INTEGRATION OF USER-PERCEPTIONS IN THE DESIGN PROCESS: APPLICATION TO MUSICAL INSTRUMENT OPTIMISATION

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Abstract

This paper describes a user-centered design method, which allows the integration of user’s perceptions in different stages of the design process, by taking into account his/her needs and preferences. It relies on two domains which remain generally distinct: the design with a scientific approach (generally math-based) and the integration of users’ perceptions, preferences, tastes, inherently subjective. We apply this method to the design of musical instruments, products for which the feelings of the user are of prime importance, and remain so far difficult to integrate for the design/improvement of an instrument. The methodology is made of two main stages: (1) a subjective study, based on the sensory analysis techniques, during which a “product space” (a family of trumpets) is assessed by a panel of experts according to sensory attributes; (2) an objective study of the instruments, based on the physical measurement of a specific characteristic of brasses: the acoustic input impedance. Then data analysis is used to correlate perceptive and objective evaluations, in order to deduce design rules and to formulate the improvement of a perceptive characteristic of the product (the intonation) as a multicriteria optimization problem. The design of the inner shape (the bore) of a “new” instrument is finally made by solving the multicriteria optimization problem using genetic algorithms.

Keywords: user-centered design, optimal design, sensory analysis, genetic algorithm, musical acoustics.
Introduction

In today’s highly-competitive market, developing new products that meet customers’ needs and tastes is a crucial issue. Beyond technical performances, the perceptions of the customer become very influential on the decision of purchase. To be successful, a product should not only satisfy objective requirements, but should also satisfy the customers’ tastes – inherently subjective. Improving the perceived quality and the “craftsmanship” of products is then an important challenge in product design. This objective is not simple to reach because it needs to include, in the design loop, a rather complex entity: the human. It is thus necessary to develop specific design methodologies which can take into account customers’ feelings and preferences during the design process [1][2][3]. Such methodologies must study and understand the links between the product characteristics (design parameters) and the perceptions or preferences of the user. They need multidisciplinary competences because user’s perceptions or preferences are very complex cognitive processes and many intricate factors are influential. Furthermore, a global model of user’s perception needs to establish links between two kinds of variables, very different in essence: on one side the “subjective quality”, relative to a holistic assessment of the consumer, and controlled by the subject’s perceptions; on the other side, the “design elements”, represented by the physical characteristics which define the product [4]. Three main categories of methods tackle this problem and are subjected to research efforts in engineering design (user oriented design):

• Methods studying products semantic and semiotics. They intend to understand how we as human beings interpret the appearance, the use and the context of a product [5]. Taking the product as a communication media between the designer and the user, product semantics tries to explain which messages a product expresses or represents. Methods based on the semantic differential and the research of “design rules” between the product form and the product semantics are proposed, using mainly tools of artificial intelligence or shape grammars [6], [7]. These methods are aiming to connect engineering design to industrial design,

• Methods based on sensory analysis. The food industry studies since many years the links between product characteristics and consumer’s perceptions. Tools and methods have been developed (panel of experts, sensory profiling, preference modelling) and can be fruitfully translated into the engineering design domain. Sensory analysis techniques are now applied to all the senses which intervene in the perception of a product. The main applications concern the automobile industry (design of car horn sounds [8] or seats fabrics [9]).

• The kansei engineering. Developed by Japanese researchers [10]. It aims to investigate customer feeling and proposes an ergonomic, consumer-oriented technology for product design. The Japanese term “kansei” gathers the concepts of feelings, emotions, affectivity. It is defined as a method which puts in relation feelings of the users towards a product with its specific design parameters. The principle is (1) to collect subjective evaluations of users on a set of product (using mainly the semantic differential and image-words), (2) to identify design factors that relate to the user’s kansei, (3) to build a quantification model with multivariate statistical techniques (conjoint analysis [11], also known as “quantification theory type I”, is mainly used to evaluate the Part-Worth utility of each design factor on a given kansei dimension) and (4) to adjust product design to societal changes and shifting user preferences [12]. The results are generally presented as large databases showing the correspondences between product image and design factors. Kansei engineering was applied for the design of different products [13], [14], [15], and various modelling methods can be
used to provide useful design rules (linear or non linear model, neural networks, rough set theory or fuzzy logic).

Our work lies in this context. We propose in this article to develop a user oriented design method, and to show how the perceptions of users can be taken into account in order to improve the product design. From the study of the literature on user-oriented design methods, we developed an integrated methodology which integrates tools and methods from various domains: the study of user’s perceptions is made using sensory analysis, the building of a model between perceptions and design factors uses key concepts of kansei, and the product design with optimization techniques is proper to engineering design.

The originality of the approach lies in the coupling between a perceptive study of products and an optimization-based approach for the design of a “new” product.

To describe our approach, we focused on a particular product for which the perceived aspects play a very important role in the assessment of the quality: a brass musical instrument (trumpet). Several objective and subjective studies were carried out by the past on musical instruments [16] [17] [18] [19], but few of them tackles the coupling between these two approaches for a design improvement.

The final objective of this study is to provide brass-instrument makers with useful tools to better know musicians’ desires and to have efficient techniques to satisfy them. From a design research point of view, the objective is to develop a generic design methodology which can be applied to various kinds of products for which the aesthetical or emotional aspects are preponderant.

We present in section 2 the user-centered methodology we developed, based on a perceptual study (sensory analysis), an objective study (physical modeling) and optimization procedures. Section 3 is dedicated to the perceptual studies of a set of trumpets, using a panel of musician-experts. The objective study of the instruments (measurement of the acoustic impedance) is presented in section 4. In section 5, data analysis techniques are used to study the correlations between the subjective and the objective data. Section 6 tackles the design of a new instrument by optimization procedure (genetic algorithms). Conclusions and perspectives are drawn in section 6.

1 Description of the user-centered methodology

The proposed methodology is based on design tools and methods used in different domains of product design: food industry, automobile industry, sound design and psychoacoustics.

The methodology combines classical stages of three main disciplines: sensory analysis (stages 1, 2, 3, 4 and 5), kansei engineering (4, 5) and engineering design (stages 6, 7, 8). Its originality lies in the connections between these disciplines, which remain so far independent because dedicated to different products. The decomposition in these 8 stages is described as follows:

1. Set up of a product space, made of existing products which roughly all answer the same usage functions, but differ according to their performances, style, aesthetics, etc. The chosen products must be different enough in order to stimulate a wide sensory range of the user, but similar enough in order to remain in the same sensory domain [20].

2. Perceptual analysis of the product space. This stage uses sensory analysis tools (definition of sensory attributes, panel of experts, sensory profiling). After a training period for the rating of the attributes, the experts perform the sensory profile of the products.
3. Objective analysis of the *product space*. This consists in measuring various objective physical characteristics of the product, and, after a physical analysis of the product, to propose objective criteria which condition the perceived sensations.

4. Study of correlations between the sensory attributes and the physical characteristics.

5. Definition of the need. The need corresponding to a new product is specified according to the sensory attributes. Various techniques based on preference-mapping can be used to detect customers’ preferences [21].

6. Definition of the technical specifications. Correlations are used to translate the requirements into technical specifications according to the physical characteristics.

7. Optimization: Formulation of the design problem as an optimization problem:
   - Definition of the objective functions and the constraints,
   - Definition of the optimization variables
   - Choice of an optimization strategy – determination of optimal solutions

8. Manufacturing of the “optimal” products and test.

The synoptic of the methodology is described Figure 1.

**Figure 1: synopsis of the user centered design methodology**

We propose to describe each stage of the methodology on a particular example in musical acoustics: a brass musical instrument (trumpet).

## 2 Perceptual analysis of brass musical instruments (trumpets)

### 2.1 Background: functioning of brass musical instruments

Oscillations of wind instruments, and particularly lip-driven wind instrument (the brasses), are driven by self-sustained oscillations of an air flow. These oscillations are induced by a mechanical oscillator (the lips of the player), acting as a valve which modulates the flow. The destabilization of the mechanical element is the result of a complex aeroelastic coupling between (1) the lips, (2) the air flow entering the instrument as a result of the static overpressure in the mouth of the musician, and (3) the resonant acoustic field in the instrument itself (the resonator). The brass instruments have been extensively studied (see, for example [22], [23]).

Several notes can be played by modifying the mechanical characteristics of the lips (the “embouchure” of the musician), and/or by changing the geometry of the resonator (use of a
slide for the trombone, or valves for the trumpet). The main design variables of the instrument, which condition the perceived quality by the musician, are:

- The dimensions of the internal geometry of the resonator, called “the bore”. The acoustic behavior of the resonator is strongly dependent on the inner form of the resonator,
- The surface roughness, which generates viscothermal loses,
- The quality and stiffness of the construction,
- The type of material and the forming process; these can have a perceptible influence on the vibrations of the wall,
- The internal gaps between the parts, which affect the air-tightness of the resonator.

We focus for this paper on the main design variables of the perceived quality of an instrument: the internal geometry of the resonator. In order to generate the “product space”, a parameterized resonator has been manufactured.

2.2 Setting up of the product space

In order to design a set of trumpets which are very different in their playing conditions, we decided to parameterize the shape of a very influential part of the resonator on the acoustic behavior of the instrument: the leadpipe. This part is roughly conical and is located between the mouthpiece and the tuning slide (Figure 2).

From the measurements of the internal form of existing leadpipes (measured with calipers), we designed a new leadpipe made of 4 different interchangeable parts, each conical and parameterized by the radii r1, r2, r3, r4 (Figure 2).

Figure 2: design of the parameterized leadpipe

Several parts 1-2-3-4, with various values for the radii r1, r2, r3, r4, have been manufactured with a numerically controlled turning machine. The proposed values of r1, r2, r3, r4 correspond roughly to dimensions of marketed leadpipes, and the assembling of the parts allows the generation of various inner profile of leadpipes (many hundreds). A coding of each leadpipe, made of 4 letters (one letter for each part, the letter corresponding to a given dimension of the radius), has been defined in order to distinguish the leadpipes.

So, using the same trumpet (Bach model Vernon, bell 43) and the parameterized leadpipe, several hundred of different instruments with notably different acoustical behavior can be designed. With this device, we finely control the variation of the design parameter of the set of instruments. Furthermore, the musician is not able to recognize which leadpipe he/she tests. This will be a very important property in order to check the repeatability of the musicians’ assessments.

2.3 Sensory analysis: training and assessment of a panel of experts

Two kinds of data are necessary for a sensory study [20]:

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• Assessments of products by experts on sensory attributes. The sensory attributes must be the most descriptive as possible and not refer to preferences. The experts are trained to provide “objective” assessments and are invited to not consider their preferences,

• Assessments of products by customers according to preference. These tests used generally a huge panel of customers (several hundred) in order to detect preferences trends in a population.

In this study, we did not carried out preference tests. Assumptions will be made according to the preference in order to define a “target” for the design.

A panel of 10 professional trumpet players has been set up for the perceptual analysis of the instruments. The panel was composed of 1 woman and 9 men, from different ages and different musical styles (classical, jazz, pop...), all teaching in the Nantes’s area.

Before the assessment of the instruments, we first worked on the definition of relevant terms to describe their quality. We used an approach based on sensory analysis and the sensory profiling: the musicians were involved in a group session and a free-verbalization task on instruments of various quality. In the first part of the session, the trumpet players used one of the presented instruments and exposed after few minutes his/her feeling about it. The second part was a group discussion (brainstorming), in order to generate a maximum of terms, answering this question: “For you, which attribute is relevant to define the quality (good or bad) of an instrument?”. The list generated was then sorted and a set of consensual sensory attributes was finally defined (table 1).

For each attribute, a definition and an evaluation procedure were proposed, in dialogue with the trumpet players.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Definition</th>
<th>Range</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intonation</td>
<td>Relative position of the height of the notes</td>
<td>out of tune / in tune</td>
<td>Arpeggio</td>
</tr>
<tr>
<td>Test note E</td>
<td>Difference of height note E (fingering 0) and note E (fingering 12)</td>
<td>similar / different</td>
<td>play notes E(0)-E(12)</td>
</tr>
<tr>
<td>Centering</td>
<td>Ability of the instrument to be centered on a note</td>
<td>bad / good</td>
<td>attack of the note G4</td>
</tr>
<tr>
<td>Response</td>
<td>Ability of the instrument to play immediately</td>
<td>bad / good</td>
<td>Detached notes</td>
</tr>
<tr>
<td>Low register</td>
<td>Width of the Dynamic range</td>
<td>limited/ big</td>
<td>dynamics pp, mf, ff</td>
</tr>
<tr>
<td>Medium register</td>
<td>Width of the Dynamic range</td>
<td>limited/ big</td>
<td>dynamics pp, mf, ff</td>
</tr>
<tr>
<td>High register</td>
<td>Width of the Dynamic range</td>
<td>limited/ big</td>
<td>dynamics pp, mf, ff</td>
</tr>
<tr>
<td>Timbre</td>
<td>Tone of the instrument</td>
<td>dark / bright</td>
<td>comparison/reference</td>
</tr>
</tbody>
</table>

Table 1 : list of the sensory attributes defined by the panel of experts

For the evaluation of the trumpets, experts were asked to assess the instruments on each of the sensory attributes, independently of their preferences. Training sessions of the panel of experts have been conducted with a set of instruments (4 different leadpipes). Each musician was asked to rate the trumpets according to the attributes of table 1 on a non-structured scale. In order to evaluate the repeatability of the experts, replications of the same instrument were provided, the order of presentation of the instruments being randomized. The experts were
trained until they were repeatable enough (analysis of the results with a two-way analysis of variance with interaction) [24].

Given that we obtained promising results with these training sessions, we decided to use the panel of experts for an assessment task. The product space consisted of a set of 12 different instruments, defined by their leadpipe code (table 2). Two replications have been proposed, the order of presentation of the trumpets being randomized.

The experts were asked to give the sensory profile of each instrument. In this article, we propose to only exploit the assessments relative to the attribute “intonation”. The average subjective score of intonation for each leadpipe is presented in table 2. The higher the average score, the better the perceived intonation. For example, ADKN (9.5) is perceived as having a good intonation, whereas DKNR (5.1) is not.

In general, according to the general methodology of sensory analysis, a preference study is needed to get the « customer target » defined in figure 1 (input of stage 5.). For our particular case, we assume that the attribute “intonation” is directly correlated to the preference (higher the intonation score, higher the preference). For this reason, it was not necessary to carry out a preference study for the attribute intonation (we suppose that the preferred instrument is an instrument with the better intonation).

3 Objective analysis of musical instruments

3.1 The input impedance $Z_{in}$

Brass wind instruments (and, more generally, wind instruments) can be characterized by their acoustic impedance $Z_{in}$, the transfer function between the acoustic flow $U_e$ and the acoustic pressure $P_e$, which depends on the frequency $\omega$ (equation 1):

$$Z_{in}(j\omega) = \frac{P_e(j\omega)}{U_e(j\omega)}$$

(1)

This quantity can be calculated or measured [25]. It’s a very important property for the characterization of a brass instrument: it gives the magnitude of the acoustic response to a forced oscillation [26]. The typical input impedance of a trumpet presents several peaks of impedance, called the partials of the resonator (Figure 3).

![Figure 3: input impedance $Z_{in}$ of a trumpet (magnitude)](image)

In playing situation, the musician produces a note whose frequency (the playing frequency) is close to the resonance frequency of an impedance peak [27]. In first approximation, we
consider that the playing frequency (which conditions the intonation) is mainly governed by the corresponding peak of the impedance.

3.2 Objective variables extracted from the impedance $Z_{in}$

The input impedance of the 12 trumpets proposed for the subjective evaluation has been measured with the BIAS device, an experimental bench for the measurements of acoustics input impedances [28]. The resonance frequencies can be defined as the frequencies corresponding to the maximum – peak amplitude - of the input impedance magnitude of the air column of the instrument. Two methods can be used to extract the resonance parameters of the impedance measurements. The first one is to directly evaluate the value of the resonance frequencies of the peaks (with a peak detection algorithm). The advantage of this method is that the algorithm is fast and easy to implement. The drawback is that this method can be sensitive to errors in the data and to the sampling rate. This method has been used to extract the impedance peaks for the calculated input impedance (indeed, there is in this case no measurement error and no sampling rate, the impedance curve being analytic).

The second method to extract the resonance parameters (resonance frequency, quality factor and magnitude) from the measured impedance $Z(j\omega)$ is to fit locally around the resonance number $n$ the experimental results with a model of resonance like the Lorentz model, as follows (Equation 2):

$$Z(j\omega) = G_0_n + G_1_n \frac{j \left( \frac{\omega}{2\pi f_{res_n}} \right) Q_n^{-1}}{-\left( \frac{\omega}{2\pi f_{res_n}} \right)^2 + j \left( \frac{\omega}{2\pi f_{res_n}} \right) Q_n^{-1} + 1}$$

where $f_{res_n}$ and $Q_n$ are the resonance frequency and the quality factor of the $n^{th}$ resonance, the complex number $G_0_n$ and the real positive value $G_1_n$ being useful to get the magnitude of the input impedance at the frequency $f_{res_n}$. More precisely, the individual peak number $n$ is selected and the complex input impedance is locally fitted with a circle in the Nyquist complex plane using a least-squares minimisation - for a review of the curve-fitting methods, see for example [29]. Even if the frequency accuracy is not easy to determine, by circle-fitting based on experimental data, we assume that it is less than 0.1 Hz. The advantage of the method is that it is less sensible to errors in the data and to the sampling rate than a direct peak tracking method. The drawback is that it requires a greater computation time. For the measured input impedance, the resonance frequencies were extracted from the impedance curves with this method (table 2).

The resonance frequencies of the input impedance of the 12 trumpets proposed for the subjective evaluation, from partial n°2 ($f_{max}(2)$) to partial n°10 ($f_{max}(10)$), are given in table 2. They were obtained with the circle fitting method.

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1 The study of sound production in brass shows that there is a complex aeroelastic coupling between the lips of the musician and the resonator. Thus, the intonation of the instrument is not only controlled by the closest resonance frequency but possibly conditioned by upper resonance frequencies of the resonator.
These objective data are next used to interpret the score of intonation.

4 Correlations

In this section, the correlations between the scores of intonation (subjective data) and the variables extracted from the impedance curve (objective data) are studied. The aim is to find out relations between these data in order to use them for the design of a new instrument. This approach needs some assumptions.

Let’s first assume that the global subjective assessment of intonation (given by experts) is a function of the intonation of the 5 main musical intervals in the tessitura of the instrument (2 octaves, 2 fifths, 1 third). Next, we made the hypothesis that the playing frequency is mainly governed by the corresponding resonance frequency of the impedance.

In other words, we assume that the intonation of the 5 musical intervals depends on the following frequency ratios: $\frac{f_{\text{max}(3)}}{f_{\text{max}(2)}}$, $\frac{f_{\text{max}(6)}}{f_{\text{max}(4)}}$, $\frac{f_{\text{max}(4)}}{f_{\text{max}(2)}}$ for the 2 fifths; $\frac{f_{\text{max}(4)}}{f_{\text{max}(2)}}$ and $\frac{f_{\text{max}(8)}}{f_{\text{max}(4)}}$ for the 2 octaves; $\frac{f_{\text{max}(5)}}{f_{\text{max}(4)}}$ for the third.

We propose to study the correlation between the intonation scores and the 5 explanatory variables $\frac{f_{\text{max}(3)}}{f_{\text{max}(2)}} - \frac{f_{\text{max}(6)}}{f_{\text{max}(4)}} - \frac{f_{\text{max}(4)}}{f_{\text{max}(2)}} - \frac{f_{\text{max}(8)}}{f_{\text{max}(4)}} - \frac{f_{\text{max}(5)}}{f_{\text{max}(4)}}$.

More precisely, we want to test if the data present a linear relationship between the intonation scores and the explanatory variables (predictors). Given that the explanatory variables are certainly correlated, a reduction of the dimensionality of the predictors via principal component analysis is necessary [30].

4.1 Representation of the objective data by principal component analysis (PCA)

A normalized principal component analysis of the $p = 12$ individuals (trumpets) and the $n = 5$ variables (predictors) leads to the factorial plane plotted Figure 4. More than 98% of variance is taken into account by only two factors $F1$ and $F2$: the initial data are effectively highly correlated.

Figure 4 also shows HA, the “Harmonic” instrument, corresponding to the instrument with mathematically harmonic ratios (see table 4) (projection as additional individual on the factorial plane).
4.2 Proposition of a model for the intonation

A quadratic model is proposed to interpret the scores of intonation \( I_i \) by objective variables. Given that the predictors are correlated (see section 5.1), a regularized regression [30] is proposed (equation 3):

\[
I_i = a.F1i + b.F2i + c.(F1_i^2 + F2_i^2) + d
\]  

The regression coefficients \( a-b-c \), the determination coefficient \( R^2 \) and the statistics \( F \) of the regression (table 3), are determined by minimization of the sum of the deviations squared.

Table 3: coefficients of the regularized regression

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>( R^2 )</th>
<th>( F )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.03</td>
<td>2.6</td>
<td>-2.02</td>
<td>0.70</td>
<td>6.14</td>
</tr>
</tbody>
</table>

The adjustment of the data on the model is correct (\( R^2 = 0.7 \)). Furthermore, the regression is significant with p-value=3.56\% (Fisher Snedecor test: \( F > F_{5\%} (k ; N-k-1) = F_{5\%} (3 ; 8) = 4.07 \)).

The proposed model being an “ideal point model”, the extremum of the paraboloid (equation 3) can be plotted in the factorial plane (point \textbf{Target}, coordinates \( \text{Target}_{F1} = -a/2c, \text{Target}_{F2} = -b/2c \)) (Figure 4). This extremum is a maximum of intonation \( (c<0) \), which indicates that, according to the data and our experts, the optimum of intonation would be located at this position of the factorial plane.

These results lead to the following comments:

- The assumption according to which the ratios of the resonance frequency are relevant for explaining the score of intonation is not to be rejected (\( R^2 = 0.7 \) - significant regression),
- The assumption according to which the global assessment of intonation by the experts is a function of the intonation of 5 main musical intervals of the tessitura of the instrument is coherent with our result.
Next, with the coordinates of the target on the factors $\text{Target}_F1$ and $\text{Target}_F2$ as input, possible values of the initial variables are computed. This is done by using the coordinate transformation relation of the PCA (equation 4):

$$F = X.U$$  \hspace{1cm} (4)

$F$: vector ($p$) of the factorial scores

$X$: vector ($p$) of the standardized data, generic term $x_i$, $i = 1$ to $p$

$U$: matrix ($p \times p$) of the eigenvectors, generic term $u_{ij}$

With the sensible assumption that the value of the factorial scores of the Target on the principal component 3, 4, 5 is null (98% of variance in the factorial plane), a unique solution $X(x_i)$ is computed by solving the following linear system (equation 5):

$$\begin{align*}
\text{Target}_F1 &= u_{11}x_1 + u_{21}x_2 + u_{31}x_3 + u_{41}x_4 + u_{51}x_5 \\
\text{Target}_F2 &= u_{12}x_1 + u_{22}x_2 + u_{32}x_3 + u_{42}x_4 + u_{52}x_5 \\
0 &= u_{13}x_1 + u_{23}x_2 + u_{33}x_3 + u_{43}x_4 + u_{53}x_5 \\
0 &= u_{14}x_1 + u_{24}x_2 + u_{34}x_3 + u_{44}x_4 + u_{54}x_5 \\
0 &= u_{15}x_1 + u_{25}x_2 + u_{35}x_3 + u_{45}x_4 + u_{55}x_5
\end{align*}$$  \hspace{1cm} (5)

After an inverse standardization of the data, the initial values corresponding to this solution (called “Target”) are given in table 4.

Table 4: ratios of frequencies corresponding to the Target, specifications for the design

<table>
<thead>
<tr>
<th></th>
<th>$f_{\text{max}}(2)/f_{\text{max}}(2)$</th>
<th>$f_{\text{max}}(4)/f_{\text{max}}(2)$</th>
<th>$f_{\text{max}}(5)/f_{\text{max}}(4)$</th>
<th>$f_{\text{max}}(6)/f_{\text{max}}(4)$</th>
<th>$f_{\text{max}}(8)/f_{\text{max}}(4)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>1.52</td>
<td>2.03</td>
<td>1.24</td>
<td>1.49</td>
<td>1.98</td>
</tr>
<tr>
<td>HA</td>
<td>1.5</td>
<td>2.00</td>
<td>1.25</td>
<td>1.50</td>
<td>2.00</td>
</tr>
</tbody>
</table>

We notice that the ratios of frequencies of this instrument are almost harmonic. This property was not at all obvious before the study. In deed, the intonation is a subjective characteristic, and it’s not a priori proved that harmonic ratios are more desirable than others. For example, piano tuners are quite aware of this fact and never use an electronic tuner to do their task. Only an approach like the one proposed in this article is able to define specifications by taking into account the feelings and perceptions of users.

Although the ratios seem very close to harmonic ratios, these apparently small variations are in fact perceptible. The Just Noticeable Difference (JND) in height by the human ear is around 5 cents\(^2\) [31]. This corresponds to a variation of the frequency ratio of $3.10^{-3}$. In table 4, all the differences between the “target” ratio and the “HA” ratio are greater than $3.10^{-3}$. So, it seems to be reasonable to say that the Target in not perceptually equivalent to the instrument HA.

With this study on the attribute « intonation » of a trumpet, we defined the specifications of a new instrument. The next step is to design such instrument by optimization techniques. More precisely, the objective is to find the inner form of the leadpipe which would have the characteristics of the Target (specifications given table 4).

\(^2\) The cent is a logarithmic unit of measure used for musical intervals. 1200 cents are equal to an octave and an equally tempered semitone is equal to 100 cents, in any part of the scale.
5 Optimization

5.1 Introduction

A lot of optimization methods are proposed and used in design, like calculus-based (gradient-based), enumerative or heuristics methods [32]. The two first schemes can be subjected to a lack of robustness if the objective function is not defined, not continuous or not derivable and a lack of efficiency in the case of very large design spaces. Moreover, calculus based methods are often local in scopes which means that the optima they find are the best “in the neighborhood of the current point”. This will induce problem of possible local minima. Concerning the design of brass instruments, a mono objective optimization using the Rosenbrock algorithm is for example proposed in [33], [34].

We have been interested in a multi-objective optimization of brasses, and we have chosen to use a search procedure based on random choices, which doesn’t necessitate the calculation of the gradient: the genetic algorithms (MOGA) [35], [36]. This stochastic optimization algorithm provides generally a family of “good” solutions in an acceptable calculation time, and is for many fields of applications an interesting alternative to gradient-based optimization [36]. It enables furthermore an exploration of a large design space.

5.2 Genetic algorithms

The principle of the progressive genetic algorithm used for our application is based on the generation of the population, an evaluation of their fitness, and a generation of the new population, selecting the best individuals.

Fitness is the rate of adaptability of an individual to the environment, like the ability to survive in the Darwin theory. Therefore, higher the fitness, bigger the chance to be in the next population. This measurement of the quality of an individual is used to rank the population. The "rank" of an individual is the number of individuals more powerful than him plus 1. To be better than the others, thus non-dominated (Pareto set), it is necessary to be at least as good on all the objectives and strictly better on at least one of the objectives. An individual who is not dominated will be then of rank 1.

5.3 Problem formulation

The calculation of the input impedance has been made by a theoretical approach based on the transmission line modeling (for more details, see Annex 1).

Using calipers, the bore of the trumpet used for the tests has been measured. The input impedance of a “current” trumpet (with fixed values of the design variables $x = [r_2, r_3, r_4]$) can then be calculated. The peaks are extracted from the impedance curve, and putted in ratio corresponding to the values:

$$\frac{f_{\text{max}}(3)}{f_{\text{max}}(2)} - \frac{f_{\text{max}}(6)}{f_{\text{max}}(4)} - \frac{f_{\text{max}}(4)}{f_{\text{max}}(2)} - \frac{f_{\text{max}}(8)}{f_{\text{max}}(4)} - \frac{f_{\text{max}}(5)}{f_{\text{max}}(4)}.$$

The design problem is finally translated into the following multicriteria optimization problem (equation 6):
The objective functions are the deviation between the target values (table 4) and the current ratios $f_{\text{max}}(3)/f_{\text{max}}(2) - f_{\text{max}}(6)/f_{\text{max}}(4) - f_{\text{max}}(4)/f_{\text{max}}(2) - f_{\text{max}}(8)/f_{\text{max}}(4) - f_{\text{max}}(5)/f_{\text{max}}(4)$ (extracted from the calculation of $Z_{\text{in}}$). The design problem is finally to determinate the values of $x = [r_2, r_3, r_4]$ which minimize the 5 objective functions.

5.4 Implementation

In our study, the individual is the leadpipe (representing the complete trumpet), broken up into 3 variables $r_2$, $r_3$, and $r_4$ (genes) which are the 3 variable radius of the portions of cylinder, each coded on 8 bits. A chromosome is thus coded on 24 bits (Figure 5).

The initial population is made of $N = 60$ trumpets, as a good compromise between a representative population and a correct computing time.

The 12 real leadpipes being used in the perceptive tests were introduced in the first population. The 48 others were randomly determined. Then, for each individual, its "fitness" is evaluated and compared to its environment. For a trumpet, the fitness $f_{\text{fit}}$ corresponds to the inverse of the objective function $e_i$ (Figure 6).

Generations of new populations are made until the convergence criterion is reached (maximum number of generations – or - threshold of acceptability – or - all individuals of rank 1).

The generation of a new population is made of 5 stages:
1. Selection of 2 parents; the parents are chosen totally randomly in our case,
2. Crossing over or reproduction of the parents in 2 children,
3. Mutation (or not, according to a probability),
4. Calculation of the fitness of the children and their rank,
5. Selection and insertion in the population of the 2 best among the 2 parents and 2 children.

Six control parameters of the algorithm can be adjusted: the maximum number of generations, the population size, the probability of mutation, the probability of cross-over, the selection method of the parents and the selection method between mates and children. Table 5 recaps the control parameters used for the application.

<table>
<thead>
<tr>
<th>Max. number of generations</th>
<th>N (pop size)</th>
<th>Probability Of mutation</th>
<th>Probability of cross-over</th>
<th>Selection of the parents</th>
<th>Selection between mates and children</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>60</td>
<td>0.15</td>
<td>0.8</td>
<td>Randomly</td>
<td>Replace by the best</td>
</tr>
</tbody>
</table>

Table 5: control parameters of the genetic algorithm

5.5 Results

The results of the multicriteria optimization are given in table 6. Five not-dominated solutions \( S_i \) (rank 1) were extracted of the Pareto set. This is done by considering an a priori preference of the decision maker, such as the sum \( \text{Sum}(j) \) of the objectives is minimum (equation 7):

\[
\text{Sum}(j) = \sum_{i=1}^{5} e_i
\]

<table>
<thead>
<tr>
<th></th>
<th>( e_1 )</th>
<th>( e_2 )</th>
<th>( e_3 )</th>
<th>( e_4 )</th>
<th>( e_5 )</th>
<th>( \text{Sum}(j) )</th>
<th>( r_2 \text{ (mm)} )</th>
<th>( r_3 \text{ (mm)} )</th>
<th>( r_4 \text{ (mm)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_1 )</td>
<td>0.0159</td>
<td>0.0933</td>
<td>0.0376</td>
<td>0.0861</td>
<td>0.0272</td>
<td>0.2601</td>
<td>4.3</td>
<td>5.4</td>
<td>6</td>
</tr>
<tr>
<td>( S_2 )</td>
<td>0.0162</td>
<td>0.0938</td>
<td>0.0377</td>
<td>0.0853</td>
<td>0.0272</td>
<td>0.2602</td>
<td>4.6</td>
<td>5.3</td>
<td>5.9</td>
</tr>
<tr>
<td>( S_3 )</td>
<td>0.0162</td>
<td>0.0938</td>
<td>0.0377</td>
<td>0.0853</td>
<td>0.0272</td>
<td>0.2602</td>
<td>4.6</td>
<td>5.3</td>
<td>6</td>
</tr>
<tr>
<td>( S_4 )</td>
<td>0.0159</td>
<td>0.0933</td>
<td>0.0377</td>
<td>0.0863</td>
<td>0.0272</td>
<td>0.2604</td>
<td>4.6</td>
<td>5.4</td>
<td>5.7</td>
</tr>
<tr>
<td>( S_5 )</td>
<td>0.0162</td>
<td>0.0938</td>
<td>0.0377</td>
<td>0.0855</td>
<td>0.0272</td>
<td>0.2604</td>
<td>4.6</td>
<td>5.5</td>
<td>5.8</td>
</tr>
<tr>
<td>( \text{BFOS} )</td>
<td>0.0177</td>
<td>0.0958</td>
<td>0.0377</td>
<td>0.0865</td>
<td>0.0272</td>
<td>0.2649</td>
<td>4.7</td>
<td>5.5</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 6: descriptions of five solutions of the Pareto set

In order to estimate the quality of the proposed solutions \( S_i \) relatively to the existing set of initial leadpipes, the criterion \( \text{Sum}(j) \) is calculated for all the leadpipes of the initial set: the “best” leadpipe among the twelve used for the tests is then BFOS (“best” according to the single criterion \( \text{Sum}(j) \)). The performances of this leadpipe are given for information in table 6. Fortunately, the performances of the optimized leadpipes are better than those of BFOS: the optimization procedure improved the objective quality of the leadpipe. But the fact that the “best leadpipe” according to the criterion \( \text{Sum}(j) \) is not the leadpipe with the highest intonation score (ADKN in table 2) needs some comments. Several reasons can be given:

1. The main reason is that the proposed model (equation 3) doesn’t fit perfectly on the sensory data. The determination coefficient \( R^2 = 0.7 \) (70%) is certainly acceptable but not equal to 1: so 30% of information is not taken into account by the model. For this reason, the closest leadpipe to the “target” in figure 4 is not necessarily the leadpipe with the highest intonation score,

2. The model (equation 3) is built on measurements of \( Z_{in} \) (the peaks of table 2). The optimisation of the objective functions (equation 6) is made iteratively with calculations of \( Z_{in} \). Even if (from experience) the differences between measurements of \( Z_{in} \) and calculation of \( Z_{in} \) are rather weak, discrepancies can
occur (Measurements are typically subjected to experimental errors – calculation are subjected to a –relative- inaccuracy of the model). Both are a distorted representation of the reality.

3. The criterion \( \text{Sum}(j) \) (equation 7) is proposed a priori to select the leadpipes. This criterion makes simply the sum of the objective functions \( e_i \). It’s a proposition to select the leadpipes, and it is assumed here that the holistic assessment of the intonation made by a musician can be represented by this criterion. This assumption seems to be sensible, but it could be studied in future works and optimisation of weights in a weighed sum could be envisaged in perspective.

Before manufacturing these 5 new leadpipes \( S_i \), it has to be proved that these leadpipes are different from a perceptual point of view (in other words, the intonation differences must be above the just noticeable difference JND).

From the geometry of a leadpipe, the resonance frequencies can be calculated. With the assumption that resonance frequencies and playing frequencies are equal, the differences of height (in cents) between the notes played by a given leadpipe \( S_i \) and another \( S_j \) \((j \neq i)\) can be determined. The notes considered are the notes playable by the trumpet (corresponding to the resonance n°2 to n°8). Table 7 presents a comparison matrix between the five solutions \( S_i \) and indicates the number of notes (on the 7 proposed) for which the difference between two leadpipes is above the JND of the human ear (5 cents typically). For example, the trumpets corresponding to the leadpipes \( S_1 \) and \( S_3 \) are perceptually differentiable on 4 resonance frequencies on the 7 studied.

<table>
<thead>
<tr>
<th>( \delta &gt; 5 \text{ cents} )</th>
<th>( S_1 )</th>
<th>( S_2 )</th>
<th>( S_3 )</th>
<th>( S_4 )</th>
<th>( S_5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_1 )</td>
<td>--</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>( S_2 )</td>
<td>--</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( S_3 )</td>
<td>--</td>
<td>2</td>
<td>2</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>( S_4 )</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>( S_5 )</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 7: Comparisons matrix of the 5 leadpipes \( S_i \): number of notes above the JND

Three groups of leadpipes are finally perceptively distinguishable: \( \{S_1\} \{S_3\} \{S_2, S_4, S_5\} \). The leadpipe \( S_1 \) is noticeably different of the others, as the leadpipe \( S_3 \). On the other hand, \( S_2, S_4, S_5 \) are not enough different to be perceived by the human ear.

The continuation of this work will be to manufacture the 3 leadpipes \( S_1, S_2, S_3 \) and to test them with the panel of experts, in order to validate the proposed methodology. Even if these tests are not yet performed, several hypotheses and conclusions can be given.

The calculation of the performances of the leadpipes \( S_1, S_2, S_3 \) according to the criterion \( \text{Sum}(j) \) shows that they are better than all the leadpipes of the initial set. First, the “objective quality” of the trumpet has been improved by the optimisation procedure.

Secondly, it remains to be proven that the “perceived quality” has also been improved. Subjective tests will be carried out to study whether the intonation of the leadpipes \( S_1, S_2, S_3 \) is better than those of the leadpipes of the initial set. Blind tests will be carried out with musicians and a set of product made up of \( S_1, S_2, S_3 \) and leadpipes of the initial set. If the
intonation of $S_1, S_2, S_3$ is significantly better than those of the leadpipes of the initial set, then all the stages of the design methodology can be validated, namely:

- The sensory assessments of the experts are reliable
- The objective variables (resonance frequencies ratio of $Z_{in}$) are effectively representative of the intonation
- The model of intonation (equation 3) is accurate enough and provide a reliable target
- The criterion $\text{Sum(j)}$ is representative of the perceived quality of trumpets (intonation)

If the intonation of $S_1, S_2, S_3$ is not significantly better than those of the leadpipes of the initial set, then at least one of these stages is not validated. Further studies will be needed to find out which stage is problematic.

6 Discussion and conclusions

6.1 Discussion on others applications

The proposed methodology can be used for various applications, for which the perceptions of the user are of prime importance. In the car factory domain, industrialists worried more and more about the “sound quality” of the cars they design. Instead of trying to decrease at any price the noise level of cars, it could be interesting to try to convey particular values with the sounds and to connote the sounds for a coherent design. Application could concern the design of car horns, “clic” of turning lights, engine sounds… After a contact with a French cars maker, an application on the perception of diesel engines is in progress.

A lot of other application’s domain of the method can be found. For example, a good sport equipment must combine comfort and effectiveness. The perception of the user is fundamental for the comfort of the apparatus according to the physical data and adjustments of the equipment. At this level, proposing many real prototypes for user assessments would be problematic because very expensive. But Virtual Reality (VR) seems to offer promising functionalities for the assessment of virtual products. The available Virtual reality interfaces are now mature enough for suggesting to the user relevant feelings and sensations. The main problem is now to learn how to use it and to define relevant methods for their integration into the design process.

6.2 Conclusions

We presented in this paper a methodology for a user-centered design. It was applied to the design of brass musical instruments (trumpets), and on a particular attribute of the perceived quality of trumpets: the intonation. The methodology is generic and can be applied to other products as car motor sounds for examples. All the stages of the methodology have been clearly described on this particular musical example. After a subjective study using a panel of experts-musician, the specifications of a new instrument have been defined. The design of this new instrument was done by multicriteria optimization using genetic algorithms.

Two kinds of results are provided by the study. Firstly, concerning musical acoustics, this work is an original approach to study the perceived quality of musical instruments. Using a consensual vocabulary and assessment procedures, several sensory attributes have been defined by the assessors. Correlations between sensory attributes and acoustics measurements have been scientifically studied, and they provide interesting links between the subjective and the objective world.
Secondly, concerning the design methodology, our study proposes an integrated approach which puts the user in the centre of the design loop. The approach starts with the user and his/her perceptions, proposes the definition of an objective function coherent with the user’s feeling, and finally provides an optimal solution which can be tested. It’s a proposition to show how an optimization approach (convergent thinking) and a subjective and emotional study with sensory analysis (divergent thinking) can be combined. It is a first step for a more rational treatment of the subjective aspects of the need in product design [].

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References


Annex 1

The instrument is modeled as the juxtaposition of cylindrical and conical segments, defined by their geometrical dimensions (length, input and output diameters) (Figure 7). Three design variables, the inner radii \( r_2, r_3, r_4 \) of three particular sections of our homemade leadpipe, have been defined for the optimization problem. The first radius \( r_1 \) was fixed, in order to join continuously with the previous part of the leadpipe, i.e the mouthpiece.

Figure 7: definition of the shape of the resonator for the calculation of \( Z_{in} \), and of the design variables \( r_2, r_3, r_4 \).

The relation between the acoustic pressure \( P_i \) and volume flow velocity \( U_i \) at the input and output of an element \( i \) is given by equation a1, where \( H_i \) is the transmission matrix for element \( i \):

\[
\begin{bmatrix}
P_i \\
U_i
\end{bmatrix} =
\begin{bmatrix}
H_{i11} & H_{i12} \\
H_{i21} & H_{i22}
\end{bmatrix}
\begin{bmatrix}
P_{i+1} \\
U_{i+1}
\end{bmatrix} =
H_i
\begin{bmatrix}
P_{i+1} \\
U_{i+1}
\end{bmatrix}
\] (a1)

For cylindrical and conical segments, the expression of \( H_i \) according to the geometry can be found in [25]. The transmission matrix \( H \) of a resonator consisting of \( N \) segments is the product of the individual transmission matrices (equation a2):

\[
H = \prod_{i=1}^{N} H_i
\] (a2)

The input impedance \( Z_{in} \) of the resonator is finally given by equation a3:

\[
Z_{in} = \frac{P_{in}}{U_{in}} = \frac{H_{112} + H_{111}Z_L}{H_{22} + H_{21}Z_L}
\] (a3)

where \( Z_L \) is the radiation impedance (termination load impedance of the waveguide). The simplest model is to suppose that \( Z_L \) is equal to 0, but more sensible assumptions can be proposed to determinate \( Z_L \).