Dirección y Organización n. 84 (2024)
https://doi.org/10.37610/84.683

A user-centered approach in complex engineering design environments

Un enfoque centrado en el usuario en entornos complejos de diseño de ingeniería

Cristina Renzi[1], **Francesco Leali**[2]

Recibido: 25/05/2024 | Aceptado: 14/07/2024

Abstract

In complex engineering design environments, the demand for high quality products and high functionality are critical, the end-user requirements have to be integrated into the design process since the earliest design stages. In such contexts, strict design requirements related to quality, safety, and usability must be taken into account concurrently. To this aim, in this work, an integrated user-centered decision-based design method is proposed in the medical design environment context. This work is aimed at proposing a design method to be applied to complex design environments. The proposed case study is the design of an intercom device, aimed at improving patient-doctor communication in the case of bedridden patients on with helmet for Continuous Positive Airway Pressure (CPAP) therapy during SARS- CoV2 pandemic emergency. Patients undergoing helmet-assisted ventilation are often immersed in a highly noisy environment, unable to fully communicate their needs to the doctors. A three-steps decision based integrated product design and process simulation are used in the early design stages, to gain optimal product designs in a user-centered design viewpoint, for novel industrial products. The first step, modular design, is aimed at defining relations between the components of the assembly in a user centered approach. Design alternatives are generated in a Design for Manufacturing and Assembly DFMA viewpoint. In the second step, the group decision making step, in a multiple criteria context, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is applied together with the fuzzy set theory, to overcome uncertainties in the verbal judgments of the decision makers. The third step is related to the simulation of the assembly and manufacturing process, with the aim of defining a final optimal design. The proposed group multicriteria decision making based design method proved to be efficient in complex user centered engineering design contexts.

Keywords User-Centered Design, Integrated Design Method, Fuzzy-TOPSIS, group multi-criteria decision making.

Resumen

Dentro de un entorno de diseño de ingeniería complejo, la demanda de productos de alta calidad y alta funcionalidad es crítica. En este artículo, se propone un método integrado de diseño y simulación basado en decisiones y centrado en el usuario final, bien integrado en el contexto del entorno de diseño médico. El caso de estudio propuesto es el diseño de un dispositivo de intercomunicación, destinado a mejorar la comunicación médico-paciente en el caso de pacientes protegidos con casco para terapia de Presión Positiva Continua en las Vías Aéreas (CPAP) durante la emergencia por la pandemia del SARS-CoV-2.

Palabras clave Diseño Centrado en el Usuario, Método de Diseño Integrado, Fuzzy-TOPSIS, toma de decisiones multicriterio en grupo.

---

[1] Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via P. Vivarelli, 10, 41125 Modena, Italy.
Email: cristina.renzi@unimore.it

[2] Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via P. Vivarelli, 10, 41125 Modena, Italy.
Email: francesco.leali@unimore.it

Early design is an uncertain stage in which several constraints should be considered concurrently, to prevent later expensive redesign activities (Renzi et al. 2019). Systematic decision-based design methods have been proved useful to handle uncertainties in complex engineering design contexts. Moreover, the fulfillment of customers' needs is crucial for market success. Hence, customer needs, should be translated into product requirements to design the product around the user, in a user-centered design context. Particularly in the design of medical devices, it is essential to systematically control the design phases to include constraints related to engineering design quality, the satisfaction of safety and usability requirements for the end user. The usability of the product in the medical field is gaining ground so that several environments are dedicated to the usability testing of devices and machines in the medical field (PE, Kendler and Strochlic 2015; Bitkina et al. 2020).

Hence, in this work, an integrated user-centered product design and process simulation method is proposed. This method is aimed at enriching the state of the art in integrated product design and process simulation in the early design stages.

In particular, the design of an intercom device is proposed as a case study, for improving patient-doctor communication in case of bedridden patients on with helmet for Continuous Positive Airway Pressure (CPAP) therapy during COVID-19 pandemic emergency Patients undergoing helmet-assisted ventilation are immersed in a highly noisy environment, unable to fully communicate their needs to the doctors. Intercom devices are addressed to the doctors for improving ease communication with the patient. Patients must wear air-based earphones inside the helmet, while the microphone is positioned outside from the helmet for safety reasons.

Since the proposed device is addressed to the medical environment it must fulfill medical certification requirements, before being adopted as a certified product at the hospital. Other than electronical safety requirements, also mechanical and quality requirements must be fulfilled. To this aim, the rules for an optimal design for assembly and manufacturing are followed (Boothroyd 1996).

1. Theoretical background

Engineering design approaches related to good practice rules for taking decisions in the medical design field are present in the literature since the early 2000 (Alexander and Clarkson 2000; Alexander and Clarkson 2002).

Multi criteria decision making methods have been largely used in several engineering problems. In particular, several examples of applications of decisional methods in supply chains related problems are mainly related to performance management measures (e.g. Grillo et al. 2018), supplier evaluation practices (e.g. Medina Serrano et al. 2022), and risk management (e.g. Curbelo et al. 2018). In manufacturing contexts, decisional methods are used for controlling and optimizing scheduling in shop floor contexts (e.g. Arauzo et al 2013, Arauzo et al 2014). Decisional methods used for the solution of engineering design problems have been already analysed in a "human" viewpoint, including design issues and user needs in the early design stages, in a designer-oriented decision-making viewpoint (e.g. Renzi and Leali 2016).

Applications of multi-criteria decision making (MCDM) in the medical sector have been used recently (La Torre 2022), as well as specific works related to healthcare and surgical management (e.g. Glaize et al. 2019, Gardas 2022). Among MCDM techniques, a modified TOPSIS has been implemented and applied to the micro-level medical device assessment and regulations (Tallarico et al. 2021). Fewer recent works are dedicated to the application of integrated decision support and systematic engineering design methods of novel medical products (e.g. Barkaui et al. 2022). In this context, integrated decision-based design approaches could help designers in the development of novel products in complex design environments. Nevertheless, the presence of end user in the product design process could be crucial for the success of the product in the market in a human centered design viewpoint (Money et al. 2011; Göttgens & Oertelt-Prigione 2021). In particular, the term 'user-centered design' (UCD) broadly describes the design processes in which the end-users influence the shape of a design (Abras et al. 2004). Hence, according to the Pahl and Beitz systematic engineering design process (Beitz and Pahl 1996), the earliest design phases consisting in planning and conceptual design phases, other than user needs, could be enriched of simulations and prediction of the user response on the product before prototyping phases. In this context, decision support methods are useful to handle complex and uncertain engineering design contexts. As remarked by Razmak and Aouni (2015), Intelligent Decision Support System (IDSS) are part of the Artificial Intelligence with the main objective of filling the gap between decision-making tools and human interactions. In group decision making problems, Fuzzy Logic is used for capturing the uncertainty in translating the decision makers' preferences in the selection of design products as largely reported in the literature and remarked also by the authors (e.g. Renzi et al. 2015; Renzi and Leali 2016; Renzi and Leali 2022). Several examples in literature improve computational efficiency avoiding ranking reversal problems (e.g. Salabun 2014).

Multi attribute decision techniques as TOPSIS are often used in the early design stages to select the most suitable concept design among several product alternatives. Concerning the selection method, the TOPSIS (Technique for

Order Preference by Similarity to Ideal Solution) (Yoon and Hwang 1995) has been proposed in this work.

TOPSIS method belongs to the Multi objective decision making MODM methods. The basic idea of this method is that the chosen alternative should have the shortest distance from the ideal solution and the farthest from the negative-ideal solution.

In Supraja and Kousalya 2016 is stated that the TOPSIS method provides the best and quickest solution in comparison to the AHP or fuzzy- AHP techniques. In fact, conversely from ranking techniques, TOPSIS is not based on pairwise comparison, but on the distance from the ideal solution.

As in Aloisi et al. 2018, the application of the intuitionistic fuzzy decision-making process provides a novel view on the uncertainty management of the verbal judgments of the decision makers. In this paper, the fuzzy-TOPSIS algorithm is the one reported in Luukka (2011), in which ranking is evaluated with less computations than original fuzzy TOPSIS. The fuzzy-TOPSIS algorithm uses trapezoidal fuzzy numbers and closeness coefficient to ideal solution with a simplified ranking method.

2. Method

Medical environments require for strict requirements related to high quality standards, and electronical and mechanical safety requirements to be satisfied. An integrated product design and process simulation method is proposed in this context Structured design methods are useful to consider all constraints in a UCD approach.

To this aim, a three-steps integrated design and process simulation approach has been carried out (Figure 1).

The first step is the modular design, in which a functional analysis is carried out to point out the interconnections between the parts of the assembly. A functional analysis is required with the aim of defining design requisites for novel products (Briant et al. 2004). This step ends with the generation of the design alternatives. In this step, Design for Manufacturing and Assembly (DFMA) rules have been adopted in the design of the connection and closures between the components, to satisfy safety requirements and to easy up assembling operations. DFMA is aimed at lowering the total cost of the final product, by reducing the number of the components, assembly time and the complexity of assembly operations.

The second step is the decision making one, aiming at considering all feasible design of case and connections for properly assembling and closing the device. The Fuzzy TOPSIS method is used to rank alternatives in uncertain contexts for decision-making process to select the most suitable design alternative for the case. To this aim, the preferences of three decision makers have been translated into fuzzy numbers, to overcome the uncertainty of verbal judgments.

The third step is related to the application of the design rules for assembly and manufacturing (DFMA). This is aimed at predicting the assembly efficiency as well as the design suitability for the selected manufacturing process. A prediction of the force required to close the assembly is carried out. A non-linear finite element analysis (NL-FEA) is performed for evaluating the final deformation of the structure after the assembly step. Hence, a simulation of the selected manufacturing process is carried out to evaluate the optimal design for manufacturing intents. In the following, the steps of the proposed approach have been described.

2.1. Fuzzy-TOPSIS for the selection of design alternatives

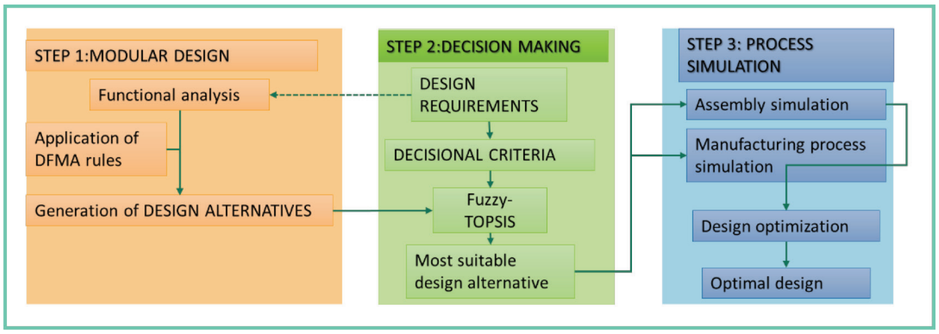
In the following the steps required for the description of the workflow of Fuzzy-TOPSIS method are defined.

2.2. Workflow of Fuzzy-TOPSIS method

Trapezoidal Fuzzy Numbers are used to describe the verbal judgments of decision makers. A Fuzzy Number could be described by its membership function $\mu_A(x)$ with the following characteristics:

$$\mu_A(x) = 0, \forall x \in (-\infty, \alpha] \cup [\delta, \infty)$$

Figure 1. A three-step integrated product design and process simulation approach.



$\mu_A(x) = 1, \forall x \in [\beta, \gamma]$;

$\mu_A(x) =$ increases monotonically in [α, β] and decreases in [γ, δ]

or it may also take these values: $\alpha = -\infty$ or $\alpha = \beta$ *or* $\beta = \gamma$ *or* $\partial = \infty$. The fuzzy number is described by a 4-tuple [α, β, γ, δ] with straight line segments for $\mu_A(x)$ in [α, β] and [γ, δ]. The mathematical form of the membership function of a Trapezoidal Fuzzy Number is: μ_A: R→ [0,1] as in (1).

$$\mu_A(x) = \begin{cases} \frac{(x-a)}{(b-a)}\, for\ a \le x \le b \\ 1\, for\ b \le x \le c \\ \frac{(x-c)}{(d-c)}\, for\ c \le x \le d \\ 0 \text{ otherwise} \end{cases} \tag{1}$$

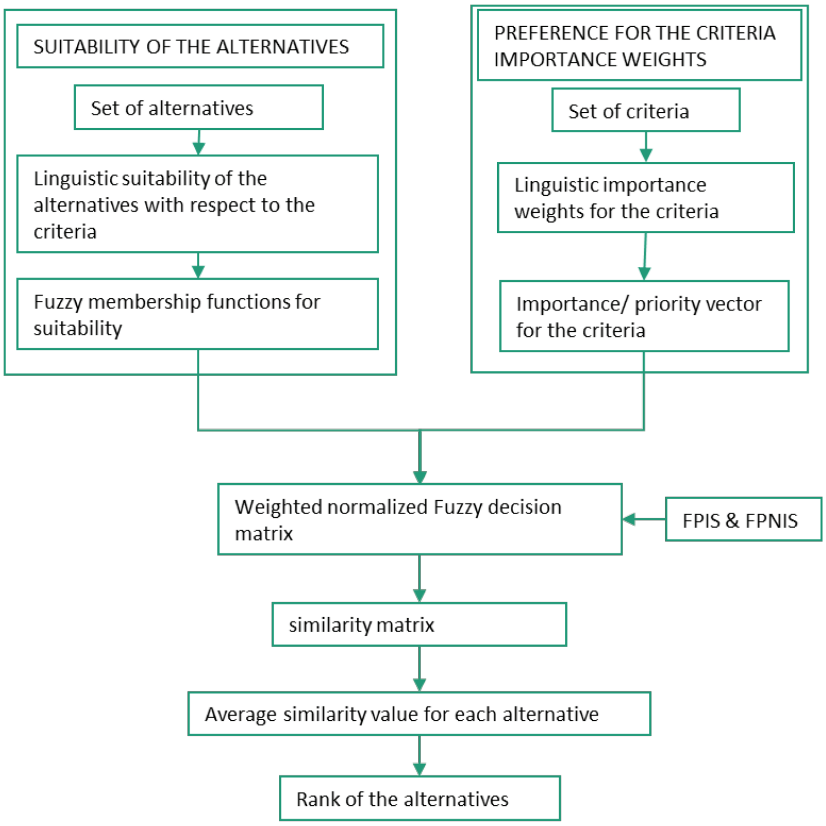
The procedure used by the TOPSIS to evaluate the design alternatives is described below and depicted in Figure 2. In particular, the decision makers express their preference by pairwise comparing the criteria: these linguistic assessments are handled using fuzzy numbers. In group decision making, a priority is defined for the criteria by decision makers' voting process, to define a matrix of mean aggregated preference weights for the criteria. Hence, the suitability of each alternative is evaluated, with respect to the criteria, by means of linguistic variables. These verbal values are translated into Fuzzy numbers (Trapezoidal Fuzzy Numbers). Finally, fuzzy score evaluation and a defuzzification procedure is carried out, to generate a vector whose values are the ranking position of each of the alternatives. An algorithm in the MATLAB environment describing the Fuzzy-TOPSIS procedure was implemented by the authors (Renzi and Leali 2016). In the adopted fuzzy-TOPSIS approach, similarity is used in place of closeness criteria. In a Fuzzy environment, the similarity between two normalized fuzzy numbers A and B is given by (2), with $S(A,B) \in [0,1]$:

$$\begin{cases} S(\tilde{A},\tilde{B}) = \left(1 - \frac{\sum_{i=1}^{4} |a_i - b_i|}{4}\right) \cdot \frac{min(P(\tilde{A}),P(\tilde{B}))}{max(P(\tilde{A}),P(\tilde{B}))} \\ P(\tilde{A}) = \sqrt{(a_1-a_2)^2+1} + \sqrt{(a_3-a_4)^2+1} + (a_3-a_2) + (a_4-a_1) \\ P(\tilde{B}) = \sqrt{(b_1-b_2)^2+1} + \sqrt{(b_3-b_4)^2+1} + (b_3-b_2) + (b_4-b_1) \end{cases} \tag{2}$$

In the fuzzy approach for multicriteria decision-making, the importance weights of the criteria and the ratings of qualitative criteria are verbal judgments that is linguistic variables to be translated into fuzzy numbers.

In the first phase, the decision makers provide their preferences for the criteria, using verbal judgments taken from a previously defined Term Set for "preferences". The weights are allocated for each criterion j, (j=1,…,i), by the

Figure 2. Fuzzy-TOPSIS procedure.



rth decision maker (r =1,…,q). In this way, a matrix of (i x q) elements is produced.

Each weight w_{jr} is a four-element vector, representing the trapezoidal number $w_{jr} = (a_{jr}, b_{jr}, c_{jr}, d_{jr})$. The linguistic values provided by the decision makers to evaluate the suitability of each alternative in relation to the criteria, are translated into the corresponding numerical values, in a *(ixqx4)* matrix (as each element is a four-element-vector). Judgments on the suitability of each alternative, with respect to the criteria must be verbally expressed by the *q* decision makers, by means of the linguistic variables taken from the Term Set of "suitability". If $S_{jmr} = (a_{jmr}, b_{jmr}, c_{jmr}, d_{jmr})$ is defined as the suitability assigned to the mth alternative (*m = 1, 2…, p*), evaluated against the jth criterion (*j = 1, 2, . . ., i*), by the rth decision maker (*r = 1, 2, . . ., q*), the suitability is given by *i* matrices of size *(p x q)*. The suitability indices (S_{jm}) are evaluated for each criterion, as in (3):

$$S_{jm} = \frac{\sum_{r=1}^{q} S_{jmr}}{q} \tag{3}$$

The matrices of the suitability indices can be collected in a single matrix that has the form of (4), with *i* criteria and *p* alternatives, which is defined as the fuzzy-decision matrix.

$$S_{indices_m, j} = \begin{pmatrix} \tilde{S}_{11} & \cdots & \tilde{S}_{1j} & \cdots & \tilde{S}_{1i} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \tilde{S}_{m1} & \cdots & \tilde{S}_{mj} & \cdots & \tilde{S}_{mi} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \tilde{S}_{p1} & \cdots & \tilde{S}_{pj} & \cdots & \tilde{S}_{pi} \end{pmatrix} \tag{4}$$

The following steps are related to the normalization of the fuzzy decision matrix. First, the set of criteria is divided into benefit criteria (the larger the rating, the greater the preference) and cost criteria (the smaller the rating, the greater the preference). Therefore, the normalized fuzzy decision matrix can be represented as (5):

$$R = [r_{ij}]_{mxn} \tag{5}$$

where the members of the matrix are evaluated in a different way, provided they are referred to benefit or cost criteria. If B and C are the sets for benefit criteria and cost criteria respectively, the members of the decision matrix are:

$$r_{ij} = \left(\frac{a_{ij}}{d_j^{\oplus}}, \frac{b_{ij}}{d_j^{\oplus}}, \frac{c_{ij}}{d_j^{\oplus}}, \frac{d_{ij}}{d_j^{\oplus}} \right), j \in B \text{ in which}$$

$$d_j^{\oplus} = max_i(d_{ij}), j \in B \quad \text{and}$$

$$r_{ij} = \left(\frac{a_j^{\Theta}}{a_{ij}}, \frac{a_j^{\Theta}}{b_{ij}}, \frac{a_j^{\Theta}}{c_{ij}}, \frac{a_j^{\Theta}}{d_{ij}} \right), j \in C \text{ in which}$$

$$a_j^{\Theta} = min_i(a_{ij}), j \in C$$

Considering the importance of each criterion, the weighted normalized fuzzy decision matrix is:

$V = (v_{ij})_{mxn}$, where $v_{ij} = r_{ij}(\cdot)W_j$

normalized positive trapezoidal fuzzy numbers can also approximate the elements v_{ij}, for all *i*, *j*, according to the weighted normalized fuzzy decision matrix.

Hence, the fuzzy positive-ideal solution is: $A^{\oplus} = (v_1^{\oplus}, v_2^{\oplus}, \quad, v_n^{\oplus})$, in which $v_j^{\oplus} = max_i(v_{ij4})$ and the fuzzy negative ideal solution is: $A^{\Theta} = (v_1^{\Theta}, v_2^{\Theta}, \quad, v_n^{\Theta})$, where $v_j^{\Theta} = min_i(v_{ij1})$.

The similarity matrix is evaluated calculating fuzzy similarity. Hence the average similarity is computed by (6):

$$S_i^{\oplus} = \frac{1}{i} \sum_{j=1}^{n} S_v(v_{ij}, v_j^{\oplus}), \tag{6}$$

and the resulting similarity is used as a measure for the rank of the alternatives.

According to the value of the average similarity of each alternative, the assessment status for the same alternative can be found, as defined in Table 1. In this work, six conditions have been defined, from the "not recommended" status, to the "approved and preferred" status.

The results of the application of the steps of the proposed integrated product design - process simulation is reported in the following.

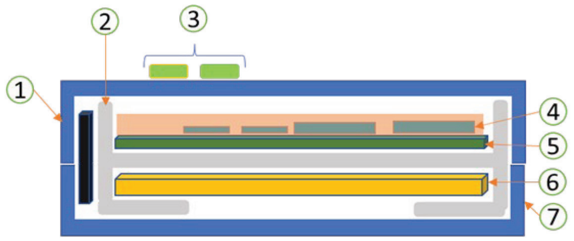
3. Results: STEP1 modular design

The concept of the case for the intercom device has been designed around the electronical and mechanical components, to gain the most compact design for the hand of the user, in a user centered perspective. To this aim, an optimized layout of the electronical components on the printed circuit board (PCB) has been chosen. A functional scheme for defining the asset of the electronical and mechanical components is depicted in Figure 3: Upper (1) and lower case (7) collect the electronical core (4,5). A holder (2), designed for rapid manufacturing purposes (Figure 4), is aimed at supporting the battery (6) separating it from the electronic components, as well as holding the speaker assembly.

Table 1. Assessment status for the alternatives, according to the similarity value.

S_i value	Assessment status
$S_i \in [0, 0.2)$	Do not recommend
$S_i \in [0.2, 0.4)$	Recommend with high risk
$S_i \in [0.4, 0.6)$	Recommend with low risk
$S_i \in [0.6, 0.8)$	Approved
$S_i \in [0.8, 1.0]$	Approved and preferred

Figure 3. Modular design of the intercom device prototype.



#	Components	Quantities
1	Upper case	1
2	Electronic components holder	1
3	Push buttons	1
4	Electronic components	• 1 Microphone Amplifier, • 1 PowerBoost 1000 Charger, • 1 Audio Amplifier, • 1 Stereo Audio Jack Terminal Block • 1 speaker assembly
5	Electronic board PCB	1
6	Li-Ion battery	2
7	Lower case	1

Figure 4. Digital concept for the 3D printed battery support.

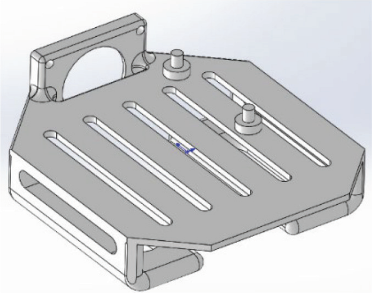
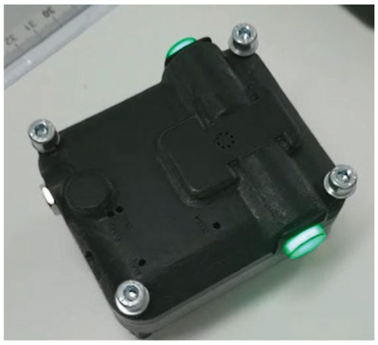


Figure 5. 3D printed prototype for electronic testing operations.



Illuminated momentary push buttons are aimed at easing up patient-doctor communication (Figure 5).

After having defined the components and the related positions of the electronical components, the upper and lower cases are designed focusing on feasible assembly approaches. As a reference for following design optimization steps, a rapid manufacturing technique prototype has been produced. It has been closed by means of four screws and nuts, as depicted in Figure 5. This prototype has been tested by means of a usability test, to verify the ergonomics as well as the effectiveness of the electronic components before introduction into medical departments.

Hence, decisional and optimization steps have been carried out, to refine the design.

Other three design alternatives have been generated, for the evaluation of the feasible assembly approaches as represented in Figure 6. In particular, "**A**" design is connected by means of four screws, "**B**" by snap fit, "**C**" by a fly-nut screw mechanisms, "**D**" by a dove-tale joint.

4. Results: STEP2 decisional step

In this step, a Fuzzy-TOPSIS method is applied for selecting the most suitable alternative for connecting the upper and lower case of the intercom device.

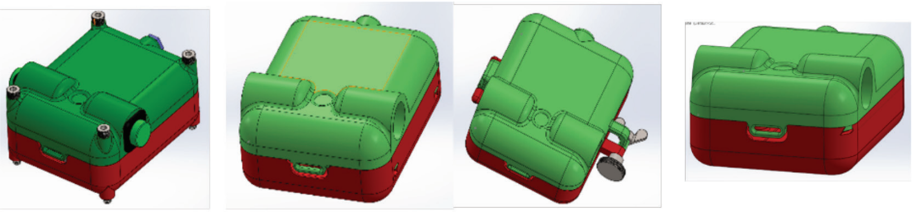
Three decision makers, namely a doctor, an engineer, and a manufacturer defined the following design criteria:

- **Criterion 1: safe closure.** This is aimed at safety reasons because the device is addressed to medical environment. The device should never be opened by users. In case specialized operators occasionally must change the battery, they should be able to, without any additional tool.
- **Criterion 2: Compact design**. This criterion is aimed at promoting de-signs with a reduced volume. The device on its final version should occupy the less volume as possible
- **Criterion 3: good ergonomics**. The doctor must hold the device in one hand and easily reach to push buttons on the case for easy communication
- **Criterion 4: aesthetics**. This criterion has been provided for better product appeal in the market.

4.1. Decisional steps: application of the Fuzzy-TOPSIS

In this section, an integrated multi-attribute decision technique and Fuzzy logic is applied to select the most suitable, among 4 proposed design alternatives. To this aim, the preferences of three decision makers have been translated into fuzzy numbers, to capture the uncertainty of verbal judgments. Moreover, the TOPSIS technique has been used to carry out the selection of the most suitable alternatives. Fuzzy Linguistic Variables are introduced to describe the preferences of the decision makers. The variables used to indicate the "preference" are taken from the Term Set {*Very Low (VL). Low (L). Medium (M). High (H). Very High (VH)*}. The variables describing the Fuzzy Variable for "suitability", are taken from the set {*Very Poor (VP). Poor (P). Fair (F). Good (G). Very Good (VG)*}. Figure 7 shows the

Figure 6. Generated design alternatives for connecting the upper and lower case of the intercom device.



"A" screw connection

"B" snap fit connection

"C" fly-nut connection

"D" dove tail connection

Figure 7. Membership functions for "Preference" and "Suitability".

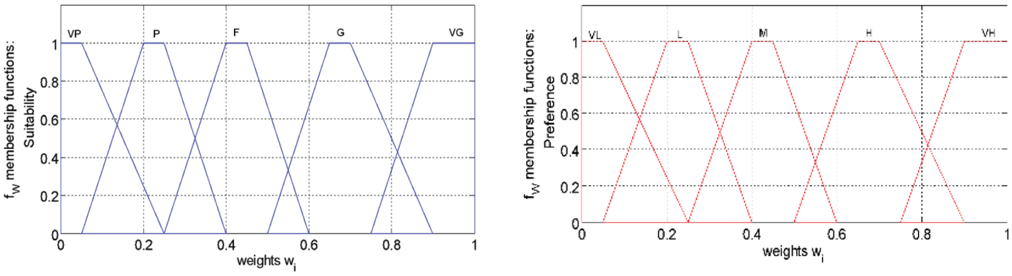


Table 2. Linguistic values for the preferences expressed by the decision makers.

		DM1	DM2	DM3
C1	safe closure	VH	VH	VH
C2	Compact design	M	H	H
C3	Good ergonomics	H	L	M
C4	Aesthetics	M	H	L

membership functions for "*Preference*" and "*Suitability*". Linguistic values are provided by the decision makers (Table 2), to evaluate the suitability of each alternative in relation to the criteria. Numerical values corresponding to the verbal judgments for the importance of each criterion are *VL* = [0.,0.,.05,. 25]; *L* = [. 05, .2, .25, .40]; *M* = [. 25, .4, .45, .60]; *H* = [. 5, .65, .7, .9]; *VH* = [. 75, .9,1. ,1.].

Decision makers (DM) are asked to analyse the suitability of the alternatives by linguistic terms. $S_{jmr} = (a_{jmr}. b_{jmr}. c_{jmr}. d_{jmr})$ is defined as the suitability assigned to the m^{th} alternative ($m = 1. 2. . . p; p = 4$), evaluated against the j^{th} criterion ($j = 1. 2. . . i; i = 4$), by the r^{th} decision maker ($r = 1. 2. . . q; q = 3$). The suitability indices (S_{jm}) are then evaluated for each criterion as in equation (3). These matrices can be collected into a suitability matrix, which is the decision matrix for the problem.

The evaluation of the Fuzzy Positive Ideal Solution and Fuzzy Negative Ideal Solutions (FPIS and FNIS respectively) are reported in Table 3. Considering the vector of the resulting average similarity for the alternatives reported in Table 4, the resulted preference, that is the alternative with the maximum value of the average similarity, is alternative **D2,** approved and preferred, **D1** approved, while **D3** and **D4** could be approved with low risk.

4.2. Step 3 process simulation

Once the most suitable conceptual design for the intercom device has been chosen and the electrical and ergonomic usability have been tested, the optimized design of the assembly of the upper and lower cases have been carried out. An acrylic based plastic material (Polymethyl methacrylate PMMA) has been chosen for injection molding of the lower and upper case due to its transparency, easy cleaning, UV resistance and scratch-resistance, which are effective criteria in medical environments (Pawar 2016).

After the snap fit assembly has been designed, a first evaluation of the mating force for assembling the upper and lower cases have been implemented.

Hence, a non-linear finite element analysis (NL-FEA) has been carried out into the Dassaults' SolidWorks-Simulation environment, to evaluate the compromise design of the snap fit assembly.

5. Results: Step 3 Process simulation

5.1. Design for assembly

To investigate the usability grade of the assembly of the case by means of snap fits, before manufacturing steps, the mating force ("push-on force") W has been evaluated. To this aim, let define the maximum strain at the base ε_0 of the snap fit as in Eq.7 in which: t is the thickness of the snap fit; L is the length of the snap fit; y_max is the maximal allowable

Table 3. Fuzzy points of positive and negative ideal solution FPIS and FNIS.

AidPos	0.75	0.90	1.00	1.00	0.42	0.56	0.62	0.80	0.50	0.65	0.72	0.83	0.33	0.48	0.53	0.70
AidNeg	0.13	0.29	0.35	0.48	0.03	0.14	0.17	0.33	0.01	0.05	0.08	0.25	0.02	0.08	0.11	0.25

Table 4. Average similarity of the alternatives.

Average Similarity	Related alternative	rank
0.64	D1	2°
1.	D2	1°
0.51	D3	4°
0.53	D4	3°

deflection of snap; Q is the magnification/ deflection factor as a function of the aspect ratio L/t defined in the BASF plastic snap fit design manual (BASF 2017):

$$\varepsilon_0 = 1.5 \cdot \frac{t \cdot y\_max}{l^2 \cdot Q} \tag{7}$$

Moreover, P is the perpendicular force acting for the deformation of the snap fit (Eq.8). Hence the mating force W(Eq.9) is a function of P and the geometric shape of the snap fit in terms of angle α (Figure 8).

$$P = \frac{bt^2 E\varepsilon}{6L} \tag{8}$$

$$W = P \cdot \frac{\mu + tan\alpha}{1 - \mu \cdot tan\alpha} \tag{9}$$

For the evaluation of the mating force W, the following snap fit design dimensions have been considered for the snap fit (Table 5)

Hence with the data collected in Table 2, Q=2,25 with L/t=4. The allowable deformation at base ε_{base} given by Eq.7 is about 4%, acceptable for acrylic based plastics (Pawar 2016)).

The mating force W is given by Eq.9, considering the perpendicular force P of 40N (Eq.8) on the snap fit considering a Young modulus E for the acrylics of 3000MPa, and the deformation ad base of 4%.

Hence, with a friction coefficient μ of 0.2 for the acrylics, a perpendicular force P of 21N, the mating force W (push force) is about 19N. As reported in Rusli et al. 2010 this result is consistent with a manual assembly of the case by a young male user.

A nonlinear finite element simulation NL-FEA has been carried out, to predict the behavior of the snap fit assembly, the stress during the assembly, and the residual deformation after the assembly. The FEA is fundamental to predict the failure of the snaps and the mating components during this process.

Figure 8. Mating force W, on the snap fit.

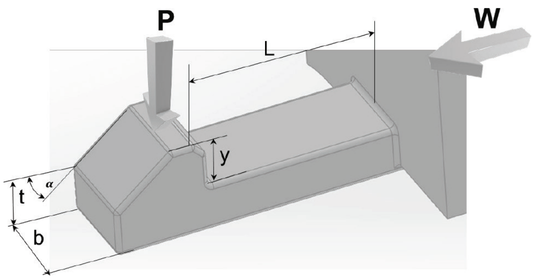
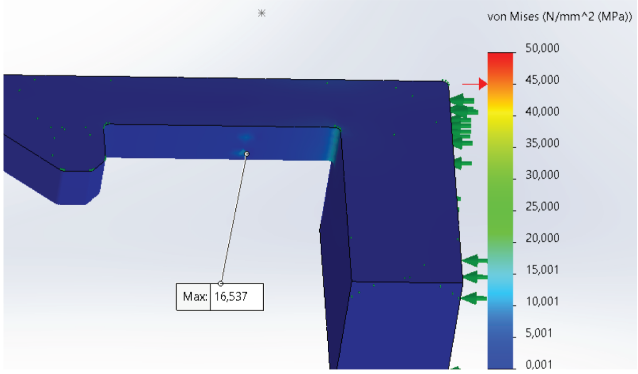


Table 5. Snap fit dimensions.

name	measure	Units of measure
b	4	mm
y	2	mm
L	15	mm
t	2	mm
α	30	degrees

Figure 9. Residual stress at the end of the simulation.

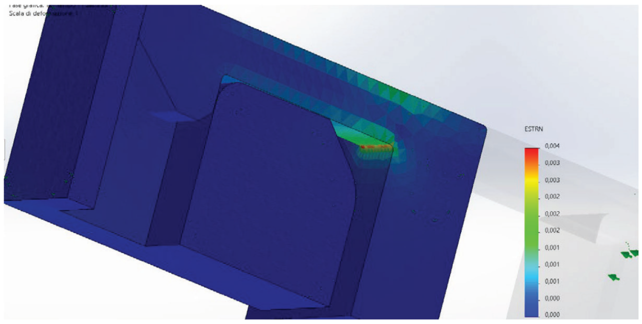


Ten phases have been considered to simulate a complete snap fit assembly lasting one second of time. The FEA model is built according to the allowed geometrical constraints fulfilling boundary conditions as:

- Symmetric geometry constraint (to simulate the presence of the rest of the case structure)
- Linear translation to simulate the displacement of the "male" part of the snap fit during assembly
- Fixed geometry on the "female" part of the snap fit

Residual stress values at the end of the simulation are low as depicted in Figure 9.

Figure 10. Residual deformation at the end of the simulation.



The maximal value of the residual deformation is at the base of the snap fit and is low (0.4%) (Figure 10).

5.2. Design for manufacturing

The manufacturing process simulation is useful to early predict possible problems due to design issues in the real plastic injection moulding process.

The CAD model of the upper and lower parts of the case have been included in the Dassault's Simulation environment to carry out the injection moulding process simulation. The injection points for both the upper and lower cases have been positioned in the center of the model to gain optimal thermos mechanical equilibrium on the part during the process. Nevertheless, a first run of the injection moulding simulation resulted in the evaluation of sink marks present in the thicker areas of the case (sink mark maximum depth amounting at 13μm (Figure 11, on the left).

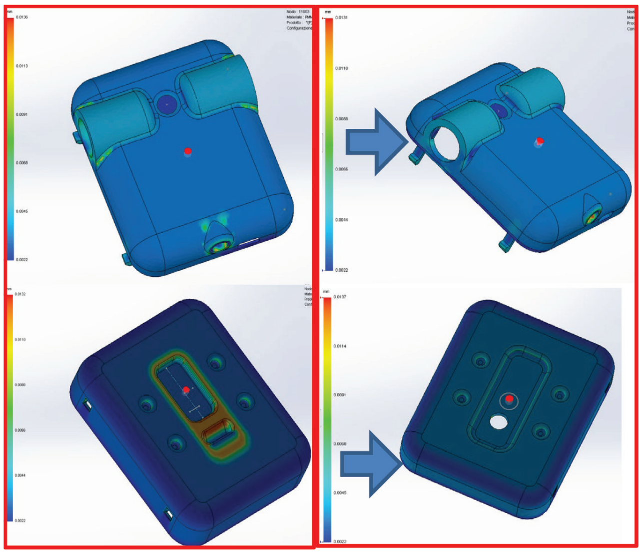
Surface sinks are depressions on the surface of an injection molded plastic part. The fundamental cause of the surface sinks is that insufficient number of polymer molecules have been compressed into one part to compensate for the shrinkage. The thicker areas could be exposed to the sink problem. This is because thicker sections of a part cool at slower rates than thinner sections, with significant shrinkage in thicker sections. Hence, whenever possible, the part should be designed with uniform wall thickness. After modification on the design of the case in terms of uniform wall thickness and minimal shape modification, optimized shape a second run of simulation have been carried out with better results (Figure 11, on the right).

6. Discussion and conclusions

The proposed integrated design method has been showed efficient for the evaluation of a novel product conceptual design in a user-centered design viewpoint in the early design stages.

One limitation of the group decision making selection process proposed is the method for aggregating the alternatives, related to the choice of suitable preference aggregation functions. Since the weighted sum approach is a compensatory strategy, a partial view of the group's overall preference could be provided, instead of an objective approach.

Figure 11. Uniform wall thickness and design modification reduce sink formation (dx).



One approach for prioritizing aggregation is proposed in the literature. As an example, in Fayek and Omar 2016, a prioritized aggregation approach is proposed to group and weight preferences of decision makers. After having described existing methods of aggregation and consequent drawbacks, authors provide a dynamical quantification of relationship between the criteria during aggregation. This could help delivering more objective results in the group decision-making approach.

As a conclusion, the proposed fuzzy TOPSIS approach in a group decision making context proved to be efficient for selecting alternatives in integrated product and process engineering design methods. This is mostly evident in the medical field in which it is essential to control the design steps so as not to neglect the numerous constraints linked to quality and to the satisfaction of safety and usability requirements for the end user.

References

ABRAS, C., MALONEY-KRICHMAR, D., & PREECE, J. (2004). «User-centered design. Bainbridge, W. Encyclopedia of Human-Computer Interaction». *Thousand Oaks: Sage Publications, 37*(4), 445-456.

ALEXANDER, K., CLARKSON, P.J. (2002). «A validation model for the medical devices industry». *Journal of Engineering Design, 13*(3), pp. 197-204.

ALEXANDER, K., CLARKSON, P.J. (2000). «Good design practice for medical devices and equipment, Part II: Design for validation». *Journal of Medical Engineering and Technology, 24*(2), pp. 53-62.

ARAÚZO, J. A., DEL OLMO, R., & LAVIÓS, J. J. (2013). «Subasta combinatoria para la programación dinámica en sistemas de fabricación distribuidos». *Dirección y Organización*, (51), 55-64.

ARAÚZO, J. A., DEL OLMO, R., & LAVIÓS, J. J. (2014). «Gaia Analysis and Design of a Multi-agent-based Shop Floor Control System». *Dirección y Organización,* (54), 26-35.

BARKAOUI, H., BEN REJEB, H., BARKAOUI, A., & TAVARES, J. M. R. (2022). «Multi-Criteria Decision Making for Medical Device Development». *Engineering Management Journal*, 1-18.

BASF (2017). *Snap-Fit Design Manual*. BASF Corporation, New Jersey, 2017

BEITZ, W., PAHL, G., & GROTE, K. (1996). «Engineering design: a systematic approach». *Mrs Bulletin, 71*.

BITKINA, O. V., KIM, H. K., & PARK, J. (2020). «Usability and user experience of medical devices: An overview of the current state, analysis methodologies, and future challenges». *International Journal of Industrial Ergonomics, 76*, 102932.

BOOTHROYD G. (1996). Design for Manufacture and Assembly: The Boothroyd-Dewhurst Experience. In: HUANG G.Q. (eds) *Design for X*. Springer, Dordrecht.

BRYANT, C. R., SIVARAMAKRISHNAN, K. L., VAN WIE, M., STONE, R. B., & MCADAMS, D. A. (2004, January). A modular design approach to support sustainable design. In *International Design Engineering Technical Conferences and Computers and Infor-mation in Engineering Conference* (Vol. 46962, pp. 909-918).

CURBELO, A. D., MUNICIO, Á. M. G., & DELGADO, F. M. (2018). «Herramientas para la gestión de riesgos en cadenas de suministro: una revisión de la literatura». *Dirección y Organización*, (64), 5-35

FAYEK, A. R., & OMAR, M. N. (2016). «A Fuzzy Topsis Method for Prioritized Aggregation in Multi-Criteria Decision Making Problems». *Journal of Multi-Criteria Decision Analysis, 23*(5-6), 242-256.

GARDAS, B. B., GHONGADE, N. P., & JAGTAP, A. H. (2022). «Application of multi-criteria decision-making approach in healthcare surgical management». *Journal of Multi-Criteria Decision Analysis, 29*(1-2), 92-109.

GLAIZE, A., DUENAS, A., DI MARTINELLY, C., & FAGNOT, I. (2019). «Healthcare decision-making applications using multicriteria decision analysis: A scoping review». *Journal of Multi-Criteria Decision Analysis, 26*(1-2), 62-83.

GÖTTGENS, I., & OERTELT-PRIGIONE, S. (2021). «The Application of Human-Centered Design Approaches in Health Research and Innovation: A Narrative Review of Current Practices». *JMIR mHealth and uHealth, 9*(12), e28102.

GRILLO-ESPINOZA, H., CAMPUZANO BOLARIN, F., & MULA, J. (2018). «Modelling performance management measures through statistics and system dynamics-based simulation». *Dirección y Organización, 65*, 20-35.

LA TORRE, D. (2022). «Multiple criteria decision making in health and medicine». *Journal of Multi-Criteria Decision Analysis, 29* (1-2), 3-4.

LUUKKA, P. (2011). «Fuzzy similarity in multicriteria decision-making problem applied to supplier evaluation and selection in supply chain management». *Advances in Artificial Intelligence.*

MEDINA SERRANO, R., GONZÁLEZ-RAMÍREZ, R., GASCÓ, J. L., & LLOPIS, J. (2019). *Sustainable supplier evaluation practices across the supply chain.*

MONEY, A. G., BARNETT, J., KULJIS, J., CRAVEN, M. P., MARTIN, J. L., & YOUNG, T. (2011). «The role of the user within the medical device design and development process: medical device manufacturers' perspectives». *BMC medical informatics and decision making, 11*(1), 1-12.

PAWAR, E. (2016). «A review article on acrylic PMMA. IOSR». *J. Mech. Civ. Eng, 13*(2), 1-4.

PE, M. E. W., KENDLER, J., & STROCHLIC, A. Y. (2015). *Usability testing of medical devices*. CRC press.

RAZMAK, J., & AOUNI, B. (2015). «Decision support system and multi-criteria decision aid: a state of the art and perspectives». *Journal of Multi-Criteria Decision Analysis, 22*(1-2), 101-117.

RENZI, C., ANGELO, L. D., & LEALI, F. (2019, September). Automotive Design Engineering: Material and Processes Selection Problems. In *International Conference of the Italian Association of Design Methods and Tools for Industrial Engineering* (pp. 373-384). Springer, Cham

RENZI, C., LEALI, F. (2016). «A Multicriteria Decision-Making Application to the Conceptual Design of Mechanical Components». *Journal of Multi-Criteria Decision Analysis, 23* (3-4), pp. 87-111. https://doi.org/10.1002/mcda.1569

RENZI, C., LEALI, F. (2022). An Integrated Modular Design and Group Decision-Making Method in Complex Design Environments. In: RIZZI, C., CAMPANA, F., BICI, M., GHERARDINI, F., INGRASSIA, T., CICCONI, P. (eds) *Design Tools and Methods in Industrial Engineering II. ADM 2021*. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-91234-5_58

RENZI, C., LEALI, F., PELLICCIARI, M. et al. (2015). «Selecting alternatives in the conceptual design phase: an application of Fuzzy-AHP and Pugh’s Controlled Convergence». *Int J Interact Des Manuf* 9, 1–17. https://doi.org/10.1007/s12008-013-0187-y

RUSLI, L., LUSCHER, A., & SOMMERICH, C. (2010). «Force and tactile feedback in preload-ed cantilever snap-fits under manual assembly». *International Journal of Industrial Er-gonomics, 40*(6), 618-628.

SAŁABUN, W. (2014). «The Characteristic Objects Method: a new approach to identify a multi-criteria group decision-making model». *Intl J Comput Tech Appl, 5*(5), 1597-1602.

TALLARICO, S., ALOINI, D., DULMIN, R., LAZZINI, S., MININNO, V., & PELLEGRINI, L. (2021). «Health Technology Assessment of medical devices. Overcoming the critical issues of current assessment». *Journal of Multi-Criteria Decision Analysis, 29*(1-2), 150-172.

YOON K. AND HWANG, C.L. (1995). *Multiple Attribute Decision Making: An Introduction*. Sage, Thousand Oaks, CA.