Material Selection in the Professional Appliances Industry

Agnese Piselli

Materials selection in the design engineering field

In new product development, one of the central decisions is the choice of materials, finishes and manufacturing technologies. Materials selection is a multi-criteria decision making problem which involves seeking the best compromise between material properties and design requirements (Ashby, Shercliff and Cebon, 2007) such as functional conditions, design limits, user behaviours and environmental conditions (Ashby, 1992; Cornish, 1987). Several methods and tools have been developed to guide material selection over the last fifty years (fig.1). Focused on technical property evaluation, engineering-based methods are the first and most commonly used approaches (Ashby, 1992; Budinski, 1996; Cornish, 1987; Farag, 2002; Lindbeck, 1995; Patton, 1968). Widely implemented also in industrial contexts (Chatterjee, Athawale and Chakraborty, 2010; Grujicic *et al.*, 2009; Javierre *et al.*, 2015), materials selection is considered a mature discipline for everything regarding material performance evaluation in technical applications (Wongsriruksa *et al.*, 2012). Other material features, known as sensory criteria or aesthetic properties (Ashby and Johnson, 2002), are embodied in the 'skin' of a product (Del Curto, Fiorani and Passaro, 2010) and can be related to users' experiences with and through materials (Karana, Pedgley and Rognoli, 2013; Manzini, 1986). These properties are usually, but not always consciously, evaluated by product designers when selecting materials and finishes. The surface features that can be perceived by the human senses as linked to a material's physical properties (Wilkes *et al.*, 2014), are named 'sensorial properties'. On the contrary, if such features are linked to a greater extent to a product's value and identity, or user experience and preference, they are identified as 'intangible properties' (Karana, 2009). Materials' sensory and intangible properties have been extensively studied in the academic contextt (Ashby and Johnson, 2002; Figuerola, Lai and Ashby, 2016; Karana *et al.*, 2015; Manzini, 1986; Van Kesteren, Stappers and de Bruijn, 2007; Zuo *et al.*, 2001), although they have not been integrated into industrial case studies in a structured way.

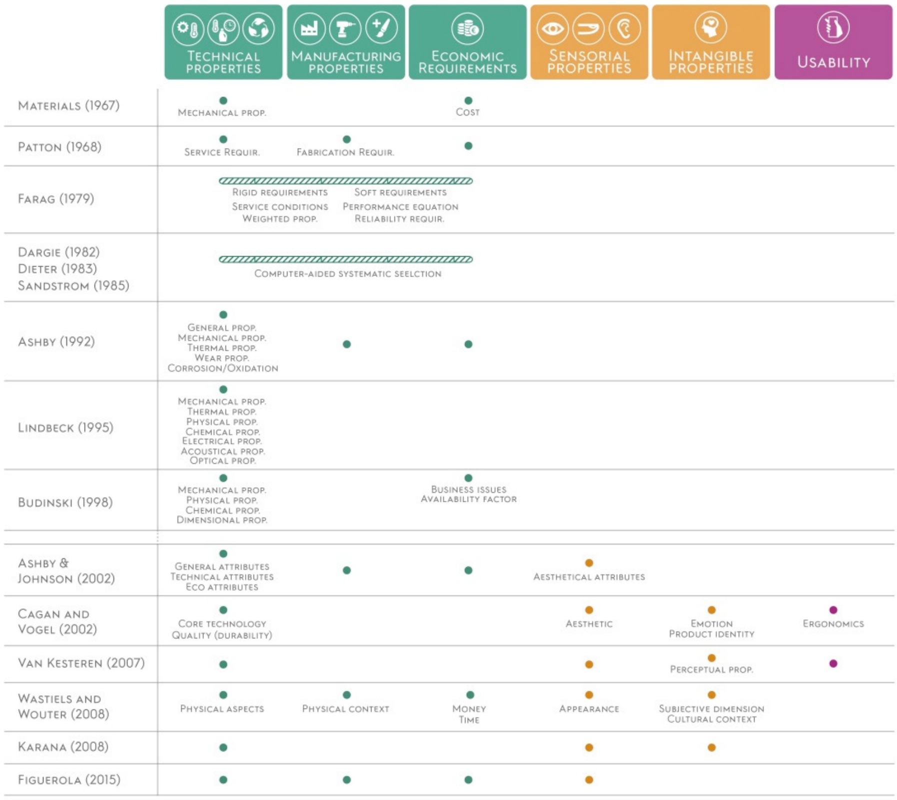

Fig. 1 - Literature review on materials selection methods.

Evidence of the problem

The engineering and design approaches to this topic are numerous and wide-ranging, reflecting a current industrial problem: throughout the product development process, engineers and industrial designers operate materials selection at various stages using diverse tools, languages and perspectives (Piselli, Simonato and Del Curto, 2016). Product engineering generally considers technical decisions based on quantitative data (Piselli, Simonato and Del Curto, 2016). Product engineering generally deliberate on technical decisions based on quantitative data (e.g., technical properties, manufacturing and economic requirements) (Ashby, Shercliff and Cebon, 2007; Farag, 2002). Industrial designers describe aesthetic decisions about materials and finishes with the aid of qualitative tools (e.g., moodboards, physical material samples, or expressive-sensorial adjectives) (Ashby and Johnson, 2002; Piselli *et al.*, 2016; Van Kesteren *et al.*, 2007). Conscious that it is not always possible to rationalize a formal and aesthetic choice, designers are increasingly called on to qualify their subjective decisions (Simonson, 1989) with quantifiable parameters (de Rouvray *et al.*, 2008), especially in the industrial environment.

Context of application

This research project was conducted in collaboration with an industrial partner leader in food preparation and laundry systems appliances manufacturing. In this demanding context, appliances are characterised by high productivity and prolonged, cyclical use over time. The materials employed are exposed to variable thermal and chemical stresses due to their service conditions and frequent cleaning operations (Basso *et al.*, 2017; Piselli *et al.*, 2017). Moreover, the finishes employed in aesthetic components, used manually, actively contribute to driving consumer quality perceptions.

Research purpose

The aim of this research is to facilitate and accelerate the decision-making process, in order to increase material choice agreement amongst engineers and industrial designers. Consequently, the general objective of the study is the development of an articulated method of selection that allows technical and design specifications to be integrated. In doing so, its first specific objective is redesigning practical tools for the analysis of sensory and intangible properties (D'Olivo *et al.*, 2013; Faucheu *et al.*, 2015). The purpose is to provide industrial designers with measurable supporting data with which to better justify their colour, material and finish (CMF) choices. With a view to improving product quality perception over time, the second specific objective of the study is to integrate sensory analysis in evaluating users' perceptions of material aging (Lilley *et al.*, 2016). The introduction of an acceptable 'aesthetic obsolescence' threshold after the materials selection phase will allow a more conscious selection process to be employed, integrating durability assessment in a more realistic operational environment.

Research approach and framework

In order to gain a comprehensive understanding of the context needs, case study based research was done involving examining twenty-four representative case studies from the professional appliances industry. The analysis helped in choosing the research approach to be used and defining the framework of the new selection process.

Approach

Holistic design is an integrated approach in which problems are considered as systems in which a range of actors are involved in the process (Pearce, 2009). In this system, secondary aspects of the problem also become primary aspects to be taken into account alongside problem-solving practices (Conole, 2010). The aim of the holistic design approach is to allow design researchers to introduce a different perspective to the problem (Prowler and Vierra, 2008). An integrated design approach to materials selection can be a valuable way of evaluating all the aspects generally considered by different professionals (designers, engineers, technicians, etc.) involved in the selection process. A holistic approach allows all the different properties that are relevant to the specific context of this research to be taken into account (fig. 2): technical properties, durability, regulatory issues and sensory and intangible properties.

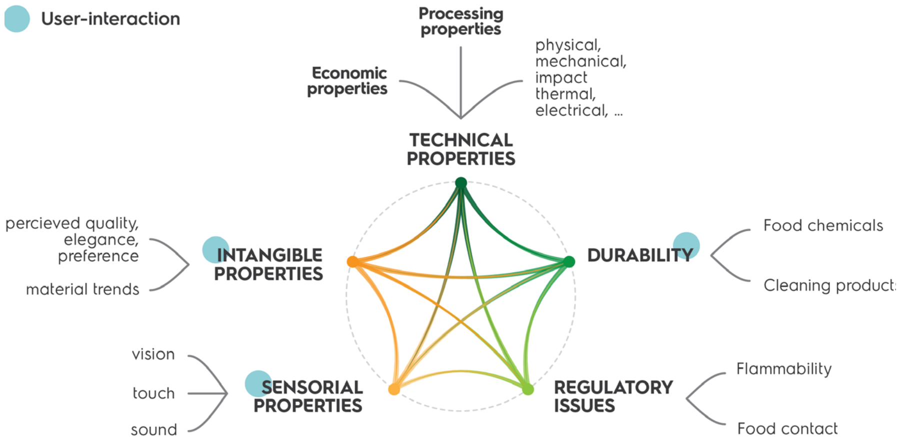

Fig. 2 - Holistic approach to materials selection: material properties.

To facilitate the examination of all these properties, fig. 3 shows the selection process in a schematic way. The general framework follows Ashby's process of selection which is organized into translation of requirements, screening and ranking, and material choice steps (Ashby, Shercliff and Cebon, 2007). Non-traditional methods and tools are adapted and designed in order to evaluate durability, regulatory issues and sensory criteria.

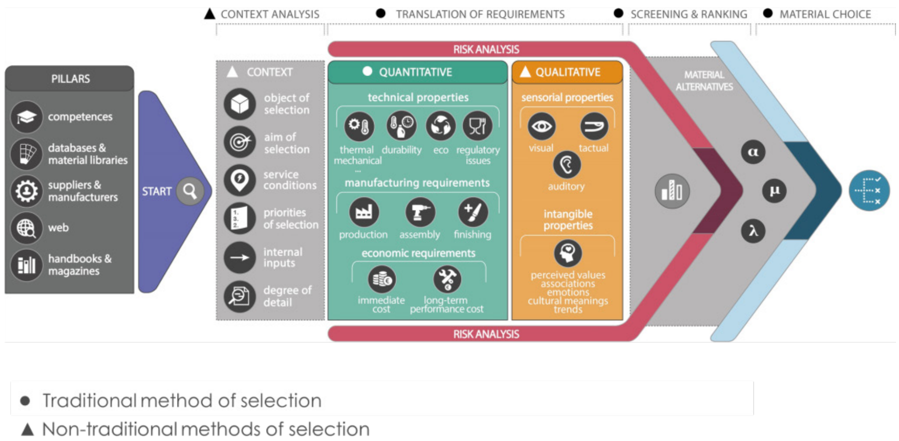

Fig. 3 - New holistic materials selection framework.

Pillars

The new materials selection method is based on different pillars that specify the skills necessary to perform analysis, the basic tools required and actors potentially involved in the process (fig. 3).

a) Competences

Those performing the selection process should have extensive knowledge of technical and aesthetic material properties and be familiar with the Ashby methodology (Ashby and Johnson, 2002), involving basic understanding of material and process classifications, material indices and property charts.

b) Tools

Handbooks, magazines and digital databases help in selection choice. Moreover, the CES Selector can contribute to shortening research timeframes and systematising selection (Granta Design, 2017). Material libraries can be a source of inspiration for designers and help them throughout the evaluation process (Del Curto and Dantas, 2009).

c) Actors involved

Design, Research & Development and Testing Laboratory departments, together with external professionals as material suppliers and component manufacturers, are generally the actors involved in the selection process.

Steps in the new selection process

The new holistic method offers a complete evaluation of technical properties and sensory criteria, even though these properties may not be analysed in each selection process. Depending on selection object and aim, indeed, only some properties are generally taken into account in each single case study. The new selection process consists of two main steps: Technical Materials Selection (TMS) and Aesthetic Materials Selection (AMS) (fig. 4).

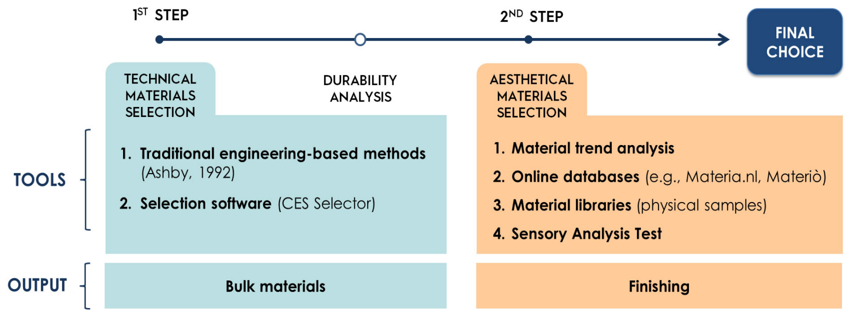

Fig. 4 - Technical Materials Selection (TMS) and Aesthetical Materials Selection (AMS).

Technical Materials Selection (TMS)

Following the traditional Ashby process (Ashby, 1992) and using Cambridge Engineering Selector (CES) software, the aim of the TMS is to choose the raw materials for a given application based on technical properties and regulatory compliance issues. To integrate materials durability analysis, raw material alternatives can be tested by accelerated life-testing (ALT) procedures (Piselli *et al.*, 2017).

Aesthetical Materials Selection (AMS)

AMS is strongly related to the Colours, Materials, Finish (CMF) discipline, focusing on the choice of surface chromatic, tactile and decorative identity (Becerra, 2016). The second step in the new process combines both traditional and non-traditional selection methods with the purpose of examining sensorial and intangible properties and translating them into numerical data. Material trends, online databases and material libraries are possible sources of qualitative and aesthetic information data about materials and finishes. Furthermore, Sensory Analysis Tests, commonly used by the food and beverage industry, have been selected and adapted to measure user-material perceptions (D'Olivo *et al.*, 2013; Faucheu *et al.*, 2015; Ndengue *et al.*, 2016), in order to link numerical data to sensory criteria. In the industrial context, the involvement of design departments is fundamental to this step in selection. AMS can be dependent or otherwise on the TMS: if the aim of selection is new product development or alternative raw material selection, Aesthetic Materials Selection should require prior Technical Materials Selection. In other situations, AMS may be implemented without doing TMS. When 'aesthetic obsolescence' evaluation is required, sensory testing can be used to assess users' perceptions of aging finishing samples (obtained through accelerated life-testing (ALT) procedures) (Piselli *et al.*, 2017).

New materials selection tools

This section presents the tools developed in order to fulfil the specific objectives of the research. The Context Analysis Datasheet and three standard sensory testing procedures collected under the name of SensoMAT protocols, will be described below.

Context Analysis Datasheet

To speed up the first steps in selection, the context analysis phase (Piselli, Simonato and Curto, 2016) has been included prior to the translation step (Ashby, Shercliff and Cebon, 2007). Context analysis is performed with the aid of a specific datasheet (Fig. 5) that allows the service conditions at which the component operates to be carefully examined. Aiming at systematizing and prioritizing the properties to be analysed within selection, the datasheet consists of five main sections: object of selection (1); selection aim (2); service conditions (3); internal inputs (4) and degree of detail (5).

SensoMAT protocols

Inspired by certain sensory testing procedures defined by ISO, ASTM and AFNOR standards, SensoMAT protocols define the conditions for material and finish perception assessment by the human senses.

a) Test room

Test rooms used for sensory evaluations must have controlled conditions (e.g., light, temperature, table and wall colour, etc.) with a minimum of distractions to reduce the potential effects of psychological factors and physical conditions on human judgment.

b) Sampling

Material specimens are the evaluation samples. All the material samples presented to the panel have to be the same shape (e.g., flat, concave, convex). To perform the tests, the materials samples must be a minimum of 45x65mm in size. The samples tested can be either new or aged to simulate potential aesthetic damage to the surface due to the use of the product over time.

c) Sampling tools

White plastic boxes can be used to hold material samples and present them to users in a standard way. A white box frame allows the sample to be visually ‘insulated’ from its background, allowing the specimens’ surface finishing to be compared in a more standardised way. 3D printed boxes were designed for this purpose (fig. 6).

Materials Selection - **Datasheet request**

Required by ______ Date ______

1. Object of selection

Category: Hot ○ Wet ○ Cold/Dynamic ○

Appliance

Component

Item

Dimension: L W H thickness

Current material

Images, technical drawings

2. Selection aim

- ☐ Material substitution
- ☐ New material implementation
- ☐ Material development
- ☐ Material pre-study

Description

3. Service conditions

- ☐ Mechanical conditions (Description)
- ☐ Chemical conditions (Chemicals, food) (Description)
- ☐ Thermal conditions
- Food contact compliance: Yes ○ No ○
- NSF/ANSI 51: Yes ○ No ○
- ☐ Electrical properties
- ☐ Sensorial properties
- ☐ UV resistance: Yes ○ No ○
- ☐ Other conditions

4. Internal inputs

Inputs from supplier, ...

5. Degree of detail

- ☐ Low (at least 2 material alternatives, NO durability, NO sensorial)
- ☐ Medium (at least 2 material alternatives, durability OR sensorial)
- ☐ High (at least 3 material alternatives, durability AND/OR sensorial)

Fig. 5 - Context Analysis Datasheet tool.

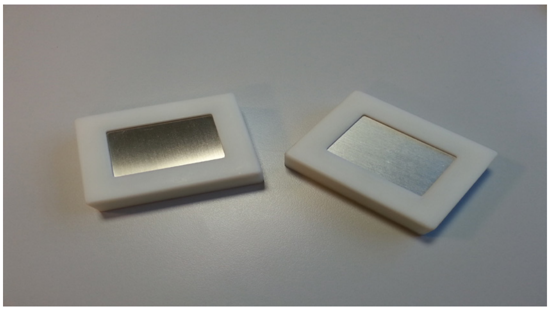

Fig. 6 - 3D printed boxes.

In order to evaluate how much the lighting incident angle affects the evaluation of materials' visual properties, sample stands (at 45° and 85°) could be used (fig. 7).

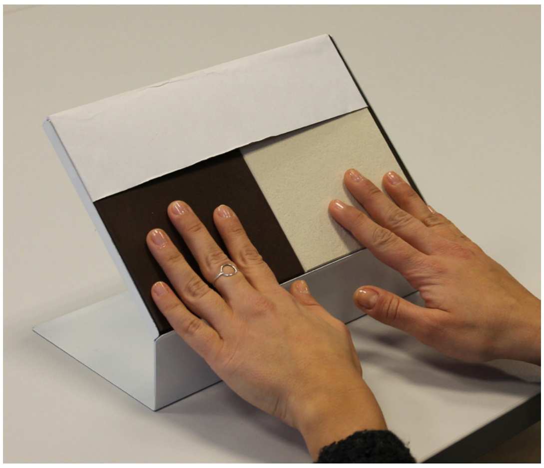

Fig. 7 - 45° stand for material samples evaluation.

d) Attributes or descriptors

Sensory attributes or descriptors are words and adjectives that account for human perception of material sensory criteria or product values. Verbalization of these properties depends on several factors: the aim of the test, the sample materials selected, panel experience, culture and language, etc. (Giboreau, Dacremont and Dubois, 2007). The following table (tab. 1) synthetizes some descriptors selected from literature (Ashby and Johnson, 2002; Baxter, Aurisicchio and Childs, 2014; Faucheu *et al.*, 2015; Karana, Hekkert and Kandachar, 2009; Özcan and van Egmond, 2012; Van Kesteren *et al.*, 2007; Wongsriruksa *et al.*, 2012; Yanagisawa and Takatsuji, 2015; Zuo, 2010) which could be used in SensoMAT protocols.

The choice of the specific attributes to be tested and the language used during the test has to be defined before each sensory test. English or Italian can be standard languages. The number of attributes tested in each session can vary.

f) Assessment panel

The test involves a panel group. The number of assessors chosen is based on the desired statistical sensitivity level. Moreover, assessors can be select-

Tab. 1 - Descriptors selected from literature.

	Sensorial property	***Descriptors***	
		English	***Italian***
Visual	**Glossiness**	Shiny – Matte	Lucido – Opaco
	Surface evenness	Uniform – Non-uniform	Omogeneo - Disomogeneo
	Colour intensity	Intense - Light	Acceso - Sbiadito
	Transparency	Transparent – Opaque	Trasparente - Opaco
Tactual	**Roughness**	Rough – Smooth	Ruvido – Liscio
	Warmth	Warm – Cold	Caldo – Freddo
	Stickiness	Sticky – Not sticky	Appiccicoso – Non appiccicoso
	Softness	Soft – Hard	Morbido - Duro
Intangible	**Quality**	Premium quality – Poor quality	Alta qualità – Bassa qualità
	Elegance	Elegant – Shabby	Elegante – Non elegante
	Innovation	Modern - Traditional	Moderno – Tradizionale
	Cost	Expensive – Cheap	Costoso - Economico
	Pleasure	Like – Dislike	Piace – Non piace

ed on the basis of their experience with products (e.g., professional appliances) or materials and finishes. The panel should preferably be made up of both men and women. A panel leader, who shows physical samples in a definite order, generally guides the tests.

g) Worksheet form

Participants are usually asked to fill in a specific assessment worksheet form.

h) Data analysis

The appropriate method for data elaboration depends on many factors, including test type, objectives, sampling numbers, assessor type (trained or untrained) and panelist numbers. If the tests follow standard procedures, data interpretation is determined by statistical tables. On the other hand, results can be analysed using Analysis of Variance (ANOVA) methods followed by post hoc tests, Principle Component Analysis (PCA) or Factor Analysis, for instance. Some software is particularly useful for data elaboration (R Studio, Minitab or SPSS Statistics) and transcription (e.g. Regavi-Regressi).

The SensoMAT analysis techniques adapted to be used in the Aesthetical Material Selection stage are Paired-comparison (ISO 5495:2005), Ranking (ISO 8587:2006+A1:2013) and Mapping test (Napping® test) (ASTM, 2017; de Morais and Pereira, 2015; Gacula, 2008; Perrin *et al.*, 2008; Piqueras-Fiszman *et al.*, 2012).

Paired-comparison tests

These evaluate whether a perceptible difference exists between two material or finish samples concerning a given attribute, but without giving any indication of the extent of that difference (fig. 8).

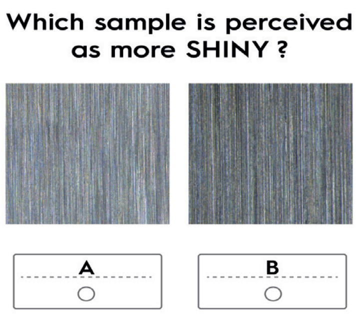

Fig. 8 - Example of paired-comparison tests applied to materials selection.

Ranking tests

This is a simple procedure involving ordering a set of samples on a line according to the intensity of a specific attribute or scaling from the least to most liked for consumer acceptance (fig. 8). Ranking tests can also be used to evaluate surface quality after life-tests and user perceptions in relation to materials aging.

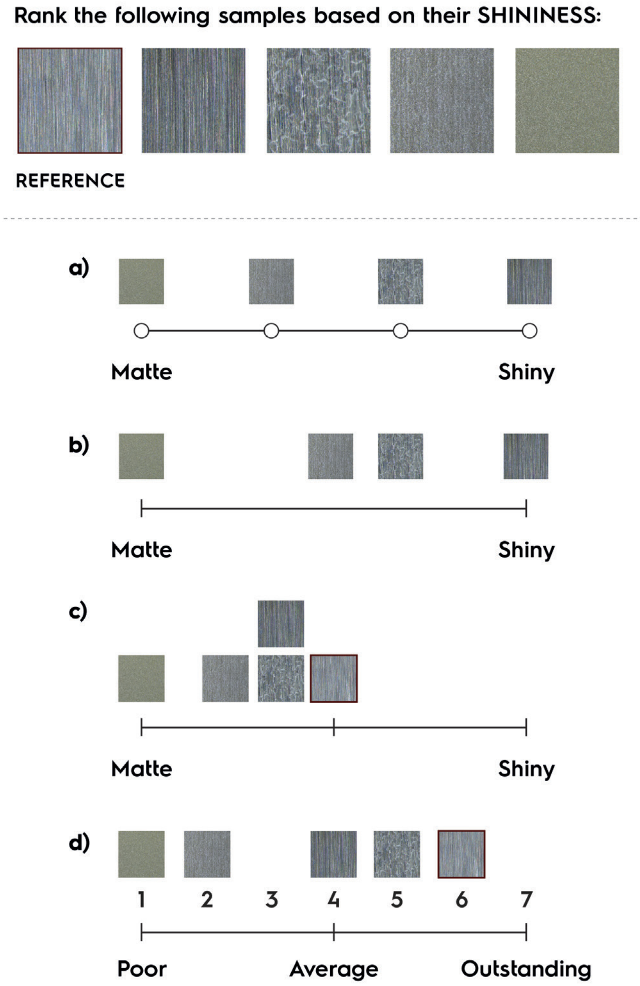

Fig. 9 - Example of ranking test scales applied to the materials selection.

Mapping tests

An adaptation of the Napping® test, a holistic sensory profiling technique which describes product sensory dimensions by their mutual distance on a two-dimensional map (Perrin *et al.*, 2008). Not currently defined by a standard, the test is commonly used to describe a large set of samples, at least 10 (Holt and Pearson, 2014). In the Mapping test, the sensory space (map) is already defined by two specific attributes (axes) selected by the panel leader (Fig. 10). The closer the samples, the more similar they are in relation to the two aesthetic attributes examined. This method can be used to select the best perceived finishing from a range of alternatives, comparing new solutions with those already used.

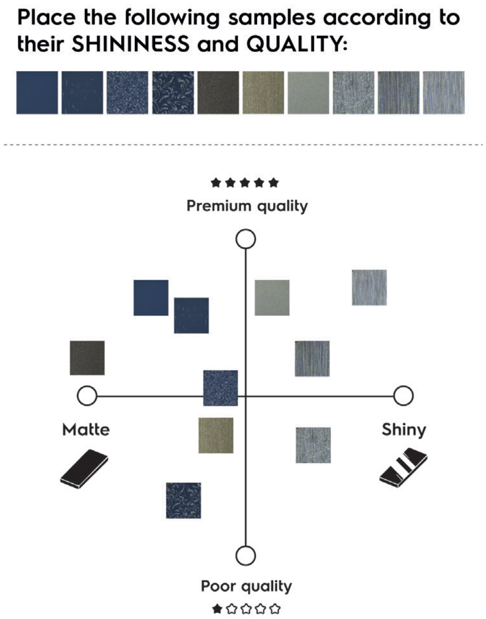

Fig. 10 - Example of Mapping test applied to materials selection.

Explorative design experiments and application case studies

The aesthetic components of products are designed with particular attention to materials, colour, shape (form), texture and lettering, as these are distinctive visual elements that usually also display the brand name (Efer, 2017). Aesthetics, indeed, from the Greek 'aisthetikos', means pertaining to the sense of perception (Veryzer, 1993; Crisci, 2012). The use of different materials and techniques can help in the creative process to design particular associations and feelings about a given product or brand. Consequently, a comprehensive approach to materials selection, an integration of sensory criteria and a materials aging perception assessment is of especial importance in designing components in manual user-interaction, those representing product visual details (Piselli *et al.*, 2016).

Current material trends have shown that high performance polymers can replace and outperform traditional metal counterparts providing several advantages such as design freedom and product differentiation. In the context of this research, stainless steel is the most frequently used material both in structural and aesthetic components because of its performance and expressive-sensory characteristics. As a result, metal-to-polymer replacement is one of the most challenging material selection issues as material replacement can affect overall product quality perception. For this reason, the tools designed within this thesis were applied to five metal replacement case studies in the professional appliance field.

"Innovation through materials selection" design workshop

An educational experience at Politecnico di Milano within the course Materials Selection Criteria in Design & Engineering (A.Y. 2015/2016) aimed at practicing the TMS step in an academic context. The workshop was a tool for incremental innovation driven by material selection. Twenty-five students explored material replacement solutions that could potentially generate performance, production process and usability improvements to a specific professional appliance.

Improvements to a planetary mixer by means of metal replacement

A master degree thesis in Design & Engineering was developed with the aim of investigating material selection for metal replacements to improve product usability. Ensuring the same performances, aesthetic continuity and production cost range, the thesis examined the potential advantages and disadvantages of metal-to-polymer replacements on a functional component of a planetary mixer.

Metal-to-polymer replacement on professional appliances

Two case studies tested the theoretical framework developed to support the selection of alternative materials to stainless steel in diverse professional appliances. First, TMS was performed to depict the candidate polymers that would exhibit comparable functional properties to the metal alloys counterpart. Then, AMS performed by sensory analysis explored the metal-look finishes that could replace stainless steel without compromising the elegance and quality perception of the product (fig. 11). Surface changes due to aging were considered in this study (fig. 7). Thirty-seven volunteers (21 males and 16 females) took part to the sensory analysis tests (Mapping and Ranking test). The non-trained assessors had a different background and experience on the industrial product context and on materials, and were based in two different locations: at the company (Italy) and at the Design Engineering Department of Imperial College (UK). The results proved to be consistent with statistical elaboration. The study outcomes are currently under review for publication into two scientific journals.

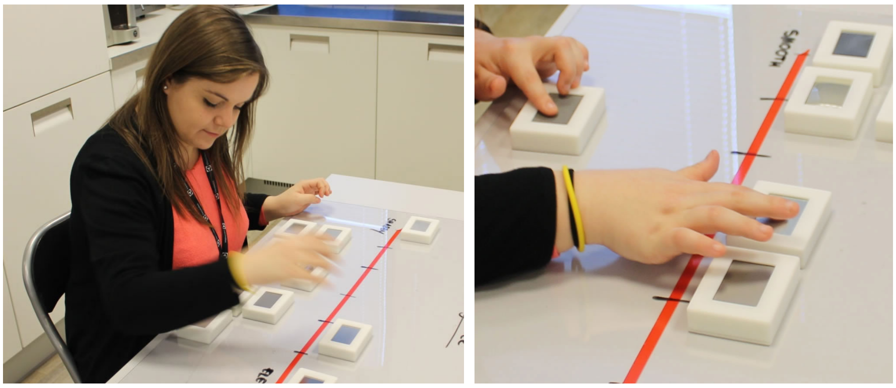

Fig. 11 - Example of ranking test performed with material samples

Metal-to-ceramic replacement on a kitchen worktop

This study was designed to evaluate the effects of abrasive wear and tear on various ceramic surfaces selected as an alternative to metals on commercial kitchen worktops. Roughness changes on aged ceramic samples were analysed by quantitative and qualitative techniques. Surface properties were investigated using laser profilometry, and then correlated with digital image processing. Paired-comparison tests, run by 12 assessors (6 M, 6 F) from the company, were used as selection tools: these permitted users' tactile responses to surface roughness modifications to be assessed as well as the finishing users perceived as having changed the least over time. The test results have been published (Piselli *et al.*, 2017).

Conclusions and future research

This work served the purpose of defining a structured method of selecting materials and finishes based on technical specifications and aesthetic requirements. This research provided original insights into the field of material selection, bridging the gap between engineers, material scientists (Wilkes *et al.*, 2014) and designers by using a holistic method and practical tools to facilitate decision-making throughout the product development process. By combining traditional and design-based methods, the main contribution of this research was to provide industrial designers with measurable supporting data to better explain their subjective aesthetic materials and finish decisions. Subsequently, the limits and advantages of applying such methodologies to the industrial context will be analysed.

Systematic selection process

The use of a structured approach to materials selection has considerable impact in time and resource savings in the product development process. The new method allows certain questions that are usually discussed in the last steps of the development process to be anticipated (e.g., aesthetic constraints, durability and compliance issues). The alignment of industrial designers and engineers on such constraints permits delays and disagreement in materials choices to be limited. For all these, the new method developed showed itself to be robust and reliable, applicable to small and big R&D organizations (Khurana, 2006) and easily adaptable to different industrial contexts. The application of new holistic methods are designed to be used by professionals with a background in engineering, material science and product design. The main constraint in applying such methods is basic knowledge of materials selection and sensory analysis test training.

Quantification of sensory materials criteria

Based on research results, sensory analysis methods (Gacula, 2008; Dal Palù and Lerma, 2015; Faucheu et al., 2015) are rapid, low cost and flexible techniques that help designers to justify better colour material and finish (CMF) choices, providing numerical supporting data by integrating users' perceptions as 'measurement tools' (ASTM, 2017). By contrast, in this type of material evaluation, it is not always easy to control certain variables that can potentially influence user perceptions of materials such as sample shape, prototype finishing, assessors' background knowledge, difficulties in getting a representative sample of consumers, etc. These methodologies reduce but do not eliminate, user evaluation complexity in subjectivity and preference terms (D'Olivo *et al.*, 2013; Lefebvre *et al.*, 2010).

"Aesthetic obsolescence" evaluation

An exploration of users' perceptions of material aging forecasts is particularly important with a view to improving quality perception of products over time (Lilley *et al*., 2016). Sensory analysis allows accelerated life-test results to be evaluated systematically, improving on traditional assessment by physical measurement. Moreover, the introduction of an acceptable 'aesthetic obsolescence' threshold allows possible quality issues based on consumer insights to be anticipated after the material selection phase. It results in a more conscious selection process: designers are able to choose the highest functional and aesthetic performance solution in a more realistic operative environment. On the other hand, possible limit may exist where such methods are used when field test records for surface damage due to ageing forecasts are not available: in such cases, creating a reference from experimental data is necessary.

Future research can further improve such insights and assess their transferability and relevance to other industrial contexts.

Risk analysis assessment

Each material selection brings with it an associated risk. As Quinn and Caniato have underlined «[Alternative material choices] could fail to perform, discolour, create a chemical reaction or even disintegrate over time. Introducing a new material […] requires investment and experimentation»

(Beylerian, Dent and Qu, 2007). Procedures that simplify risk assessment and provide information in risk management decisions might help in materials selections for industrial application.

'Multipurpose' behaviour of sensory analysis

Surface aesthetic properties actively contribute to driving consumer quality perceptions (Piselli *et al.*, 2016; Yanagisawa and Takatsuji, 2015; Falk *et al.*, 2014). Quality and R&D department joint working can help to improve product quality after the material selection phase. In the industrial context, sensory analysis techniques can be employed not only to evaluate consumer preferences, acceptance or perceptions of products and materials. They can be applied in quality control (e.g., quality assurance, raw materials specification, storage stability) (Costell, 2002; Debrosse *et al.*, 2010; Thackston, 2013), product development (e.g., competitor analysis, cost reduction, product sensory specification) (Spence and Zampini, 2006; Llinares and Page, 2007) and research purposes (e.g., analytical/sensory relationships, etc.).

"User-material experience designer"

The fast-changing industrial panorama increasingly calls for multidisciplinary design professionals integrating design thinking and engineering knowledge in developing new products and services. Multidisciplinary professional figures with expertise in product design, materials selection, colour and material trends, sensory and consumer analysis, usability and quality can act as links between different company departments such as R&D, Design, Marketing, Testing Laboratory and Quality. Design researchers with these skills will ensure design products characterized by a user centred-approach, innovative materials and technologies and high quality surface metrics, with a view to cost, manufacturability, aesthetics and performance optimisation.

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