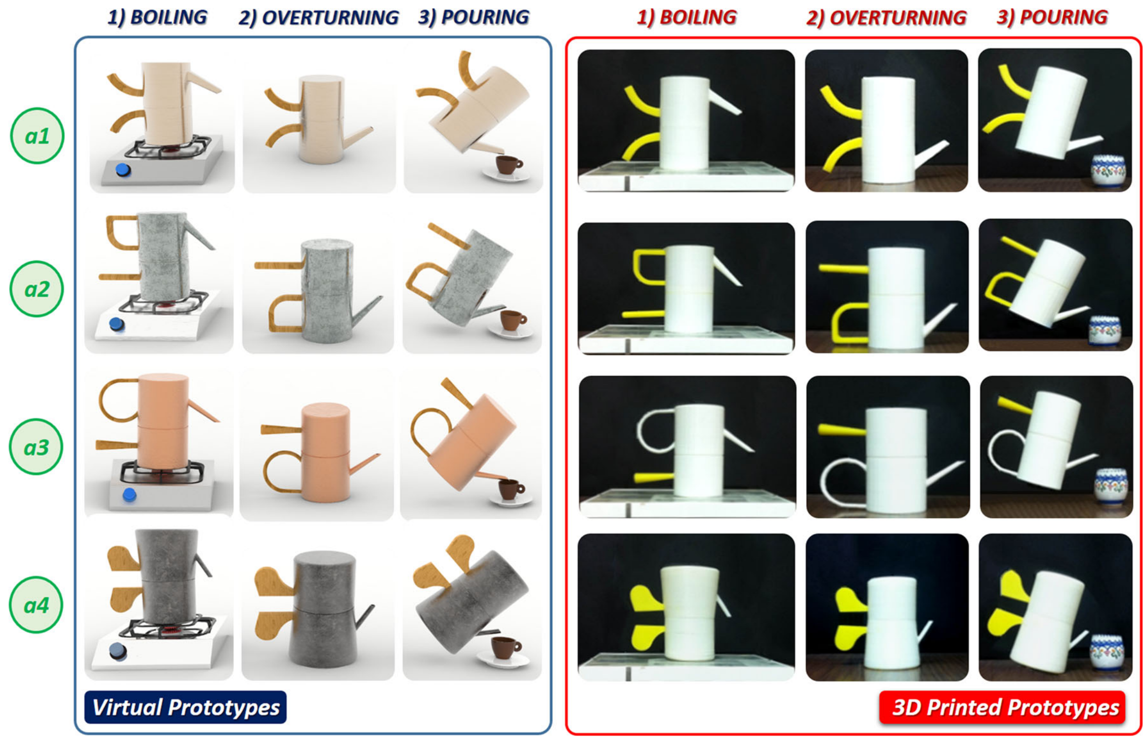
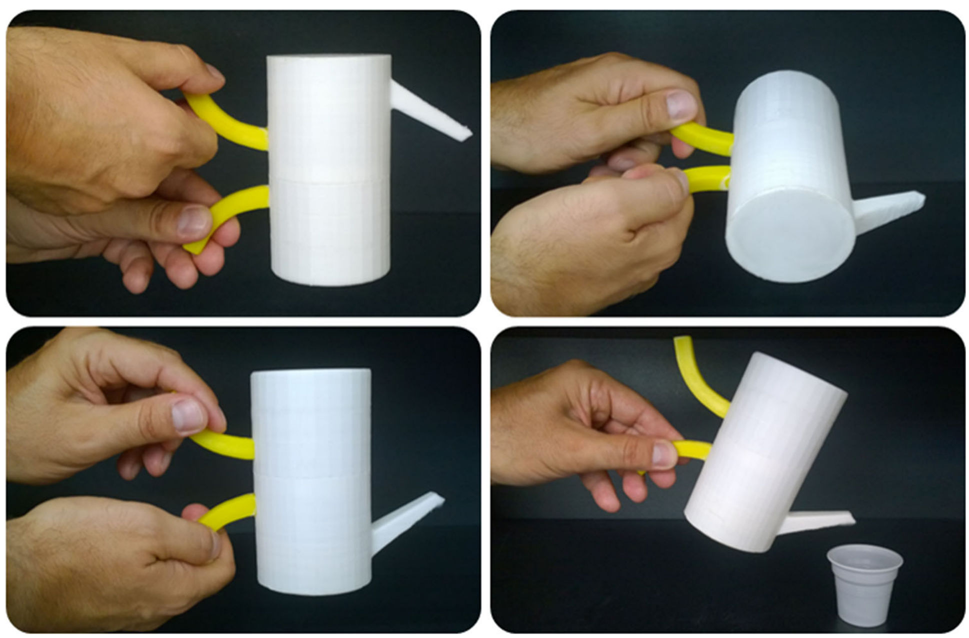


Fig. 3 Sequence of operations needed to prepare coffee according to the virtual and physical prototypes

Fig. 4 Examples of real operations needed to prepare coffee using one of the 3D printed prototypes, according to steps 6–9 of Fig. 1



tan coffee maker overturning. Finally, the fourth prototype (a_4) is compact and essential and, at the same time, is characterized by round and funny shapes.

The sequence of the operations to be done to prepare coffee using the Neapolitan method are shown in Fig. 3, for the virtual (left) and physical (right) prototypes. A particular of the sequence is given in Fig. 4.

4.2 Designing the experiments

An experimental phase, was set up in a virtual environment following the analogous principles that guide the designing of physical experiments in order to avoid any nuisance from spurious factors (i.e. the symbols attached to the specimens and the order of execution of the trials).

Table 2 Name assigned to each alternative

Prototype	a_1	a_2	a_3	a_4
Name	Lesbia	Plania	Clodia	Delia

The four different alternatives considered for the study were collected into the set A:

$$A = \{a_1, a_2, a_3, a_4\} \tag{1}$$

Five experts participated in this phase (one for each of the categories singled out above). They were collected into the set E:

$$E = \{e_1, e_2, \ldots, e_5\} \tag{2}$$

Therefore, a plan to schedule the trials has been deployed, by assuring that each expert should evaluate all the alternatives in a random order. As above mentioned, aiming at avoiding any influence by numbers, letters and any other labelling system intrinsically carrying an order relation, each alternative was dubbed with a fictitious name. The fictitious name of the different prototypes are reported in Table 2. The plan for the evaluation trials, with respect to the criteria selected above, is summarized in Table 3.

Table 3 Random order of trials to be executed by each expert

Dreyfuss' category	Order of trials for each expert			
	1	2	3	4
e_1: *appearance*	Clodia	Delia	Lesbia	Plania
e_2: *usability*	Delia	Clodia	Plania	Lesbia
e_3: *maintanability*	Lesbia	Plania	Clodia	Delia
e_4: *communication*	Plania	Lesbia	Delia	Clodia
e_5: *resources*	Lesbia	Delia	Plania	Clodia

4.3 Evaluation phase

Each expert received an evaluation form in order to collect her/his judgments about one of the category for all the alternatives. The trials were introduced by a facilitator who summarized the scope of the research and explained the general protocol to guide each expert toward the evaluation. Preliminary each expert, with the help of an explication leaflet, had to define her/his personal scale of evaluation, by sketching a variable number of fuzzy sets over a [0, 100] linear scale printed onto the form (see e.g. Fig. 5).

The leaflet advises to set up a scale on the base of an odd number of ordinal labels, say g, by: (i) singling out g base points almost evenly distributed along the interval [0, 100] and (ii) depicting the degree of membership of the values in the interval to each of the related sets by means of g triangular or bell shaped functions with their maximum equal to 1 in correspondence of the base points. Therefore, each expert was able to define his/her scale and autonomously complete the evaluation of all the four alternative prototypes accordingly to the order in Table 3 and recorded the judgments in the related section of the form.

Each expert was allowed to use both the prototypes for each alernative to perform his evaluation trials; in the following are reported the degrees of preference and the distinct roles attached to the two.

The expert involved in the *appearance* evaluation preferred to evaluate prototypes mainly through virtual models. The similarity of the surfaces, obtained through the textures, together with the realism of the virtual illuminations allowed him to well evaluate the appearance of the different concepts in the study. His relative preference between virtual and physical prototypes is about 8–2.

The expert involved in the *usability* evaluation used the virtual prototype to understand the parts and their assembly, then he preferred to use the physical model to carry out the tests of overturning and pouring the coffee. A coarse estimate of the relative preference between the two kinds of prototype could be 3–7.

The expert involved in the *maintainability* evaluation, firstly used the digital models, with the immediate visualization of the components with their materials, in order to imagine possible failures due for example to the coupling. Afterward, he preferred to investigate all the aspects with the inspection of the physical model. The estimate relative preference is 4–6.

The expert involved in the *communication* evaluation used the virtual coffee-makers to glimpse and identify them, while he manipulated the real prototypes with care and attention before expressing his judgment. The estimated relative preference is 1–9. It is important to notice that the expert had more experience and familiarity in using physical models rather than virtual prototypes.

The expert involved in the *resource* evaluation has immediately analyzed the virtual models to get the main information for his interest: weight, sheet thickness and the like. For this category, some answers are faster obtained through the analysis of virtual models; for example, investigating the size of the surface of the main body of the cylindrical coffee pot is immediate. His relative preference between virtual and physical prototypes is about 7–3. Table 4 summarizes the above mentioned estimates of the preference attached by each expert to the two types of prototype when performing the trials. The percent values could be considered proxies of the perceived utility of virtual and physical prototypes for completing the rating of alternatives with regard to each Dreyfuss' category.

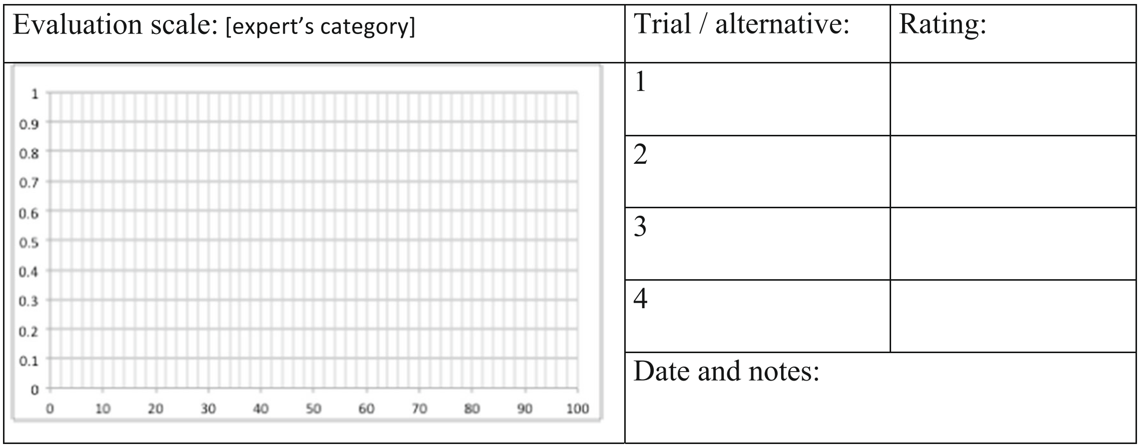


Fig. 5 Evaluation form supplied to each expert

Table 4 Estimates of the preference attached by each expert to the two types of prototype

	Prototypes	
Dreyfuss' category	Virtual (%)	Physical (%)
e_1: *appearance*	80	20
e_2: *usability*	30	70
e_3: *maintanability*	40	60
e_4: *communication*	10	90
e_5: *resources*	70	30

4.4 Pooling the linguistic rating of experts: computing with words

The ratings collected from the trials are related with the unique scale adopted by each expert; being they left free to adopt for their semantic scale the numbers of degrees they were most comfortable with, the granularities stemmed different, see Fig. 6 in the following. The linguistic performance values recorded for each alternative prototype are summarized in Table 6.

After adjusting the different granularity of the five experts judgement scales on an unique Best Linguistic Term Set, BLST, the collective performance value for each prototype can be computed by means of OWA. Based on these, a fuzzy preference relation expressed in term of the fuzzy sets is obtained [29]; finally, a set of solutions for the design candidate identification problem can be singled out and the alternatives ranked accordingly to their degree of membership to it (see "Appendix" for the details). In such a way a single index of non-dominance is obtained for each prototype enabling to rank the concepts, as shown in Table 5 which includes also the final ranking of the four alternative prototypes. The whole computation procedure is summarized into the "Appendix".

Table 5 Index of non-dominance and final ranking of the four alternatives

	Alternatives			
	a_1	a_2	a_3	a_4
Index of non-dominance μ_{ND}	0.953	**1.000**	0.810	0.891
Soft ranking	2	1	4	3

The bold value indicates the best alternative

4.5 Results

The procedure for selection and ranking of alternatives is straightforward, once collected the evaluation of each candidate design solution by the selected experts. For the case study, moving from the data aggregated by OWA as collective performance profiles on the BLST, a fuzzy preference relation has been computed and therefore it has been possible to identify the best design(s) by means of the ratings shown in Table 6. The analysis phase of the procedure mainly aims at deriving a fuzzy subset of non-dominated alternatives, which might be suggested as a solution to the fuzzy decision-making problem considered here. The results of the procedure are summarized in Table 6. The alternative a_2 turns out to be the only uniformly non-dominated one, hence the design to focus upon. At the same time should be not overlooked that a quasi-order relation stems from the proposed index of non-dominance: this sort of soft ranking could be exploited to highlight strengths and weaknesses of the candidate design so helping to steer the next stage of product development. The final ranking obtained accordingly could help the designer to identify the design features to be further developed in order to reach the optimal design of the product, indeed.

In finalizing the case study was observed that:

– The evaluation of a barely pleasant appearance about a_2 alternative does not prevent that this concept remains the

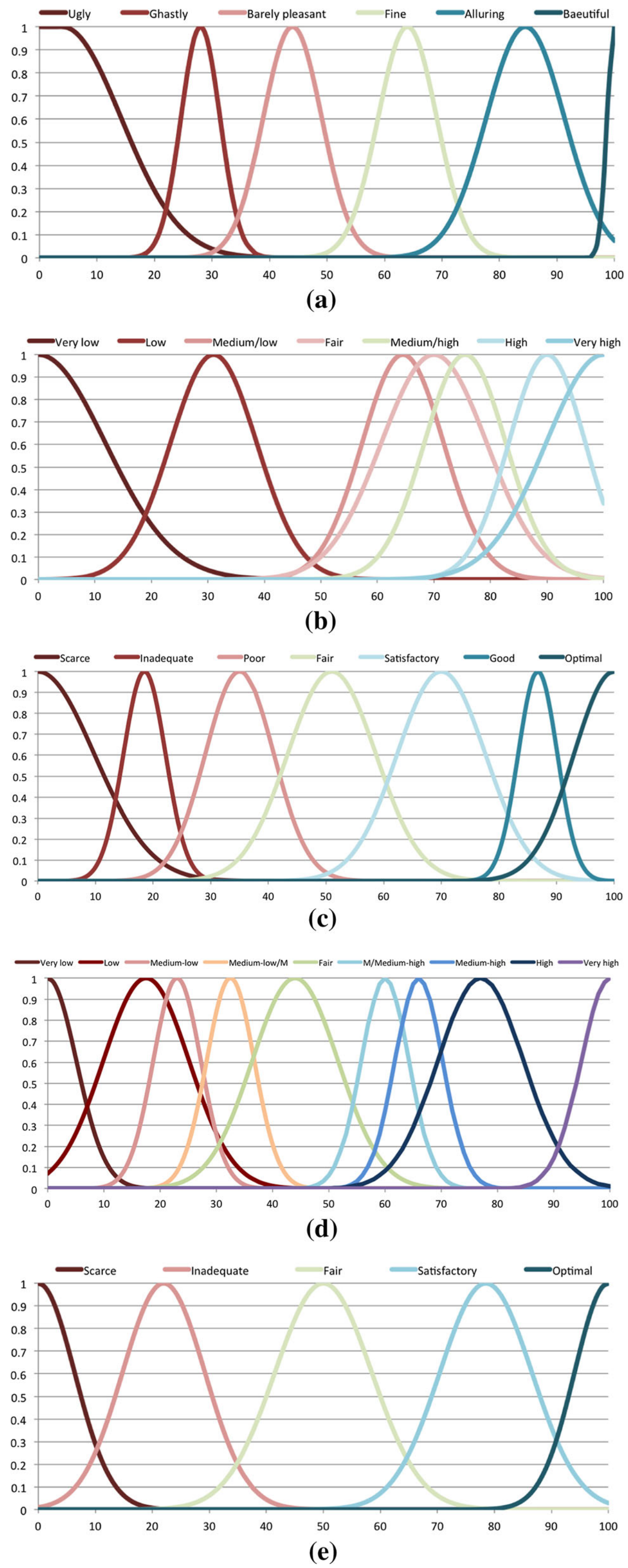


Fig. 6 Linguistic scales adopted by the experts according to the design dimensions. **a** Expert e_1: grades about *appearance* on a six-level scale, **b** expert e_2: grades about *usability* on a seven-level scale, **c** expert e_3: grades about *maintainability* on a seven-level scale, **d** expert e_4: grades about *communication* on a nine-level scale, **e** expert e_5: grades about *resources* on a five-level scale

sole non-dominated one in the set of candidates; conversely, the a_4 alternative, even if top rated with regard to appearance since its friendly and playful design, eventually was dominated and ranked only 3rd, because negative evaluations in terms of usability, maintainability, communication and use of resources;

- The a_2 alternative surpassed all the other ones thanks to its better features about usability, maintainability, communication and use of resources; indeed it guarantees more suitable assembling and disassembling operations; furthermore its large arms allow both to overturn it easily and differentiate it (strongly communicate an original design) so that the alternative was judged as innovative and highly recognizable compared to the classic Neapolitan coffee-maker.

5 Concluding remarks

The main lesson of the case study is that the definition of suitable criteria for attaining a trade-off among the critical targets is the key point to evaluate the design of complex products and to effectively operate a selection among a set of design candidate alternatives. A great advantage of the proposed approach lies in avoiding any need for explicitly assigning arbitrary weights to each evaluation category, since relative importance is integrated into the algorithm used to get the overall performance of each alternative. Some critical aspects emerged regarding the evaluation form during the early test round. Therefore, the explication leaflet was improved in order to avoid difficulties for the expert when he/she is asked to express her/his own scale and related ratings. For instance, it was possible to invite some of the experts to represent the fuzzy sets that expresses the grades of the scale for the judgements by different colors, whose shades blend together where the sets overlap. In the end, the proposed methodology shows noticeable and practical opportunities in virtual environments, even the simpler ones that could be privately shared over internet, for concept selection and further highlight how their straight integration with rapid prototyping techniques, such as AM, could improve quick and inexpensive trial tests to collect the judgements from many experts located all around the world. Further works will go toward a distributed implementation of this methodology.

Acknowledgements With regard to the case study, authors would deeply thank the Italian designer Riccardo Dalisi, who kindly allowed to use some prototypes from his laboratory for the reverse engineering of their design; prof. Donnarumma for his lessons on fuzzy logic; the prof. Alfonso Morone and prof. Massimiliano Giorgio for their active involvement into the evaluation trials.

Table 6 Linguistic performance values recorded for each alternative prototype and evaluation category

Dreyfuss' category	Alternatives			
	a_1	a_2	a_3	a_4
e_1: *appearance*	Fine	Barely pleasant	Fine	Alluring
e_2: *usability*	Medium/high	High	Fair	Medium/low
e_3: *maintanability*	Satisfactory	Good	Satisfactory	Fair
e_4: *communication*	Medium/medium-high	Medium/high	Medium-low/medium	Medium-low
e_5: *resources*	Fair	Satisfactory	Fair	Inadequate

Table 7 Best Linguistic Term Set degrees

	BLTS degrees								
k	Worst 0	Very low 1	Low 2	Quite low 3	Fair 4	Quite high 5	High 6	Very high 7	Best 8
r_1	0.000	0.001	0.000	0.003	0.195	0.588	0.621	0.361	0.001
r_2	0.000	0.000	0.000	0.000	0.021	0.057	0.054	0.408	0.053
r_3	0.000	0.003	0.001	0.009	0.273	0.430	0.371	0.218	0.001
r_4	0.000	0.021	0.013	0.068	0.159	0.019	0.049	0.048	0.000

Appendix

Once the m experts rated the n alternatives by linguistic performance values, as in the $m \times n$ Table 6, the need for obtaining a collective performance evaluation for each alternative requires deploying a two steps process: making the multi-granular information uniform and suitably aggregate the ratings.

1. The linguistic performance value is translated into the BLTS ($S_T \left\{c_0, c_1, \ldots, c_g\right\}$ choosen as the scale with the greatest number of grades among the linguistic term sets $S_j \left\{l_0, l_1, \ldots, l_{p_j}\right\}$ expressed by the experts $p_j \leq g$) via a multi-granularity transformation $\tau_{S_j S_T}$ so defined as:

$$\tau_{S_j S_T} : S_j \rightarrow F\left(S_T\right) \tag{3}$$

$$\tau_{S_j S_T}\left(l_{ij}\right) = \left\{\left(c_k, b_k^{ij}\right)\right\} \tag{4}$$

where:

$$b_k^{ij} = \max_y \min\left\{\mu_{l_{ij}}\left(y\right), \mu_{c_k}\left(y\right)\right\}$$
$$i = 1, 2, \ldots, n; \quad j = 1, 2, \ldots, m; \quad k = 0, 1, \ldots, g$$

Therefore, the linguistic performance values are homogenized onto the BLTS as:

$$r_{ij} = \left(b_0^{ij}, b_1^{ij}, \ldots, b_g^{ij}\right) \tag{5}$$

2. The linguistic performance values are aggregated into *collective linguistic performance values* as:

$$r_i = \left(b_0^i, b_1^i, \ldots, b_g^i\right) \tag{6}$$

by means of a OWA generated by a *regular increasing monotone*, RIM, linguistic quantifier.

Since the experts evaluated the alternantives whit reference to different dimensions, all needed for a successful design, the chosen quantifier is *as many as possible* and the resulting OWA weights are calculated accordingly (w_j : [0, 0, 0.2, 0.4, 0.4], orness: 0.2, entropy: 1.05); therefore the $n \times (g + 1)$ matrix in Table 7 represent the profile of each alternative onto the BLTS.

Having all the alternatives rated on the BLTS as fuzzy sets, a *fuzzy preference relation* can be computed and a suitable choice method to rank the alternatives and identify the best one(s) applied. Following the approach of possibility of dominance, the matrix $D = [d_{ih}]$ is calculated by pairwise comparing any alternative i to the other $h \neq i$, where:

$$d_{ih} = \max_{c_k} \min_{c_k, c_l} \left\{\mu_r^i\left(c_k\right), \mu_r^h\left(c_l\right)\right\} \tag{7}$$

so as to obtain the d_{ih} values collected in Table 8.

Finally, the non-dominance choice degree (i.e. the membership of each alternative to the set of non dominated ones ND, μ_{ND}) is easily computed from the strict non dominance

Table 8 Values d_{ih} of the matrix D

i, h	1	2	3	4
1	–	0.361	0.430	0.159
2	0.408	–	0.408	0.159
3	0.430	0.218	–	0.159
4	0.159	0.049	0.159	–

Table 9 Values δ_{ih} of the matrix Δ and index on non-dominance μ_{ND}

i, h	1	2	3	4
1	–	0.000	0.000	0.000
2	0.047	–	0.190	0.109
3	0.000	0.000	–	0.000
4	0.000	0.000	0.000	–
μ_{ND}	0.953	1.000	0.810	0.891

scores δ, obtained by matrix D as:

$$\delta_{ih} = \max\{d_{ih} - d_{hi}, 0\} \quad (8)$$

$$\mu_{ND} = \min_{a_h}\{1 - \delta_{ih}, h \neq i\} \quad (9)$$

which yields to the matrix $\Delta = [\delta_{ih}]$ and finally to the μ_{ND} vector, as reported in Table 9.

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