博士論文(要約)

Incorporation of Aesthetic Performance into Material Selection Support Tools

(材料選定支援ツールへの美観性能の組込み)

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Introduction

1.1 Background

Materials play an essential role in architectural design. Despite being the fundamental matter for construction, materials are the medium architects use to define a building's environment and to determine its character. With today's vast diversity and availability of building materials, architects have ample means to explore their designs through materiality. However, material selection can be a complex and delicate task due to the multiple factors that have to be considered when evaluating building materials. Materials are embedded with intrinsic and attributed properties, geometric behaviour and manufacturing constraints, and they must conform to a range of performative requirements within the building's system - technical, functional, environmental, economical, operational, aesthetic, among others.

Computational tools used to assist in multiple criteria material selection processes have been a substantial development. They hinge on extensive databases on material's measurable properties related to their physical behaviour (mechanical, chemical, physical, optical, acoustical and thermal nature), attributed properties (such as life cycle cost, recyclability, safety), and manufacturing processes, and have been proven successful for selecting materials according to various performative requirements. However, when approaching requirements related to aesthetic performance, a problem has been diagnosed: most multiple criteria material selection tools take on an engineering approach, where aesthetic aspects of materials are seldom regarded.

Aesthetic performance relates to the manner in which a material successfully accomplishes the task of responding to the sensory and aesthetic requirements of a design. It is concerned with our sensorial perceptions and responses to materials - its appearance and feel - and is attributed to aspects of roughness, color, transparence and such. In the design domain, the materials' aesthetic and sensory behaviour are just as important as meeting technical requirements (Ashby & Johnson 2002; Malnar & Vodvarka, 2004; Pallasmaa, 2005; Wastiels & Wouters, 2008; Karana, 2009), thus multiple criteria material selection tools should include such aesthetic-related performance in order to establish an approach that could be more useful within the design process of architecture and, consequently, could become a more holistic material selection system. The question is: how to address and empirically evaluate aesthetic performance criteria of materials as to include it in multiple criteria material selection tools?

1.2 Opportunities in Material Selection

Architecture is congenitally bound to materiality, since materials are what transform architects' concepts into formal tectonic. The array of materials available today may raise dilemma on translating ideas and intentions into buildable matter. However, it also raises multiple design opportunities. Material selection focused on the aesthetic and sensory characteristics of materials can help embody the desired perceptual qualities in a design. When experiencing a building, the user's senses are aware of the materials that constitute that space. Users feel the texture of the materials, see the colors and how the materials interact with the environment. By developing a conscious approach to materials, architects can create a critical framework to analyse, conceptualise and contextualise their architecture through materiality.

Material availability and usage have a strong impact in the development of architectural forms, but in order for an architect to explore the potentialities within materials, he must consider its application possibilities, physical behaviour, and performative aspects embedded in them. Materials are the medium to imagine, design and build environments that can be functional - yet rich in meaning. They generate multiple experiences, and have great influence in the user's perception of space. Therefore, when appointing materials, the architect does not only consider the material's technical properties, but should equally consider their sensorial perception and aesthetic characteristics, since these aspects directly affect the way people perceive, use, relate and experience a built environment. Consequently, a conscious approach to material selection generates opportunities to create more user/context sensitive designs.

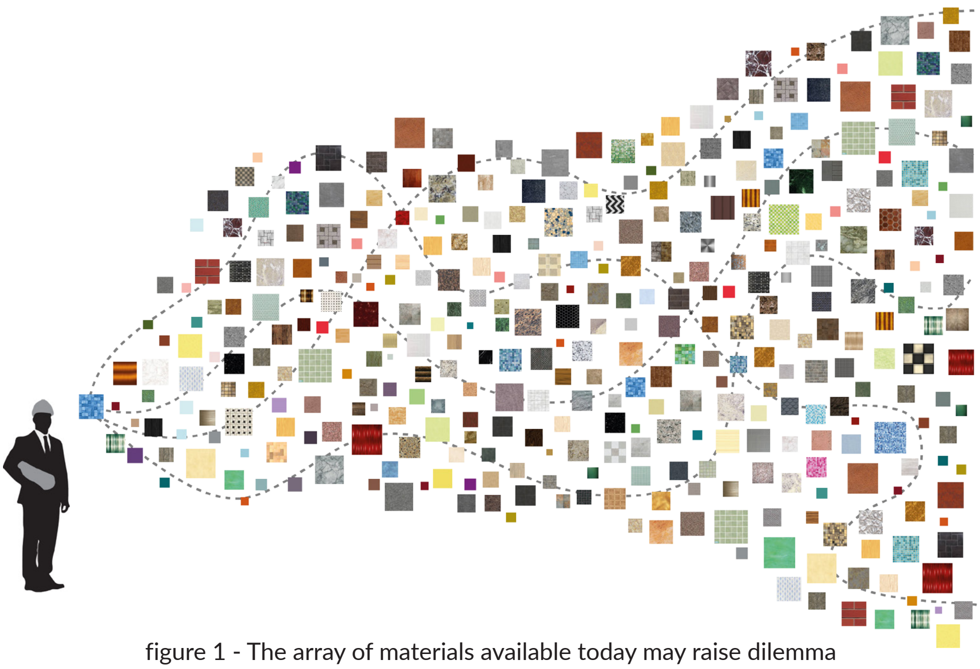

figure 1 - The array of materials available today may raise dilemma on translating ideas and intentions into buildable matter

1.3 Research Objective

Material properties are defined by the material's chemical composition, atomic structure and manufacturing technique. They are the intrinsic and measurable aspects of materials that relate directly to their physical behaviour - mechanical, chemical, physical, optical, acoustical and thermal nature. These properties are what determine the material's attributes, performance and application within a building system.

Most existing multiple criteria material selection tools and databases are based on material science and engineering models, where thorough information on physical properties useful for specifying material's technical performance can be assessed (Wastiels & Wouters, 2008). They have also been proven useful to specify material's functional performance related to environmental, economical and operational issues (Mangonon, 1999; Ashby, 2005). However, when regarding material's aesthetic performance, these tools lack an objective approach that could be more useful for architects.

To reach a desired aesthetic performance - the identity and appearance the architect wants to transcribe into a project - a material has to be selected depending on its set of properties in relation to its sensorial and aesthetic characteristics. Although these characteristics are directly related to materials' physical properties, they need specific parameters of interpretation, which are not fully explored by existing selection tools and databases. As a consequence, architects are more inclined to either reach to material samples to explore these attributes more intuitively (Wastiels & Wouters, 2008), rely on previous experience or in easily accessible sources of information - like books, magazines, catalogs, etc - which are less objective and structured methods. Unfortunately, this may lead to inappropriate materials selection, with unforeseen outcomes. A systemised procedure for material selection is therefore indispensable if the choice is to be made responsibly, with reduced time and efforts, but also with the assurance that no possibility is overlooked.

The objective of this research is to explore the issues that could make the material selection process more effective in the sense that leads to a more informed and systematic approach in architecture. The question is: Can a concept for an improved material selection process with a holistic approach be developed? It entails that in order for the material selection process to be able to respond to all building's demands, it has to be improved in a way to consider evaluating materials for all relevant performative requirements, where emphasis is given to functional and technical aspects as well as to considerations on aesthetic and sensory perception. Therefore, by incorporating aesthetic performance into existing multiple criteria material selection tools that appraise technical issues, a framework towards integrating and balancing these different issues in selection may be achieved. This concept aims to assure materials will not only fulfil its function, but will also provide positive user experience and aesthetic appeal within the building, without overlooking other performative issues such as cost, energy, resources, etc.

1.4 Methodology

In order to set a balance between functional and aesthetic aspects in material selection, a method for the incorporation of aesthetic performance into multiple criteria material selection tools is proposed. At first there was a need to identify which sensorial aspects are attributed to the aesthetic performance of building materials. Literature review on research developed on the subject provided an extensive and diverse assessment for establishing the relevant aspects for defining what will be called the sensory/aesthetic attributes of materials. Following, the correlation of the sensory/aesthetic attributes of materials and their physical properties was studied. Our sensory perception of materials is a combination of perceptions of numerous material properties (Chen et al., 2009), therefore, it was necessary to find the relevant and dominant physical properties that corresponds to the sensory/aesthetic attributes of building materials so that the two domains can be bridged.

Next, critical analysis of the methods used by architects to seek for information on materials, how the overall process of material selection takes place, and an investigation on the existing computational tools and databases for material selection was carried out in order to establish what issues have been overviewed and should be contemplated in a concept for an improved material selection process.

Subsequently, a tool for selecting materials according to their aesthetic performance is proposed. It will have an add-on format - a computer software component that adds features to an existing program. The idea is that this tool will complement existing computer aided multiple criteria material selection programs by adding on the selection criteria of aesthetic performance. It will operate by utilising materials' physical properties information available on the existing program's database to correlate with the desired parameters for the sensory/aesthetic attributes, resulting in a practical resource of information and holistic material selection system.

The development of this add-on tool started by the examination of the quantitative data on the physical properties related to the sensory/aesthetic attributes that were chosen to categorise aesthetic performance. It will take place through instrumental measurements of building material samples as to acquire detailed in-sight on the implications involved in the method of incorporating aesthetic performance into multiple criteria selection tools. These experimental process and findings will contribute to establish correlations between quantitative and qualitative data sets, and determine if the chosen sensory/aesthetic attributes are able to define aesthetic performance. The results were subsequently synthesised into parametrical inputs to enable the aesthetic performance criteria of building materials to be assessed with the add-on tool. Finally, a comprehensive design for the interface of the tool was proposed, and its success was tested in the last stage of this proposed methodology as to confirm its validity.

This holistic material selection concept aims to attend the specific needs of professionals within the design process of architecture, such as architects, engineers, contractors, consultants, clients and other stakeholders, as well as aid to increase mutual understanding and to form consensus among them when selecting materials for a project. A material selection tool that incorporates aesthetic performance is, therefore, potentially of considerable value.

1.5 Scope

In the process of designing a building, the act of selecting materials is not only conducted by the architect. Clients, engineers, contractors, consultants also influences the selection process significantly, although each has their own concerns and motivations. For example, engineers tend to choose materials based on their structural performance, contractors for their feasibility and workability, and consultants for their availability. When it comes to clients, selection involves practical concerns such as materials' cost, quality and durability. However, clients and architects share common concerns on the perceptual aspects of materials related to sensorial and aesthetic considerations.

Many scientific papers have been published on research about the qualitative aspects associated to the aesthetic and emotional expression of materials and their relationship to physical properties. Studies in the field of product design claim that the "meaning" of materials influences the usability and personality of a product (Ludden et al. 2008; Karana, 2009; Karana & Hekkert, 2010). Materials can evoke emotions of desire, joy, disgust, sadness (Crippa et al., 2012), or can be considered elegant, futuristic, masculine, toy-like (Karana & Hekkert, 2010). In the field of architecture, studies claim that the emotional expression of materials determines how users perceive the overall atmosphere of a building (Wastiels et al.,2007; Wastiels & Wouters 2008), where materials can be described as being trendy, luxurious, energetic, old-fashioned, etc (Wastiels et al., 2013). However, these researches are based on particular case studies. They recognise that the emotional expression of materials is intangible and of undefined quantitative value (Crippa et al., 2012), and that emotional reaction to materials differ from every person, being influenced by particularities such as mood, preference and culture (Wastiels et al.,2013).

The present research, as opposed to these existing qualitative studies on the theme, aims at a method to select materials according to aesthetic performance requirements in the way to match peoples' expectations to materials' aesthetic in relation to sensory perception. This approach will follow the proposed definition that sensory/aesthetic attributes are those that can be distinguished tactually and visually, and that have direct correlation to the physical properties of materials, such as a smooth texture, a blue color, or a distinct pattern. This correspondence to the physical properties permits the sensory/aesthetic attributes of materials to, therefore, be objectively and quantitatively appraised, and will enable the hard data to be used as parametrical inputs to select materials according to their tactual and visual characteristics within the selection tools. Ultimately, its add-on format will conveniently allow the assessment of aesthetic performance criteria together with other performance requirements, rendering a more integrated material selection system.

1.6 Significance of Research and Originality

People's experience of architecture is essentially multi sensory (Pallasmaa, 2005), where the materials that shape a built environment will have a direct impact on the user's perception of space (Chen et al., 2009). Consequently, a conscious approach to materiality can create more user/context sensitive designs, where material's characteristics - its properties and attributes - intermediate this relationship. These characteristics are the point of convergence between the disciplines of design and engineering (Rognoli, 2010), and therefore should be considered during any material selection process (Zuo et al., 2004).

The existing material selections tools have been, in general, developed within the field of engineering, where objectives and constraints are generally determined by requirements related to technical performance (Ashby & Cebon, 2007), and material selection corresponds to this criteria. In architecture, however, besides fulfilling such technical requirements, materials must also be appealing to the senses and assist in defining the character of the building. The process of selecting the most suitable materials for a new design project is therefore based on sensorial descriptions, which implies an assessment of the aesthetic and perceptive values of materials.

This thesis therefore, seeks to define the sensorial and aesthetic perceptual categorisation of materials through a quantitative and comparative evaluation. Although it may seem contradicting, all material's characteristics are fundamentally rooted in their physical properties. Our human senses are designed to recognise these properties - which are the same that can be measured instrumentally. Various authors and scholars have engaged this subject, specially in the field of product design, where the methodology consisting largely on surveys. However, this human-centered perspective on materials still remains underestimated as a subject of study, specially in the field of architecture, where the selection of materials is such a vital part of the design process and building construction.

The methodology used for the incorporation of aesthetic performance into multiple criteria material selection tools proposed in this thesis attempts to amplify the scope of material appraisal by using scientific procedures to explore these perceptual attributes of materials that are largely ignored by the material selection tools. As opposed to the survey methods used in previous research on the theme, the approach implemented in this thesis aims to establish an objective strategy, and to ensure this research's originality. It will contribute to demonstrate that materials can have other profiles of categorisation than of traditional engineering, which help assist in non-technical appraisal and communication between different stakeholders involved in any design project. It will also contribute to demonstrate how the interaction between physical properties leads to specific sensory/aesthetic attributes, and how these could be manipulated to produce customised materials that attend better to demand profiles for new products within the material manufacturing industry.

1.7 Thesis Outline and Structure

The structure of this thesis is organised in three main parts, that were developed along seven chapters (figure 2).

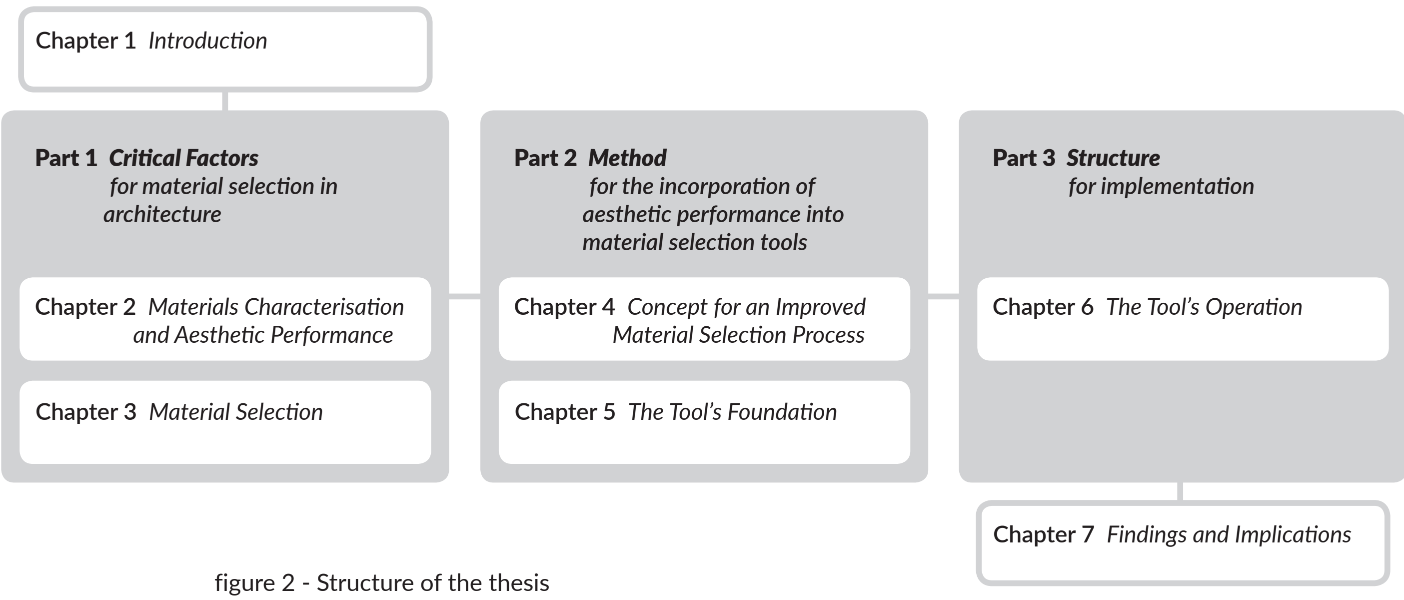

figure 2 - Structure of the thesis

Part 1 intends to explain the context of this research through outlining the critical factors for material selection in architecture. It describes the essential role that materials play in architecture design, and how materials are characterised, as to provide a conceptual clarification of the terminology for material appraisal used in this thesis (Chapter 2). Furthermore, a bibliographical investigation on material screening and selection methods, and on digital databases and material selection softwares aimed at providing information for establishing the important elements for an improved material selection process for architecture (Chapter 3).

Part 2 presents the proposed methodology for the incorporation of aesthetic performance into material selection tools. Based on the examination of the critical factors for material selection in architecture identified in Part 1, Part 2 primarily outlines the approach for an improved selection framework. The aim is to arrive at concept that may be a more appropriate for the architectural design process and the involved stakeholders (Chapter 4). Consequently, the proposition of a tool for assessing aesthetic performance by selecting materials according to their sensory/aesthetic attributes is explained. Details on the implications involved in this assessment are presented and described (Chapter 5).

Part 3 depicts the structure for implementation of the proposed tool. The implications of the tool as an operational system are discussed, and an evaluation is proposed for assessing its validation. This assessment aimed at understanding the situation in which the tool would be effective for improving the framework of material selection in architecture (Chapter 6).

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| PART 1 |
CRITICAL FACTORS FOR MATERIAL SELECTION IN ARCHITECTURE

Part 1 explains the context of this research through outlining the critical factors for material selection in architecture. It describes the essential role that materials play in architecture design, and how materials are characterised, as to provide a conceptual clarification of the terminology for material appraisal used in this thesis (Chapter 2). Furthermore, a bibliographical investigation on material screening and selection methods, and on digital databases and material selection softwares aimed at providing information for establishing the important elements for an improved material selection process for architecture (Chapter 3).

I CHAPTER 2 I

Materials and Aesthetic Performance

Other than contributing to the technical qualities of a building, materials have a great impact on how users perceive architecture. In literature, many acknowledge the significant role of materials in defining a building's environment and determining its character (site). This chapter explains the importance of a conscious approach when assigning materials and briefly explains material's characterisation. It also provides a conceptual clarification of material sensory perception and aesthetic performance, and defines the terminology for material appraisal as used in this thesis.

2.1 Material's Essential Role in Architectural Design

Architecture is congenitally bound to materiality, as materials are the basic physical matter for shaping our environment. History of man-kind can be explained through the use and development of materials - the Stone Age, the Bronze Age, the Iron Age and the Steel Age - thus showing the importance of materials for our evolution. As for building materials, they evolved from our basic need of shelter to our constant desire for improvements, playing a crucial role in the development of architecture.

The materials available and used since pre-history all occur naturally - wood, bones, skins, stone. Man only had to be creative and adapt them to their needs. The earliest man-made materials were simple composites: adobe and pottery. With time and by observing some of nature's chemical processes, man was able to mimic the confection of glass and cement. Further and more significant material development came with thermo-chemistry, and later with polymer chemistry and the industrial revolution. In the last 20 years, it is estimated that more new materials have been developed than in all history combined (Brownell, 2006).

This array of materials available today may raise a dilemma: architects need to consider its application possibilities, physical behaviour, manufacturing constraints, cost and the building's performative requirements when appointing them. However, it also raises multiple design opportunities. Herzog & de Meuron's architecture practice expresses a creative inspiration brought by materials: "Our work has always been conceived to appeal to all five senses, consciously involving also tactile issues and even smell. This clearly demonstrates that we believe in an architecture that stresses its material and physical conditions to perform successfully, in conscious contrast to an architecture based on illustration and imagery." (Herzog, 2002) Numerous building projects by architects such as Kengo Kuma, Ryue Nishizawa, Peter Zunthor, and Rafael Aranda, Carme Pigem & Ramon Vilalta (RCR Arquitectes) also demonstrate how the choice of material's not only serves to accomplish constructive requisites, but also directly influence the building's character and how the user experiences it (figures 4,5,6,7). This concerns technical aspects related to material's expansion coefficient and permeability, and also aspects such as the material's texture or translucency. By developing a conscious approach to materials, architects can create a critical framework to analyse, conceptualise and contextualise their architecture through materiality.

figure 03 (top) - Great Bamboo Wall by Kengo Kuma © Satoshi Asakawa
http://kkaa.co.jp/works/architecture/great-bamboo-wall/
figure 04 Teshima Art Museum by Ryue Nishizawa

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figure 05 (top) - Therme Vals by Peter Zumthor © Helene Binet http://www.helenebinet.com/photography/architects/peter- zumthor.html
figure 06 - Les Cols Pavilion by RCR Arquitectes © Erieta Attali http://www.erietaattali.com/architectural-photography/rcr-architects/les-cols-pavilion-olot/

"An architect's design intention, and the materials used to realise it are inextricably bound up with each other" (Wastiels et al. 2013). Materials are the medium to imagine, design and build environments that can be rich in meaning, generate multiple experiences, and have great influence in the user's perception of space. Authors such as Rasmussen (1962), Auping & Ando (2002) and Pallaasma (2005) write about how the experience of architecture is multi sensory, highlighting the importance of architects' to develop the sensibility to foresee how people perceive space and materiality. Architects should be conscious and consider the potential of design and material decisions in manipulating of sensorial and aesthetic qualities.

Different materials express and evoke distinct sensorial and aesthetic qualities, as figures 4, 5, 6 and 7 clearly illustrate. A building space composed of wood will have very different visual hues than a concrete walled space. Another composed of stone will feel much rougher to the touch than a glass cladded one. Hence, a user's perception and evaluation of space is influenced by numerous aspects brought about by the materials selected to compose it. This is the reason why, when appointing materials, the architect should not only consider the material's functional and technical performance. Sensorial perception and aesthetic characteristics should be equally considered, since these aspects directly affect the way people perceive, use, relate and experience a built environment. Consequently, a conscious approach to materiality can create more user/context sensitive designs.

2.2 Materials' Characterisation

Material research in applied sciences is concerned with behavioural and functional aspects of materials and their application - with materials science focusing on the "why" and engineering on the "how" (Addington & Schodek, 2005). Both fields are centred around understanding, investigating, examining and determining materials characterisation. This characterisation is defined by the material's chemical composition, structure, properties, attributes, processing and manufacturing, and are used to predict how the material will perform in specific applications. These are important issues to apprehend when aiming for a more conscious approach to material selection in architecture as they can direct affect on building designs.

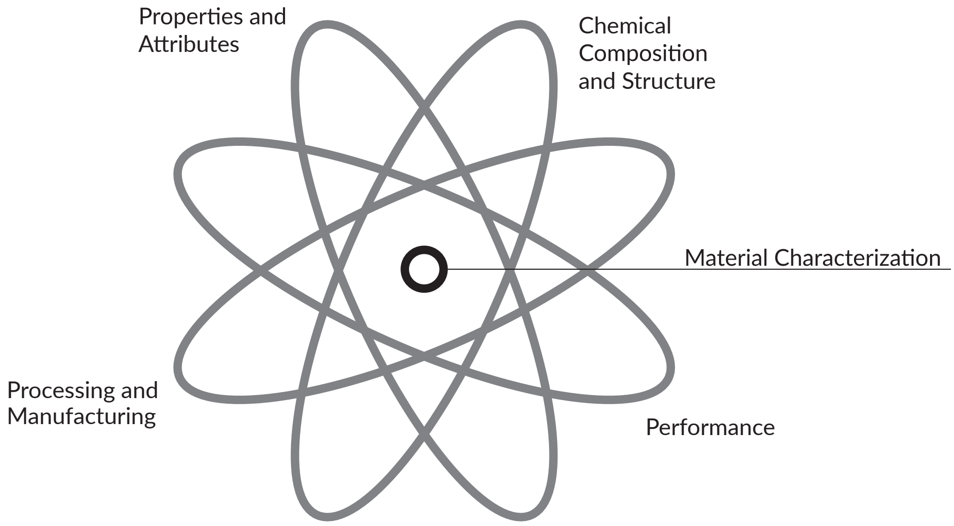

figure 07 - Fundamentals of material's characterization

Material's structure concerns the way in which its atoms and molecules, and their arrangement, affects its behaviour and influence on the material's properties. It can be examined in 4 different levels in accordance to the hierarchical constitution of materials. The configuration of the atomic structure and nanostructure is what constitutes the essence of matter, such as the chemical and mechanical properties. The microstructure of a material is what classifies them into metallic, polymeric, ceramic and composite, and influences their bulk and physical properties. Material's macrostructure is the what we see with our naked eyes, and it influences the material's physical, bulk and surface properties (Askeland & Fulay, 2006).

Material's properties are defined as the measurable physical characteristics of materials. They are inherited by the material's structure, resulting in characteristics that relate directly to the material's physical behaviour in relation to its nature. Physical properties are those that can be determined without changing the composition of a material - e.g. density, solidity, porosity, hygroscopy, frost resistance. Furthermore, the terminology "physical properties" can also be used customarily to define the specific properties of materials under particular strain, and are the ones engineering tends to focus on. They are indicated by instrumental measurements, which renders them quantitative values to be used as metrics when materials have to be compared, and follow specification standards in manufactured materials:

- Mechanical properties relate to how materials behave when subjected mechanical stress - e.g. hardness, elasticity, plasticity, yield strength, creep, fatigue, stiffness.
- Electrical properties relate to how materials behave when conducting electric currents - e.g. capacitance, permittivity, resistivity, conductivity.
- Magnetic properties relate to how materials respond to magnetic fields - e.g coercivity, diamagnetism, hysteresis, permeability.
- Optical properties relate to the material's interaction with electro-magnetic radiation - e.g. radiation transmission, light reflection, refraction, scattering.
- Thermal properties relate to the materials behave when subjected to transfer and storage of heat - e.g. thermal conductivity, melting temperature, flammability, expansion coefficient.

Sets of properties define the attributes of materials, or property-profile. Attributes are used to qualify materials and define their terminology into families or classes - e.g metals, ceramics, glasses, polymers (Ashby & Cebon, 2007). Terracotta tiles and bricks, for example, are part of the same ceramic family for their chemical composition, and for carrying the same attributes of being hard, brittle and corrosion resistance. Aluminium and steel are from the metal family, and have the attribute of being ductile, tough and electrical conductors. Moreover, attributes are used to appraise the material's efficiency for specific applications in the fields of engineering, design and architecture.

The way materials are processed and manufactured also have a great influence on its properties and application. Processing, or synthesis, involves the manipulation and/or creation of a material in a nano/microstructure scale. Many raw materials obtained in the environment need to undergo processing to be able to acquire the necessary structure to perform. Mixing different raw materials may also be necessary in order for a specific composition to obtain the desired properties for a material. Manufacturing, on the other hand, involves processes in a macrostructure scale as to adapt the material to specific properties, geometries, and/or appearance as to make components or products. Many building materials don't need to synthesised, like woods and rocks, but all must go through manufacturing processes to become suitable for application in construction, resulting in a direct effect on the material's surface properties. Most building materials are manufactured to have planar/sheet/film, volume/block, or tube/profile geometries, and go through finishing processes to protect the material against deterioration, to produce special characteristics for the surface such as reflectivity or insulation, or to give the material special decorative effects.

All these factors are responsible for outlining the characteristics of materials. Furthermore, they are used to analyse their behaviour in terms to predict their service performance. In engineering, performance relates to the material's ability to conduct itself properly in relation to its application. In architecture however, this definition has a broader connotation, since materials must also attend a range of specific performance requirements to the field. Performance is the ability and efficiency of which a task can be fulfilled, and the right choice of materials ensures the successful implementation of the building as a system, in the way that it must fulfil functional, technical, environmental, economical, operational and aesthetic requirements - among others. Materials' attributes, and consequently their properties, are directly associated to materials' performance, as they determine that materials carry out their intended requirements.

2.3 Aesthetics and Aesthetic Performance

2.3.1 Defining Aesthetic

The concept of aesthetics originates from the concept of sentiment and taste, and is used to designate judgement, experience and value (Shelley, 2015). As a branch of philosophy it explores the nature, expression, creation and appreciation of beauty, and of subjective and sensory-emotional values (Zangwill, 2014). However, its meaning can differ depending on the perspective of approach. Formal aesthetics is often what artists and designers strive to provide with their work. It is concerned with the experience of pleasure, delight or appeal initiating from the sensory channels, in relation to shape, colour, texture, proportion and spacing - and their combination. When it is said that a shape is pleasant, a color is beautiful, or a texture is soothing, it is because the shape, color, and texture provide stimuli to the sensory organs such as the eyes and the skin, and evoke associations in the brain which are the core of aesthetic appreciation.

2.3.2 Defining Aesthetic Performance

In literature, Manzini (1986) was one of the first authors to write about aesthetics of materials and their performative role in shaping positive user experiences. He was followed by Ashby and Johnson (2002), who proposed aesthetic attributes should be added as a criteria when appraising materials. In their definition, aesthetic attributes relate to sensorial aspects of perception and response - the material's appearance, feel, smell, sound - and are ascribed to aspects of warmth, softness, roughness, colour, transparence and such.

Zuo et al. (2004) research addresses the issue more extensively. They claim that aspects related to sensation, perception and aesthetics of materials conceptually overlap. These aspects are connected in a subjective-objective interaction, and are characterised by sensorial attributes perceived by humans via sensory organs, and that evoke physiological and psychological responses. The objective interaction refers to the content of the sensory attributes, like a smooth texture, a blue colour, a natural odour or an irregular pattern, which exists physically and have direct correlation to the physical properties of materials. The subjective interaction refers to the interpretation of the physical property, which is the result of the sensory perception being processed in the brain. It refers to the result of psychological processes involving context, memory, meaning and judgment.

Much research on the theme of the subjective interaction with materials followed and evolved into studies on aspects associated with their aesthetic and emotional expression. Within the field of product design, studies claim that materials have "meanings" which influences the usability and personality of a product (Ludden G et al., 2008; Karana, 2009; Karana & Hekkert, 2010; Crippa et al., 2012). Materials can evoke emotions of desire, joy, disgust, sadness (Crippa et al., 2012) or be considered elegant, futuristic, masculine, toy-like (Karana, 2009; Karana & Hekkert, 2010). In the field of architecture, studies claim that the emotional expression of materials determines how the users perceive the overall atmosphere of a building (Wastiels et al.,2007; Wastiels & Wouters 2008), where materials can be described as being trendy, luxurious, energetic, old-fashioned, etc (Wastiels et al.,2013). These researches attempt to correlate these expressions of materials to their physical properties. However, they base themselves on particular case studies, and recognise that the emotional expression of materials are intangible and of undefined quantitative value (Crippa et al., 2012), and that emotional reaction to materials differ from every person, being influenced by particularities such as mood, preference and culture (Wastiels et al.,2013).

At this point, there is a need for the conceptual clarification of aesthetic performance that will be adopted in this thesis. The author considers that aesthetic performance relates to the manner of which a material successfully accomplishes the task of responding to the aesthetic and sensory requirements of a design. Therefore, when targeting aesthetic performance, architects should focus on the aesthetic and sensorial characteristics/aspects of materials that will communicate their intentions into their design, and that may be appreciated by its users. As the discernment between aesthetic and sensorial aspects is not so clear, this thesis proposes to adopt a united term sensory/aesthetic attribute to describe the objective perceptional characteristics and responses to materials which exists physically and have direct correlation to the physical properties of materials. Previous studies revealed that sensorial experience related to visual and tactual aspects of materials are prioritised over olfactory and auditory interactions (Schifferstein & Spence, 2008; Nefs, 2008;

Karana, 2009). Therefore, the sensory/aesthetic attributes will be related only to tactual and visual aspects as they are deemed more relevant to the appraisal of materials regarding judgement and value. In sum, to reach the desired aesthetic performance - the character and appearance the architect wants to transcribe into a project - a material has to be selected depending on its set of physical properties in relation to its sensory/aesthetic attributes. Table 1 shows he terminology of material descriptions as used in this thesis:

table 1 - Terminology of material descriptions as used in this thesis

physical properties	the measurable physical characteristics of materials - e.g. density, elasticity, stiffness
sensory/aesthetic attributes	defined by the correlation to sets of physical properties, relates to characteristics of materials that describe their sensory perceptional characteristics and responses in relation to aesthetic - e.g. translucency, color, texture
aesthetic performance	defined by the sensory/aesthetic attributes, relates to the manner of which a material successfully accomplishes the task of responding to aesthetic and sensory requirements of a design

2.3.3 Assessing Aesthetic Performance

It is of significant importance to consider all aspects of materials when appointing them for specific applications. The information about the sensory/aesthetic attributes of materials is equally important to be considered in comparison to the technical properties of materials, and has the potential to be more objectively explored. Physical properties such as stiffness, porosity and photosensitivity are usually assessed to foresee how a material will perform technically, but not to how it will be perceived by the people that experience them (Wilkes et al., 2015). In order to be able to assess aesthetic performance systematically, it is necessary to focus on the objective manifestation of the sensory/aesthetic attributes in correspondence to their actual demonstration as physical properties. This correspondence will allow the sensory/aesthetic attributes to be evaluated quantitatively, permitting the aesthetic performance criteria of materials to be empirically assessed.

2.3.3.1 Identifying the Sensory/Aesthetic Attributes Related to Aesthetic Performance

First, it is important to identify the sensory/aesthetic attributes that are related to aesthetic performance. Studies developed by Johnson et al. (2003), Zuo & Jones (2005), Van Kesteren (2008), and Rognoli (2010) have made contributions for establishing which aesthetic and sensorial aspects are relevant to be considered when appraising materials. All sensory/aesthetic attributes found to be used by these authors to appraise materials are listed in table 2. Note that the sensory/aesthetic attributes are usually denominated semantically by a pair of antonym adjectives, which are used to define the criteria of discernment, representing the two extremes of the attribute.

table 2 - List of attributes found to appraise sensorial and aesthetic aspects of materials

author	sense/relation	sensory/aesthetic attributes
Johnson et al. (2003)	vision/optics	transparent/translucent/opaque
		reflective
	vision/color	clear color
		muted color
		bright color
		white/grey/black
	touch/feel	smooth/rough
		organic/angular
Zuo & Jones (2005)	vision/optics	shining/non-shining
	touch/feel	plain/bumpy
		smooth/rough
		regular/irregular
		repetitive/non-repetitive pattern
		simple/complex
van Kestern (2008)	vision/optics	reflective/not reflective
		glossy/matte
		transparent/translucent/opaque
		brilliance/no brilliance
		rough/smooth
		regular/irregular texture
	vision/color	hue of color
		one color/ many colours
		monochrome/multicolour
		dark/light
		pattern
	touch/feel	smooth/rough
		regular/irregular texture
Rognoli (2010)	vision/optics	transparent/translucent/opaque
		gloss/matte
	touch/feel	smooth/uneven

2.3.3.2 Correlating the Sensory Attributes to Physical Properties

Following, it is necessary to focus on the objective evidence of the sensory/aesthetic attributes, which refer to their actual physical demonstration, like a red color or a coarse texture. Some sensory/aesthetic attributes of materials, like color, can be correlated into equivalent measurable properties. However, most sensory/aesthetic attributes are influenced and defined by underlying sets of parameters, being a combination of the perception of numerous physical properties, which can derive from the material's bulk or surface structure. In that case, the relevant and dominant properties that corresponds to the sensory/aesthetic attribute of building materials needs to be determined so that the technical and non-technical domains can be bridged. Information on these correspondences needs to be researched in books and handbooks on material science and engineering, and will be addressed in Chapter 5.

2.4 Discussion

People's experience of architecture is intrinsically multi sensory in nature (Pallasmaa, 2005), where the materials that shape a built environment will largely influence the user's perception of space (Wastiels & Wouters, 2008). Materials cannot just be considered elements that can be classified by numbers and datasheets (Ashby & Johnson, 2002). They need to be approached as a means that directly affects the way people perceive, use, relate and experience a building. Consequently, a conscious approach to materiality can create more user/context sensitive designs.

This thesis proposes that a systematical approach to materiality could be attained through the assessment of the sensory/aesthetic attributes of materials that subscribe to aesthetic performance. It is through these attributes and the physical properties that correspond to them that materials are experienced in architecture. By evaluating them, it becomes possible to recognise how users' sensory and aesthetic expectations can be fulfilled.

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I CHAPTER 3 I
Material Selection

With the vast options of building materials available today, architects are in the risk of overseeing the potentialities that this diversity has to offer. In the previous chapter the role of materials in architecture, and the complexity of characterising materials and aesthetic performance was explained.
The aim of this chapter is to conduct a critical analysis of the methods used by architects to seek for information on materials, how the process of material selection takes place, and display an overview on the existing computational tools for material selection: what kind of tools exist, how they function, what are the considerations in the selection, and if they are suitable for selecting materials for architecture. A bibliographical investigation was performed on material screening and selection methods, and on digital databases and material selection softwares. This information will be helpful to establish the important elements for an improved material selection process.

3.1 Designating Materials

As described in the previous chapter, material sciences defines and designates materials based on their composition, where the material's structure and properties classifies them into broad descriptive categories of families such as metals, ceramics, polymers, etc. This leads to the comprehension of the specific attributes/qualities that characterise every material. The field of engineering designates materials according to their application, focusing on how they can accomplish the requirements towards product performance.

Within the field of architecture, material designation is institutionally oriented towards attending building codes and standards requirements. Indexing and classification systems adopted by organisations such as Royal Institute of British Architects (RIBA), and the North American Construction Specifications Institute (CSI) define codes that revolve around generic classification and common uses of materials. They provide tables that arrange building materials according to their shape - e.g. tiles, panels, films, blocks, profiles, tubes, wires - their substance - e.g., wood, glass, concrete, metal - and their function - e.g structural, cladding, flooring. This only serves to account to what a material is useful for, and to where it should be applied (Wastiels, 2010).

Each discipline has its own reasoning that correspond to their concerns and necessities in relation to materials. However, indexing and classification systems used to designate materials in architecture do not seem to correspond to the design process of architecture, assist in material selection, nor reflect the advancements of the material industry. Considering material's essential role in architectural design and the array of opportunities in selecting materials, architects are more inclined to designate materials according to their behavioural qualities and performance.

3.2 Material Selection - A Problem Solving Activity

Selecting materials for a design project is a crucial undertaking within the design process of architecture. Materials selection is an activity that architects perform from the moment a new project is assigned, until the materials are specified in document as to how they will be implemented in a building. To select from the array of material choices available today, information is needed on all their aspects. Materials are embedded with intrinsic and attributed properties, geometric behaviour and manufacturing constraints. They must attend a range of performative demands within the building's system, and will furthermore, directly affect the way people perceive, use, relate and experience the architecture. These issues can be tackled individually when making decisions, but most often they are interrelated and should be considered holistically. A good example of this interrelation is the difference between carbon steel, stainless steel and titanium: "stainless steel has good corrosion resistance, for which carbon steel is not compatible, but carbon steel has better manufacturing flexibility particularly in welding, and is cheaper than stainless steel; titanium alloys are even better than stainless steel in corrosion resistance, with a slightly darker tone of grey and more elegant color, and are also much lighter in weight, however they cost much more." (Zuo, 2010) Consequently, material selection is considered a problem solving activity (Ashby & Johnson, 2002) since it deals with substantial and continuous flow of information (Pahl & Beitz, 1996). When designing, architects need to integrate these different inputs and considerations. Seeking for information on materials is the first step of the process.

3.2.1 Acquiring Material Information

Architects use various ways and sources to obtain information on materials. The initial purpose is to get acquainted with the different options and characteristics of the materials available today. To seek information is a crucial part of the problem solving activity of selecting materials, and it assists at reducing uncertainty about a relevant topic (Rouse & Rouse, 1984). The following is an investigation on the traditional sources of information architects make use as to show the array of options, and the intricacy, time and effort involved into this activity.

Architecture books and magazines portrait completed building projects, where the solution given by the choice of material by another architect may be a source of inspiration or a reveal a solution for a design project. In recent years, a number of books focused on materials and oriented for architecture have been released. They typically present their content structured around material families, as in material science, where materials are grouped by common physical properties and behaviour. Searching for material information on such sources can be a time consuming procedure, since the information on the featured materials is often limited as for inspiration, leading into further investigation in other sources in order to obtain thorough details.

Specialised journals and periodicals focus on a type of material per issue as an editorial theme, usually in a case study format. They give detailed information on the material, types of application, issues of integration, its qualities and common technical problems associated to its installation, and relevant aspects to consider during the design process. Usually suppliers references are included, leading the reader to contact them to obtain further information in concerns to its viability of use.

Suppliers and manufacturers are commonly considered when information on specific materials is needed. This is usually done by getting in touch to a company and having personal meetings with a representative, where samples, catalogs and more detailed information on the materials are provided, or attending events such as fairs, trade-shows or seminars. However, these representatives are affiliated to businesses and are not able to advise on other materials than their own. Setting up and having meetings may also be time consuming.

Architects often rely on professional colleagues as in-house advisors to acquire information about materials from past experience. This type of knowledge transfer is a useful method for a designer to build upon the knowledge of someone who has dealt with a similar situation. Nowadays, many architecture offices also have an individual or group of professionals who have further knowledge related to detailing and construction issues, and act as specialists on technical aspects of material specification.

Specialised material consultants are professional that have deeper, practical and independent information on materials. They have understanding of materials' functional and performance issues, and thus can provide technical and managerial assistance during all phases of the design process. Hiring them can be costly, and depend on the available budget of the project. Setting up and conducting meetings may also be time consuming.

Material libraries are physical collections of material samples. They allow professionals to interact physically with materials, get acquainted with them and develop a sensitivity to their sensory/aesthetic attributes. They also provide a good overview on the range of new materials available today. Usually, the samples are accompanied by digital data entries with detailed information for every material. However, material libraries don't exist everywhere, and they are either located within universities, where only students and alumni can have access to, or they are private initiatives that require membership.

Web-based resources are easy, fast and low-cost providers of information on materials. Architecture websites are a source of inspiration that can be easily assessed in comparison to books and magazines. Many specialised periodicals also have their online version. Material suppliers and manufacturers websites, in comparison to printed catalogs and such, are constantly updated, and its digital format allows the management of information for specification and to be incorporated into drawings.

Digital data sheets and databases on materials found on the internet or in media format can also be assessed to acquire deeper information and compare different types of materials. These sources are structured around technical informations, usually sorted by the material's name, the material's family and the materials' properties. Most of the databases are efficient with their ability on storing and sorting data (Ashby, 2005). However, they mostly require experience in materials or sufficient background knowledge on material properties in order for an architect to comfortably make use of them.

table 3 - Common sources of information on materials used by architects

source of information	examples
magazines	Architect Magazine Detail - Magazine of Architecture + Construction Details Architectural Record Building Design + Construction Magazine
books	Architecture in Detail: Materials (Riera Ojeda et al. (2003) Material Architecture (Fernandez, 2006) Transmaterial (Brownell, 2006) Construction Material Manual (Hegger et al. (2006)
journals / periodicals	Construction and Building Materials - ScienceDirect Concrete Construction American Journal of Construction and Building Materials Journal of Building Materials and Structures
suppliers / manufactures / catalogs	Lixil Asahi Glass Company Acme Brick Company Hering Architectural Concrete
fairs / trade-shows / seminars	Material Xperience - Materials Event for Creative Professionals Batimat - Building and Remodelling Solutions Bau - Trade Fair for Architecture, Materials and Systems
advisors	in-house advisors
consultants	Arup Formas Materials Council
material libraries	Material ConneXion Materia Materials Library at the California Polytechnic State University Materials Library at the University College London
web-based sources	www.architonic.com www.transmaterial.net www.archdaily.com www.archiexpo.com
digital datasheets / databases	in-company databases ASM Material Information Campus Plastics database Prospect Wood database

As problem solving activity, material selection demands the management of all information regarding materials, since there often is more than one option/ solution for a particular application. Architects may use the sources of information mentioned above for inspiration or for initial screening of materials for a project. However, inadequately, they may also use them for selecting materials, along with trial and error experiments, or just by relying on previous experience. When using non-structured information together with the lack of a methodology for selecting materials, only few objective functions end up being considered. Many factors and/or variables are become compromised, making the decision process below par (Jahan et al., 2009). As for hiring a materials' consultant to assist in the material selection, it can be a costly and a time consuming endeavour. Only with the appropriate information on materials and by utilising systematic methods for selection, are architects be able to compare candidates and select the most suitable materials to solve possible design problems, fulfil specific requirements of the project and achieve the desired design concepts.

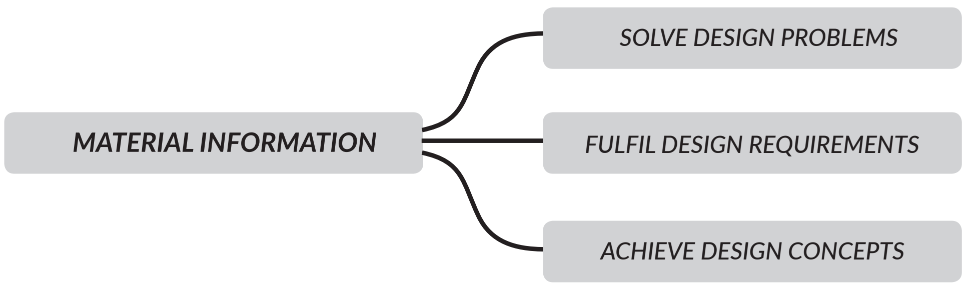

figure 8 - Diagram on how information on materials may assist on the architectural design process.

3.2.2 Selecting Material Candidates

According to Ashby et al. (2007), over 160,000 materials are available today. This great amount of options makes it critical to select them with awareness. Hence that not all these materials are applicable in architecture, but nonetheless, architects must not rely on distinct considerations when selecting materials. The use of systematic methods for material selection intends to assist in this problem-solving activity. Since selection dependents on a diversity of requirements, where there is the need to compare different materials using multiple parameters, which are based on different and often conflicting criteria, systematic methods must consider all aspects of materials in order to come to a rational choice.

Research on material selection methods has traditionally been a domain of the field of engineering, where various authors defined the critical aspects of materials to be considered in the selection process, of which Patton (1968), Farag (1979), Sandstrom (1985), Cornish (1987), Ashby (1992), Lindbeck (1995), Budinski (1996), Charles (1997), and Mangonon (1999). They state that in order for a material to be a good candidate for selection, it must fulfil multiple performance criteria through qualitative and quantitative evaluation of its mechanical, physical, chemical, thermal electrical, acoustical, optical, dimensional and eco properties; service, fabrication and economic requirements; business issues; property, processing and environmental profile; cost and availability.

However, selecting materials is an interdisciplinary endeavour. Besides the prominent inputs from material science and engineering, material selection should also allow the considerations from experts in the field of application (Jahan et al., 2009). Since Ashby and Johnson (2002) acknowledged the importance of aesthetic attributes as criteria to be appraised in material selection, great attention has been drawn to it, leading a lot of research on the subject to be developed in the field of product design. Authors such as Ashby & Johnson (2002), Zuo (2004), Van Kesteren (2006), Karana (2006), Rognoli (2010), and Schifferstein & Hekkert (2011) state that designers need information not only of the physical dimensions of materials, but also on the dimension related to user-experience in order to make an adequate selection of materials for a product. Therefore, they must consider the technical criteria, but should also include sensorial and emotional appraisal of materials through qualitative and quantitative evaluation of their properties.

Unfortunately, not much research on material selection has been developed in the field of architecture. Fernandez (2006) was the only author found to write about a methodology for selecting materials, but he adopts the engineering approach. This fact shows that material selection for architecture is an underdeveloped topic. The present research speculates that it is reasonable that considerations and strategies for selecting materials developed in both fields of engineering and product design can give insight into assigning materials for architecture. Therefore, the approach and methods adopted by both fields were analysed. However, a critical posture was assumed, since each field has specific needs of concern.

3.2.2.1 Selecting Material Candidates in the field of Engineering

As a multi criteria decision making problem, the analytical approach to selecting materials for engineering applications generally begins by setting objectives and constraints for formulating ranking criteria, which are then linked to the properties of materials, as to rate and compare them. The methods rely on accurate information, models and rules, where materials that match the desired criteria are then selected. The criteria are usually determined by the need to minimise cost while meeting product performance goals (Dieter, 1997; Sharma et al, 1993). In 1988, Chiner proposed five steps for a multiple criteria material selection method in which he applied a weighting factors according to constraints and objectives: definition of design in order to establish objectives and constraints , analysis of material properties that are necessary to fulfil the established objectives and constraints , screening of candidate materials by consulting a database for material properties that match the criteria, assessment and decision for optimal selection, completing with tests for verification.

Farag (1979, 2002) also proposed a weighting method , which was defined by three stages of selection based on sets of objectives and constraints: initial screening (through consulting databases), comparing the alternatives, and selecting a material for the optimum solution, where performative requirements are categorised as lower and upper limit properties, and target value properties. In his approach, relative importance of criteria was calculated by multiplying the numerical value of the property by the weighting factor, where imposed limits can eliminate materials. Following, the imposed limits can be used to optimise the selection within the materials that remained. Farag also classified performative requirements of material into rigid requirements, which should be met by the material, and soft requirements which are subject to negotiation and trade-offs.

Ashby is probably the author who has written the most about material selection for both fields of engineering and product design. When selecting materials for engineering design, he suggests that the best approach is the multi objective optimisation method, where a number of conflicting metrics (e.g. volume, mass, power-to-weight ratio, energy, cost) of performative requirements for a product needs to be optimised (Ashby, 1999). In 1992, he developed a material selection system that focuses on data modelling through scatter plots. Based on a database, the plots compare the ratio of two or more properties of materials or of families of materials, which can be easily visualised and evaluated. Ashby later developed a chart method for optimum material selection through performance indices, where three different sets of variables are input: the inherent properties of materials as the constraints (e.g. density, conductivity, melting temperature), changeable variables (applied forces such as tension or bending), and limits imposed by the design as the objectives. The chart numerically quantifies how desirable the material is in performance indices, through demonstrating the attributes that characterise performance for a specific application (Ashby, 1999).

In 1993, Sharma et al. were the first to propose an expert system as a multiple criteria decision making method based on TOPSIS (Technique for Order of Preference by Similarity to the Ideal Solution) for selecting materials. TOPSIS is an improvement to additive weight methods, which requires the input of information on relative importance to be considered in the selection process in respect to one another. When used in material selection, the input would be the database's information on attributes of materials, and the user would provide an index of relative importance for different attributes according to his/her performance goals. However, the problem with using only TOPSIS is that users may not arrive at the same conclusion due to their different rating technique even though they have the same performance goals, affecting the final result. Their expert system provides margins of comparison so that users can arrive at values of relative importance of the attributes and get uniform results.

3.2.2.2 Selecting Material Candidates in the field of Product Design

As considerations on non-technical issues related to materials started to gain interest, scholars in the product design domain have developed material selection techniques to guide designers in the creation of sensory and emotional experiences through their choices of materials. Ashby & Johnson (2002) propose that selecting materials for product design "involves converting a set of inputs - the design requirements - into a set of outputs - a list of viable materials and processes". In order to do so, they propose four methods with different strategies and information needs. In the analysis method, the most systematic of the methods, information about characteristics of materials are screened from a database to match the performance metrics of the product requirements according to non-technical objectives and constraints. In the synthesis method, information on experience and analogy of previously solved problems is assessed to match the product's requirements (of intention, aesthetic and perception), and then a material database needs to be investigated. In the similarity method, an attribute profile for a new product is created to find previously used materials solutions that match to it. The inspiration method consists of acquiring ideas for materials from other designers' work, from books, magazines, etc., or exploring random ideas.

As requirements depend greatly on the designer's sensitivity and on his skills to translate user's expectations into products, the overall strategy used for material selection in product design - as in the techniques exemplified in the following studies - is to set the objectives and constraints according to emotional perceptions and sensory attributes wanted for a product, manage them by setting parameters of comparison to match correlating physical properties of existing materials, and finally consulting materials' databases to find materials that match the criteria.

Zuo et al. (2005) developed a database named Matrix of Material Representation. It is a visual model created to "provide information about the factors involved in the human perception of materials and the interrelationship between these factors" (Zuo et al., 2005). It primarily focuses on the appraisal of material texture, where a dimension-lexicon system attempts to appraise material texture into geometrical, physical-chemical, emotional and associative parameters and find relationships between them. The data is generated by correlating the geometrical and physical-chemical dimension (acquired through physical measurements) with the emotional and associative dimension (acquired by asking people to describe material samples).

Van Kesteren et al. (2006) research suggests that materials selection should follow the basic steps: formulate criteria for material selection, set some material candidates, compare material candidates, and choose material candidate. Their Materials in Products Selection (MiPS) method, focused on user-product interaction, which aims to bridge the desired product personality to the required materials properties. MiPS is a set of devices to be used in briefs between designers and with clients consisting of: a picture tool, with images of products as examples; a sample tool, with samples of materials; and question tool used to evaluate sensorial aspects of materials throughout various phases of the user-product interaction. However, when evaluating MiPS, it was found that only few user-interaction aspects were able to be translated into sensorial attributes. In 2010, Van Kesteren proposed the Materials Selection Activities (MSA) model as a reevaluation of MiPS. MSA is centred on product designers' activities, as to assist in the materials selection process by focusing on the profile and information on materials in regard to the end-user's needs. MSA method is to be integrated with MiPS, with the addition of a relation sheet tool, focused on translating the sensorial attributes of materials into technical properties.

Karana et al. (2009) developed a meaning driven material selection tool. The Meaning of Materials (MoM) tool is based on the reasoning that a designer that understands the relationships between materials and meanings can then systematically create and manipulate meanings in products assisted by the material selection process. Its database of meaning of materials was generated through interviews, where people were asked to select materials expressing a particular meaning and evaluating them on a sensorial attribute scale. Quantitative results from the sensorial scales are presented through ranking, and the interpretation is left to designers as to stimulate inspiration.

Although these methods and tools have interesting approaches to aesthetic and sensory experience, they show limitations regarding the actual means of appointing materials to fit criteria of selection, and it is unclear how the sensory attributes are correlated to physical properties of materials, and what type of data is obtained, rendering them subject to further research and development.

3.2.3 Aesthetic Performance and Computational Tools for Material Selection

To select from the diversity of material choices available today, architects must not lean on distinct considerations presented by non-structured sources of information, but instead use systematic methods that considers all aspects of materials in order to achieve a rational choice. Considerations and strategies for selecting materials developed in both fields of engineering and product design can give insight into assigning materials for architecture. Moreover, selection on both fields have one thing is common, they both depend on materials' database at the final stage of the selection process in order to assess the necessary information on materials. This shows the importance of databases and the potential of computer aided selection tools. When performing systematic operations for managing and analysing large amounts of data, computer aided selection tools are optimal. In association with digital databases on material properties, these computational tools are numerically based and programmed to evaluate and match the desired attributes against the materials available in its database (Jahan et al., 2013). They hinge on multiple performance criteria, rather than considering single factors, rendering them ideal for choosing best material for a specific application.

In 1973, the first approach to computer aided material selection was proposed (Hanley & Hobson, 1973). From then, computational tools have been in constant development in the field of engineering. However, their databases focus mainly on the bulk physical properties of materials, manufacturability, and technical/ functional attributes and technical performance (Ashby, 1999; Mangonon, 1999; Addington & Schodek, 2005).

Ashby and Johnson (2006) have stated that designers express frustration for not being assisted while selecting materials based on non-technical characteristics, and the ASM International only recently acknowledged that designers have special information needs in regard to aesthetic values of materials (Abbaschian & Marshall, 2006). Conceivably - following such considerations - in recent years, computer aided tools that integrate aesthetic and sensory properties of materials as a selection criteria have been made available.

Within the commercially available computer aided selection tools, Cambridge Engineering Selector (CES) is the most known today. It was developed by Mike Ashby at the Engineering Department of Cambridge University in 1992. Currently it is owned the company Granta Design, but it is independent of the material industry. The software categorises materials by families (in tree-structures), and provides quantitative data of material's physical properties (such as mechanical, thermal, optical, eco and functional), manufacturing process properties, price and an illustrative image of the material. It uses the chart method developed by Ashby since it explicits that performance is not dependent on individual material properties, but by the association of two or more . Since its release, CES has been in constant development. But although Ashby concentrated a lot of his research on sensory and aesthetic attributes of materials (Ashby & Johnson, 2002), aesthetic performance was only included in the software in 2008, and is represented by the sensory/aesthetic attribute of color, which is appraised quantitatively in the Pantone color system.

Many multiple criteria material selection tools are also made available in web-based format. This format has the advantage of being easily and quickly accessed. However, they are clearly distinguished between engineering-oriented and design-oriented. Matweb (matweb.com) is a well-known engineer-oriented material databases for selection. Developed by Automation Creation Inc, it has a database with more than 74000 materials, but its selection criteria only allows technical performance attributes, such as physical, mechanical, thermal, optical, and electric properties to be evaluated. However, it does not include any sensory/aesthetic attribute.

Material ConneXion (materialconnexion.com) and Materia (materia.nl) are two digital databases with a design-oriented multiple criteria selection system. Material ConneXion publicises itself today as the largest global resource of new materials, with an extensive database that combines materials by categories, processing, physical properties, performance, sustainability and availability. Aesthetic performance is represented by few attributes: surface/texture and transparency. The material selection is based on a qualitative appraisal executed by steps, through selection of the desired criteria and visualisation of the material options. Materia, developed by Aart van Bezooyen, presents materials by category, technical performance and qualitative information on sensory aspects - glossiness, translucence and texture. Both tools, however, promote themselves as being sources of inspiration and do not provide a general material overview since the materials included in their database are focused on new developments from the material manufacturing industry. Furthermore, they also lack to provide systematic information on the quantitative properties of their featured materials.

table 4 - Existing material selection tools that appraise attributes related to aesthetic performance

Tool	attribute	aspects of appraisal	type of appraisal
Cambridge Engineering Selector (CES)	color	Pantone	quantitative
Material ConneXion (www.materialconnexion.com)	texture	regular/irregular	qualitative
	surface	glossy/matte	qualitative
	transparency	opaque/translucent/transparent	qualitative
Materia (www.materia.nl)	glossiness	matte/satin/glossy/variable	qualitative
	translucence	0%/ 0-50%/50-100%/100%	quantitative
	texture	coarse/medium/smooth/variable	qualitative

3.3 Discussion

Material selection is a complex process that requires the management of great amounts of information about material properties, and where there is often more than one solution for a particular application (Chiner, 1988). Architects need to incorporate and balance these issues during the material selection process as to assure that the materials appointed for their design will not only fulfil its technical and functional prerequisites, but produce aesthetic interest and evoke positive user experience (Zuo, 2010). Since not much research or methods for selecting materials have been developed in the field of architecture, common procedures used by architects consist in trial and error, relying in previous experience, researching through editorials, reaching for material samples through material consultants or material libraries, or searching material databases for the best material for a particular application.

figure 9 - Common sources and procedures used by architects to select materials

These practices compromise many factors, making for a selection method that is complex, time consuming and that could cause serious consequences in a design project. The only way to rationalise the materials selection is to make materials information more accessible. This is the perfect situation for the computer. Digital tools are considered to have high potential, not only technically, but also for their dynamic character which is compatible to the design process (Charles et al., 1997; Ashby et al., 2004). Computer aided selection tools allow materials to be evaluated within multiple criteria decision making method. It is a systemised procedure that utilises sets of objectives and constraints as inputs, and compares them with the properties of the materials in its database - with reduced time and efforts, and assuring that no possibility is overlooked.

Besides the functional/technical factors and constraints imposed by the project, architects are inclined to select materials according to their sensory/ aesthetic attributes. However, these attributes are poorly represented in the existing tools - hence that most of the computational tools for selecting materials have an engineering approach. This may be because, unlike functional/technical requirements which are defined in quantitative terms and can be assessed objectively, the sensorial and aesthetic aspects of materials are expressed in qualitative terms and are therefore less objective and more difficult to interpret (Schifferstein & Hekkert, 2007). As considerations to sensorial and aesthetic aspects of materials are indispensable during the material selection process in architecture, they demand for more structured material information (Wastiels & Wouters, 2011). As to provide an adequate multiple criteria method to material selection that includes the aesthetic performance criteria, the sensory/aesthetic properties need to be interpreted systematically in order to be incorporated into computer aided selection tools. A system based on the conversion of qualitative appraisal into quantitative data is a direction to allow comparisons between each type of information. By utilising data on the physical properties of materials and setting parameters of interpretation, aesthetic performance can be assessed and evidence the advantages of one material versus another in material selection.

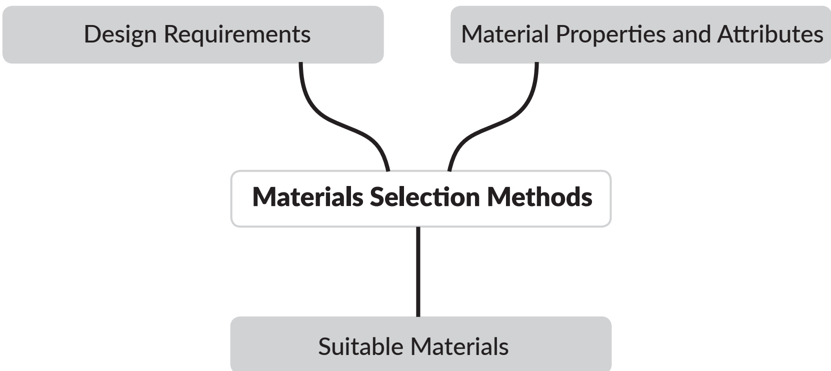

figure 10 - Diagram of inputs and output of the material selection process

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| PART 2 |
METHOD FOR THE INCORPORATION OF AESTHETIC PERFORMANCE INTO MATERIAL SELECTION TOOLS

Part 2 presents the proposed methodology for the incorporation of aesthetic performance into material selection tools. Based on the examination of the critical factors for material selection in architecture identified in Part 1, Part 2 primarily outlines the approach for an improved selection framework. The aim is to arrive at concept that may be a more appropriate for the architectural design process and the involved stakeholders (Chapter 4). Consequently, the proposition of a tool for assessing aesthetic performance by selecting materials according to their sensory/aesthetic attributes is explained. Details on the implications involved in this assessment are presented and described (Chapter 5).

I CHAPTER 4 I

Concept for an improved framework for material selection

The previous chapters explained the role of materials in architecture and the complexity of materials decisions. This chapter will outline the approach for an improved framework for material selection. The concept concerns the incorporation of aesthetic performance as a selection criteria as to make the material selection process more holistic and appropriate for architecture.

4.1 The Design Process in Architecture

All architectural design process starts with a client who wants a building product, and the architect who will interpret the client's ideas and requirements into a building design. For the architect, this process can follow numerous paths, depending on also numerous factors such as his architectural convictions, the client's orientation and intentions for the building's use, the site and context of the project, etc. Based on a design brief, which is the clarification of the task, the following development phases of the project are intended to approach these issues systematically through the refinement of the building's specification: the concept design, schematic design, design development, and detail design phase. Within this framework, however, the architect can adopt two different types of approaches to selecting materials: they can be defined at the end or at the beginning of the design process.

The more traditional design approach is when materials are assigned at the end of the design process. It considers, primarily, the macro performance of the building, and secondarily, how the micro performance of the material will fulfil it. The architect - after defining the buildings concept, form and function - searches and assigns materials that have the ability to perform up to the client's established requirements - be it aesthetic, functional, economical, etc - and be adaptable to his formulated design. The main advantage of this approach is that the concept of the building can be elaborated in its initial stages, and the architectural form is not restrained by the choice of material, but complimented by it.

When materials are assigned at the beginning of the design process, it considers primarily the micro performance of the material which, secondarily, will influence the macro performance of the design. The aim is the integration of material, structure and form by incorporating the materials' performance requirements. The main advantage of this approach is that, inspired by a material's capabilities, the architect can explore design concepts determined by its performance - be it aesthetic, functional, economical, etc.

Both design frameworks are oriented by material's performance. The difference is that in the first process the formal typology of the design precedes material selection, and in the second process the selection of material precedes and determines the formal typology (figure 11). Both processes can equally benefit from an improved material selection process.

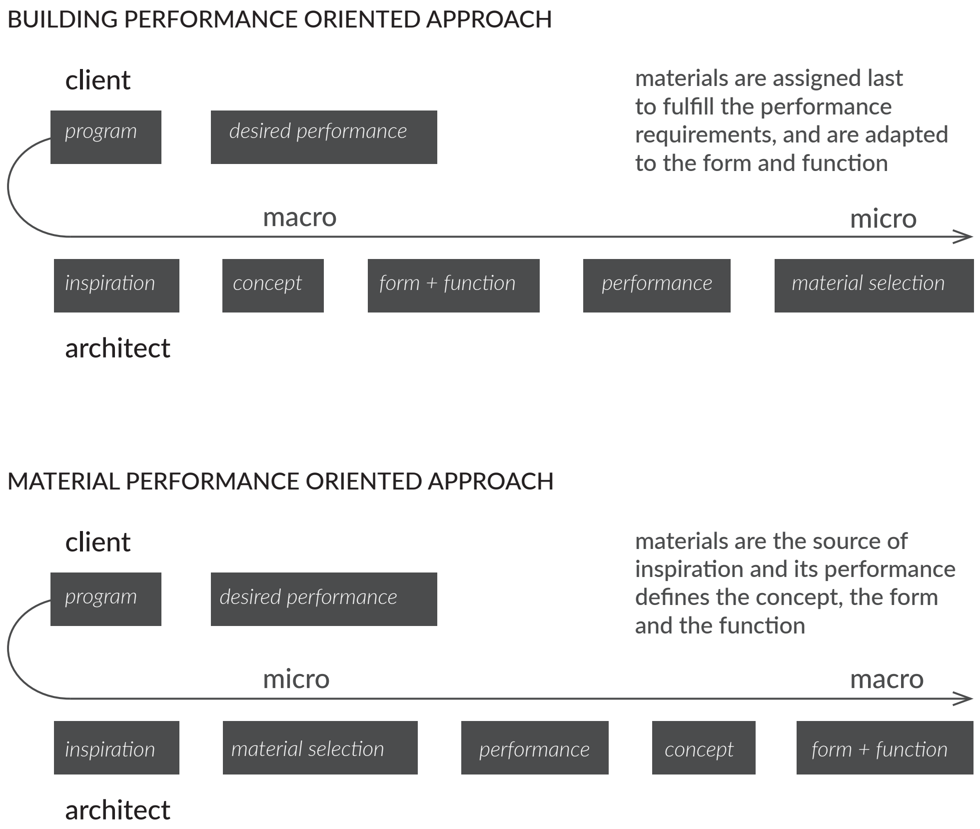

figure 11 - The types of approach to material selection within the design process of architecture

4.2 Towards an Improved Material Selection Framework

Material selection in the field of architecture is an underdeveloped topic of research and as a practical process. Consequently, in order to propose an improved material selection framework for architects, the present research speculated that it is reasonable that considerations and strategies for selecting materials developed in both fields of engineering and product design can give insight into assigning materials for architecture. Therefore, the approach and methods adopted by both fields were studied in depth to gain deeper understanding of this activity. The study conducted in Chapter 3 offered a realistic view of the differences in the materials selection framework within each field, enabling the critical factors for an effective process in architecture to be identified and structured.

4.2.1 The Concept

The large number of materials available today, combined with the intricate associations between selection criteria, make the activity of selecting materials for a building design a rather complex task. In order to avoid unintentional outcomes, architects must not lean on distinct considerations presented by non-structured sources of information, but instead use systematic framework that considers all aspects of materials in order to achieve a rational choice. Methods, strategies and considerations for selecting materials developed in both fields of engineering and product design give insight into assigning materials for architecture. In the field of engineering, emphasis is often given to technical and economical aspects. Accepted selection methods, which generally rely on weighting methods of established functional and technical criteria, are defined by material's physical properties. In the field of product design, emphasis is given to considerations on aesthetic, meaning and sensory experience. Methods and tools focus on translating the sensory and aesthetic attributes into properties of materials as to set the selection criteria for functional and aesthetic performance. However, many issues remain superficially explored since it is not clear how this translation is accomplished and what is the resulting output.

When selecting materials in the field of architecture, material selection - besides complying to building codes and standards requirements - should comprise broader considerations. Buildings are great undertakings from a practical, technical and financial point of view. They impact not just the site where it stands, but all urban environment around it. Its where people spend most of their time, with their design influencing how people use, experience and respond to it.

Consequently, buildings require attention in all performative aspects to be successful. The concept for an improved material selection framework for architecture comes from the premise that a proper assignment of materials has the potential to assist in all these aspects. It entails that in order for the material selection process to be able to respond to all building's demands, it has to be improved in a way to consider evaluating materials for all relevant performative requirements. In other words: it should have a holistic approach, where emphasis is given to functional and technical aspects as well as to considerations on aesthetic and sensory experience (figure 12).

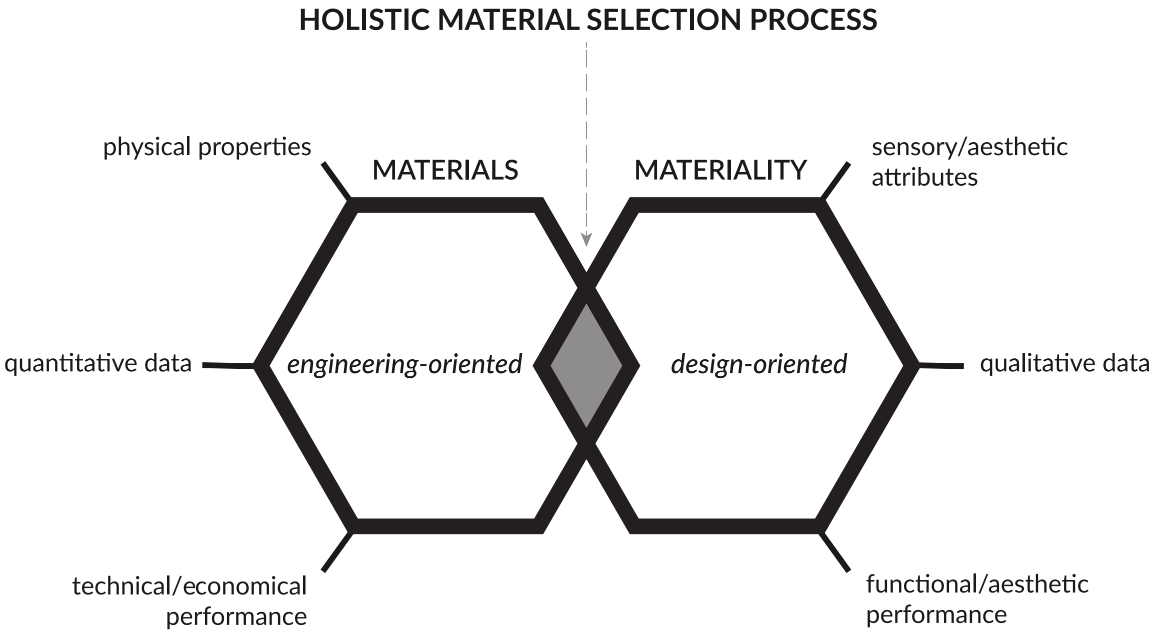

figure 12 - The necessary inputs for a holistic material selection process

4.2.2 The Method

Selecting materials is a complicated process (Brechet et al., 2001), since there is the need to match sets of requirements, that are often contradictory, to an array of material properties that vary in each material. This often leads to compromises in the selection criteria and in the building design. A performance-based multiple criteria material selection method could be a successful approach for an improved material selection process for architecture. Performance-based entails that, as materials are selected according to the various performative requirements to ensure the successful operation of the building system as a whole, materials' attributes become the criteria of their judgement. It intends to be holistic approach to material selection, which is developed in a five step basic cycle for a systematic method:

Step 1 - Clarification of the objectives and constraints of the project through specifying the context of the design and its requirements.
Step 2 - Establishing weighting of performative requirements in accordance to the constraints and objectives of the project, where the most important performative requirements are prioritised.
Step 3 - Identifying the desired attributes related to the performative requirements.
Step 4 - Screening candidate materials by consulting computer aided selection tools to match the criteria of the material attributes of the desired performative requirements.
Step 5 - Repeat Step 3 and 4 by the order of result of Step 2 until a material matches all desired criteria.

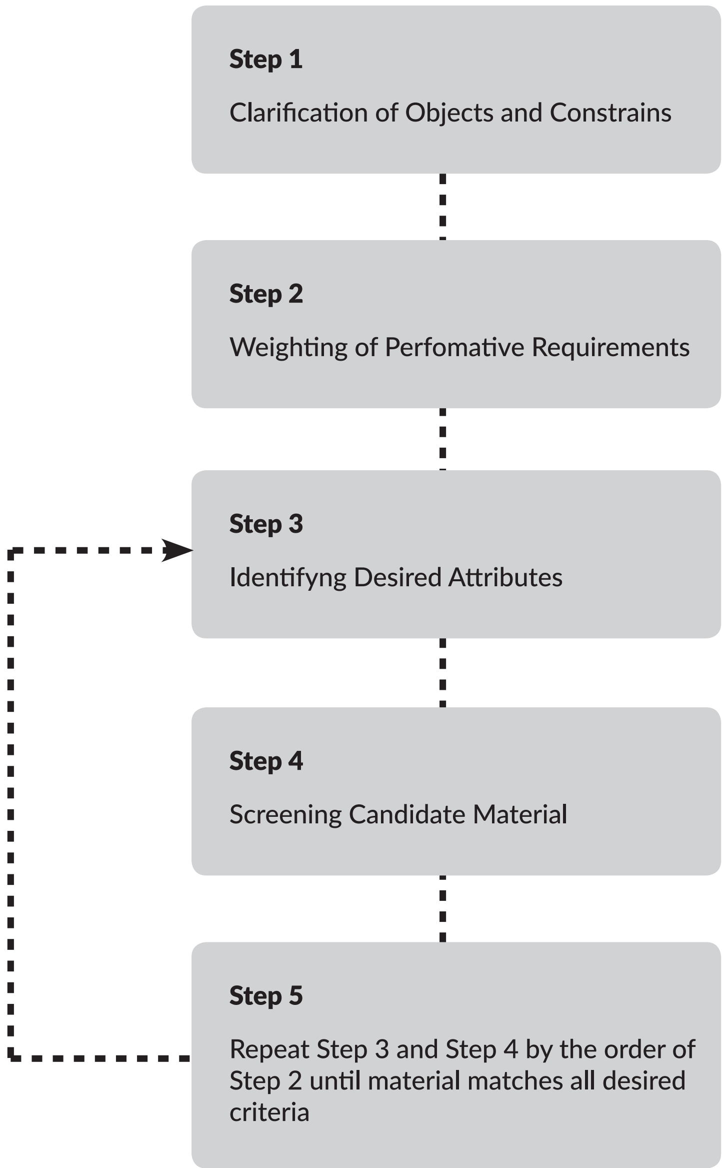

figure 13 - Basic cycle for a systematic and holistic material selection method

4.2.3 The Strategy

Since methods for selecting materials according to technical and functional attributes are already well established, and many tools exist to assist this selection criteria, this thesis proposes that the incorporation of aesthetic performance into material selection support tools as an additional selection criteria will improve the material selection process. The analysis conducted in Chapter 3 shows that the current computer-based multiple criteria material selection tools in association with digital databases provide extensive information on the physical properties useful for specifying material's technical performance. They have also been proven useful to specify material's functional performance related to economical, environmental and operational issues (Ashby, 2005). However, when regarding performance related to aesthetics, the existing tools fail to explore relevant attributes related to sensory and aesthetic appraisal of materials, resulting in sources that lack an approach that could be of more assistance within the design process of architecture. This is the basis of judgement that material selection tools can improve, and need a more adequate and systematic approach to aesthetic performance, to consequently, provide a more holistic material selection system.

Considering the performance-based multiple criteria material selection method, a tool for selecting materials according to their aesthetic performance is proposed. It is based on the conversion of quantitative information - the material's physical properties - into qualitative information - the sensory/aesthetic attributes - allowing an approach to determine the basis for direct comparisons between each type of information. The intention is for it to have an add-on format - a computer software component that adds features to an existing tool. The objective of this format is that it will be able to share and complement the structure of an existing computer aided multiple criteria material selection tools oriented for engineering by adding on the selection criteria of aesthetic performance (figure 14). It is envisioned to operate by utilising an existing tool's database on the physical properties of materials in order to correlate it to sensory/aesthetic attributes parameters as a strategy to achieve a practical resource of information and in a holistic material selection system.

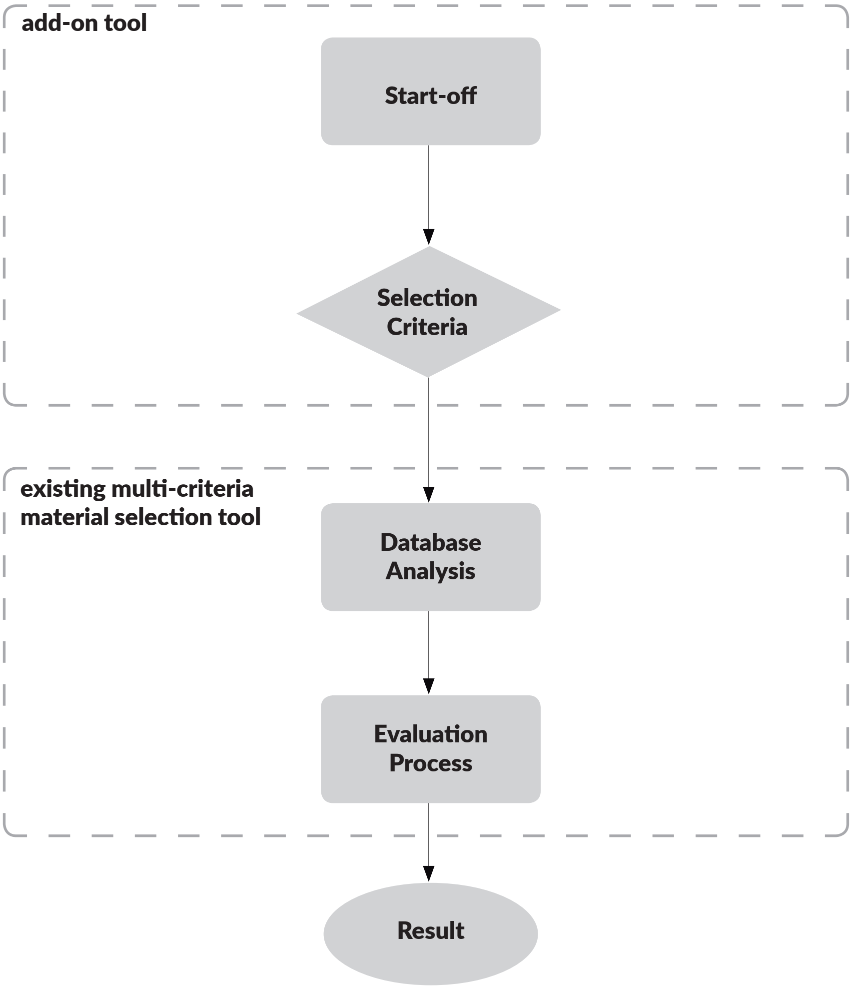

figure 14 - Structure of the add-on tool

4.2.4 Directions for the Development of the Proposed Tool

Considering that for architects the materials' appearance and sensory behaviour are just as important as meeting technical requirements (Ashby & Johnson, 2002; Fernandez, 2006; Malnar & Vodvarka, 2004; Pallasmaa, 2005), the question is: how to address and evaluate aesthetic performance criteria of materials empirically and incorporate it in multiple criteria material selection tools?

The development of the proposed add-on tool aims at a system to select materials according to aesthetic performance requirements, as to match peoples' expectations regarding materials' aesthetic in relation to sensory perception in an objective and systematic manner. This approach will follow the definition that sensory/aesthetic attributes are related to tactual and visual appraisal of materials, and that have direct correlation to the physical properties of materials, such as a blue colour, a smooth texture, or a distinct pattern. This correspondence to the physical properties of materials permits the qualitative sensory/aesthetic attributes to, therefore, be appraised quantitatively and enables the hard data to be used as parametric inputs within material selection tools. Based on Ashby et al. (2004) qualitative versus quantitative approach to material selection, the tool will adopt the following strategy based on three main factors:

- The formulation of clear requirements that must be satisfied by the material as to fulfil the desired performance.
- The formulation of a performance metric to measure how well a material matches the desired requirement
- The use of a search procedure for identifying materials that meet the requirements

The theoretical analysis conducted on Chapter 2 provided an extensive and diverse assessment for establishing the criteria that will be used to appraise aesthetic performance in the proposed tool. Foremost, the relevant sensory/aesthetic attributes to categorise aesthetic performance of materials were defined. The six sensory/ aesthetic attributes chosen to categorise aesthetic performance were defined through evaluation of their relevancy within the scope of materials used in architecture. Later, their correlation to physical properties was established. Books and handbooks on material science and engineering provided the information on which sets of physical properties - including mechanical and optical - are related to the sensorial perception of materials. Table 5 shows the results of the analysis and lists the sensory/aesthetic attributes that were chosen to categorise aesthetic performance in the proposed tool, with their corresponding sets of material properties.

table 5 - list of the sensory/aesthetic attributes chosen to categorise aesthetic performance in the proposed tool

	SENSORY/AESTHETIC ATTRIBUTES relevant to architecture		correspondent set of **PHYSICAL PROPERTIES**
tactual aspect	**TEXTURE** (smooth/coarse)	↔	lay, roughness, waviness
visual aspects	**TRANSLUCIDITY** (transparent/translucent/opaque)	↔	total transmittance
	BRILLANCY (matte/semi-glossy/glossy)	↔	specular reflection, roughness
	PATTERN (seamless/distinct)	↔	lightness L*, red-green value a*, yellow-blue value b*
	COLOR	↔	lightness L*, red-green value a*, yellow-blue value b*
	TONE	↔	lightness L*

The sensory experience related to touch is activated by contact between an object and the skin, which implies reciprocity of touching and being touched. Different sensory cells in the skin - pressure cells, movement cells and temperature cells - are responsible for the sensory experiences (Geldard, 1972), where tactile aspects of materials become perceptive through manipulation, like pressing, bending or by friction. Texture was chosen as the sensory/aesthetic attribute related to tactual aspects of material to be appraised in the proposed tool because of its direct influence in materials' appearance. It is related to the physical and bulk properties of materials, and to surface properties resulting from the manufacturing techniques and surface finish. Texture is an attribute that can also be perceived visually - as an impression of the geometrical configuration of a material's surface. However, this visual impression is the result of a mental synthesis which leads to a subjective visual interpretation of texture (Zuo & Jones, 2005). Studies have found that texture was considered equitably whether the material was perceived by touch alone, by vision, or both modalities. (Lederman & Abbott, 1981; Bergmann Tiest & Kappers, 2006) Therefore, this thesis will attain itself to approaching texture as a tactual attribute to preserve its objectivity.

The sensory experience related to vision happens through the human eye, which has two kinds of sensors, one for light perception and one for color perception. In a material, light and color are visual aspects generated by its physical and optical properties, which are the material's response to incident electromagnetic radiation. To define the visual aspects of materials in relation to light, the sensory/aesthetic

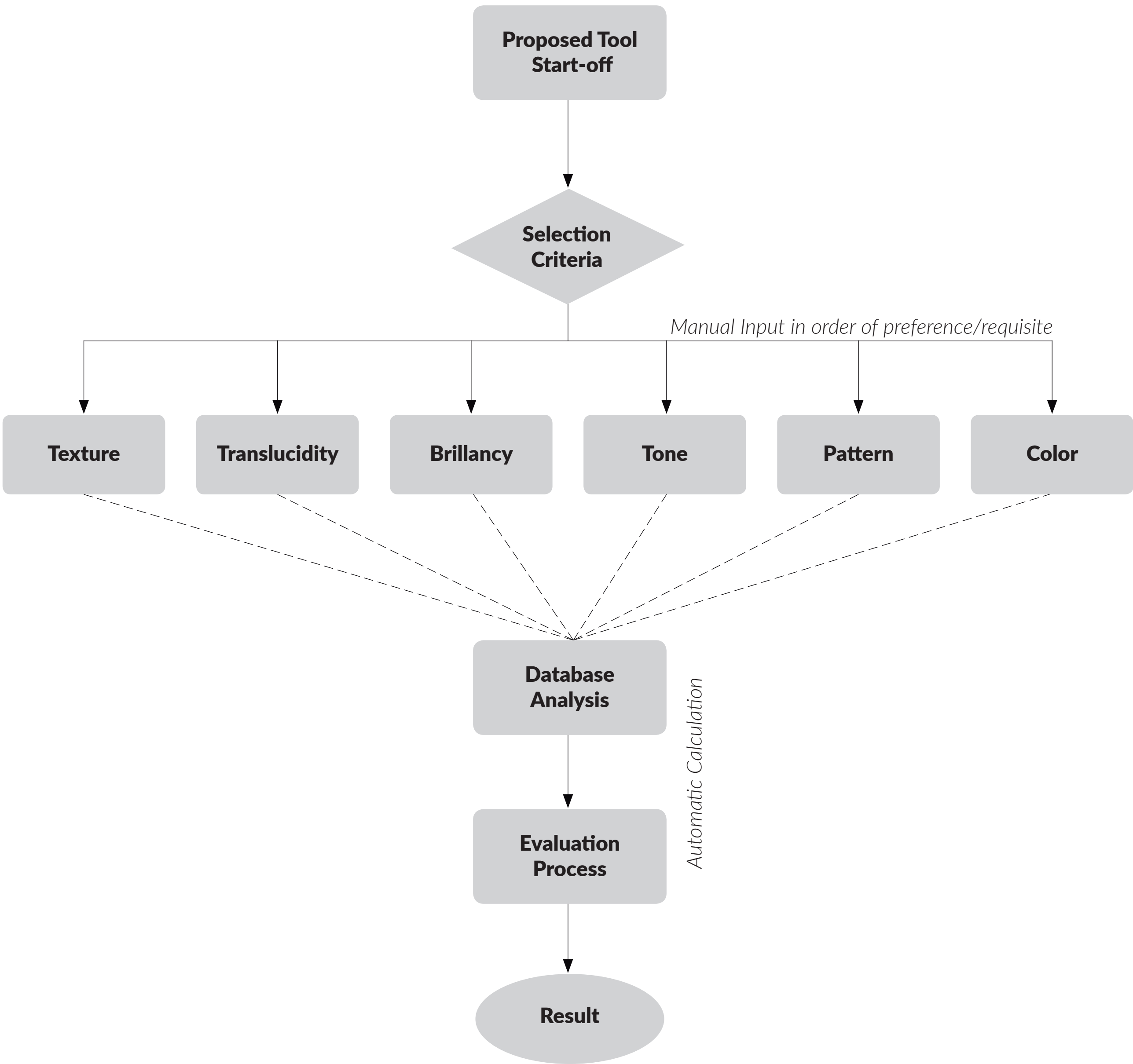

figure 15 - Structure of the proposed tool

attributes of translucidity and brillancy were chosen to be appraised by the tool. Both translucidity and brillancy are influenced by the material's manufacturing techniques and surface finish, however, translucidity relates to bulk and surface of materials, and brillancy only to surface. As for defining the visual aspects of materials in relation to color, the sensory/aesthetic attributes of pattern and tone will be appraised. Furthermore, color will also constitute a sensory/aesthetic attribute. Pattern relates mostly to bulk properties of materials. Color and tone attributes also relate to bulk properties of materials, however, they can be influenced by the material's manufacturing techniques and surface finish.

Since materials should be selected for applications based on measurable criteria, the quantification of the physical properties related to these sensory/aesthetic attributes allows aesthetic performance to be appraised in the proposed material selection tool. As to acquire detailed insight on the implications involved in incorporating aesthetic performance into multiple criteria selection tools, an experimental process is proposed, where samples of building materials were chosen and evaluated through instrumental measurements. The quantitative data on the physical properties that correspond to these qualitative sensory/aesthetic attributes chosen to categorise aesthetic performance will form the proposed tool's database. The purpose of this experimental process is to obtain first hand information and clarify the synthesis of the quantified data into qualitative parametrical inputs. It will enable the aesthetic performance criteria of the evaluated building materials to be assessed, and to have an operational tool that can be appraised and tested. The experimental process will be explained in detail in Chapter 5.

The theoretical analysis on methods for selecting materials conducted on Chapter 3 provided the assessment for establishing a selection structure to be used in the proposed tool (figure 15). The tool should work as an assistant to identify which materials have particular aesthetic and sensory qualities that are important for a design or that the user is looking for. This identification intends to clarify the aesthetic performance requirements for material's search, where minimum steps of interpretation should be needed to find the materials that fit the requirement. A weighting method based on TOPSIS (Technique for Order of Preference by Similarity to the Ideal Solution) was found to be the most appropriate to evaluate aesthetic performance against multiple sensory/aesthetic attribute criteria, since it is useful for comparing qualitative and quantitative data. In the proposed tool, the user should define the material selection criteria by order of preference/requisite of the attributes that he/she is looking for in a material. The user may also choose how many attributes he/she wants the selection to be dependent on - from one up to all six. Based on these manual inputs, the tool should automatically search its database through an evaluation process, and as a result, suggest the suitable material/materials to fit the selection criteria. The operational system for the proposed tool will be explored further in Chapter 6, as well as the relevant aspects to be considered to ensure its functionality and effectiveness.

4.3 The Stakeholders

The proposed tool also takes into consideration the stakeholders involved in the architectural design and material selection processes. Within these processes, architects may be the main figure. But they are not the only people involved in them. Clients, engineers, consultants and contractors - and many more - all play critical roles in the decision making (figure 16). Although each has their own influences, concerns, objectives, working strategies and motivations, they can all benefit from an improved material selection system.

Within the architecture design process, the architect's role in relation to material selection is to translate the different issues and resolve them into one buildable solution. He occupies a strategic position in the organisation of this process, where he is the mediator exchanging information from one party to the other. The proposed tool can be beneficial in guiding architects in a more straightforward material selection approach, where materials' information becomes readily available during the design process.

Initially working closely to the client to clearly understand their needs and general characteristics for the proposed building, the architect subsequently defines the detailed specification it must have in order to succeed. Here, the activity of selecting materials entails the need to fulfil the clients' objectives and achieve the desired characteristics in the building, which involves practical concerns with materials' cost, quality, durability, and perceptual aspects of materials related to the senses and aesthetic. The architect, therefore, is responsible for translating these wishes of the client into spacial and material terms with which the contractor can build. However, clients are often unable to clearly specify which materials they would like to see appointed in their project. The proposed tool intends to assist in this manner, when during client's briefs, materials for a design project needs to be discussed and evaluated. Architects can utilise aesthetic performance criteria to communicate the perceptive characteristics intended for the materials within their design proposal, or to understand the client's perspective on them. The client's involvement in the formulation of the desired material profile for the design may result in fewer changes of candidate materials through this opportunity to clearly establish the expected outcome of the material selection. Furthermore, the client's involvement in setting the objectives and constraints for materials diminishes the need to clarify the selection criteria if changes were to be made, since the knowledge about the material profile helps to identify which materials could be suitable substitutes.

In the same manner, the proposed tool can assist towards integrating and balancing different factors in material selection. Engineers tend to choose materials based on their structural performance, contractors based on their workability, and consultants on availability and feasibility. Therefore, the activity of selecting materials entails the need to fulfil all these objectives in order to achieve the characteristics in the building in relation to the clients concerns and the architects proposal. At this point there is a need to optimise material selection across this range of performative requirements. The add-on format of the proposed tool can assist to evaluate the aesthetic performance of materials together with the other performative criteria offered by the standard computer-aided selection tools. It is up to the stakeholders to decide which performance criteria are most important in each project, as to make informed material selection decisions. Looking only at one criteria can result in decisions that may be incomplete or short-sighted, and which can have crucial effects on the project.

Other stakeholders who could benefit from the proposed tool are the professionals of the material manufacturing industry. Through the analysis of the sensory/aesthetic attributes that are appreciated by architects and clients, manufacturers may be able to produce customised materials or define a demand profile for new products to be developed. Identifying and understanding the relationships between objective measures of physical properties and the sensory/ aesthetic attributes can also help recognise particular manufacturing processes to create desirable material properties (Zuo, 2010). This can be of great significance in the development process of new materials.

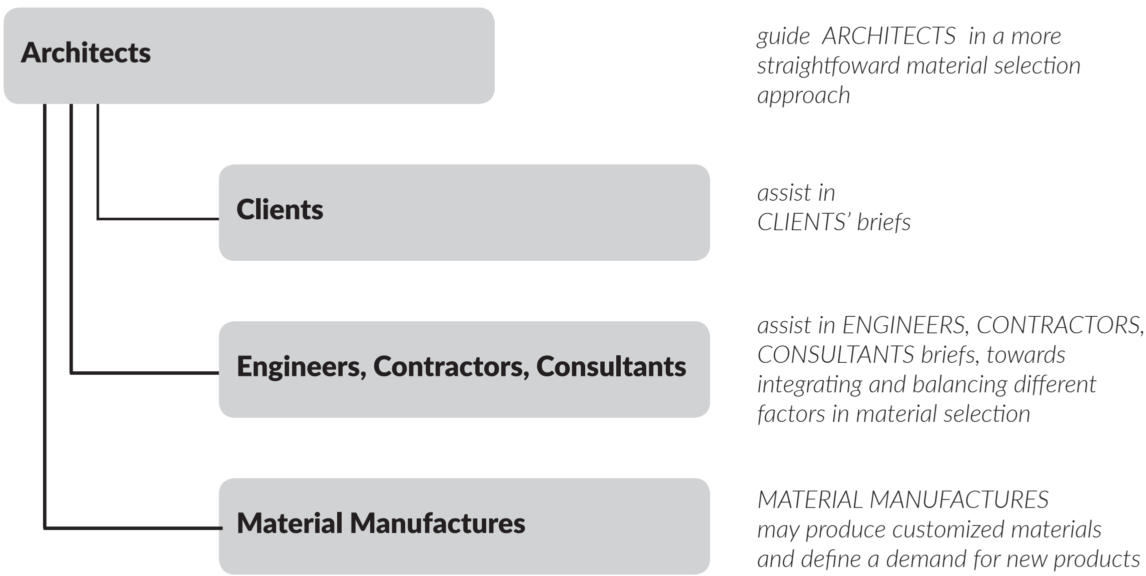

figure 16 - Benefits that an improved selection process can bring to stakeholders involved in the architectural design process

4.4 Conclusion

When selecting materials in the field of architecture, material selection - besides complying to building codes and standards requirements - should comprise broader considerations than those of the engineering and product design fields. Furthermore, the array of materials available today, combined with the intricate associations between selection criteria, make the activity of selecting materials for a building design a rather complex task. In order to avoid unintentional outcomes, architects must not lean on distinct considerations presented by non-structured sources of information, but instead use systematic framework that considers all aspects of materials in order to achieve a rational choice. A performance-based multiple criteria material selection method could be a successful approach for an improved material selection framework for architecture. Performance-based entails that, as materials are appointed to accomplish the various performative requirements of a design, their selection may ensure the successful operation of the building system as a whole.

For this reason, the proposal of a material selection tool for assessing aesthetic performance can be of value. The existing material selections tools have been, in general, developed within the field of engineering design, where constraints and objectives are mainly determined by technical requirements (Ashby & Cebon, 2007)), and materials are selected accordingly. In architecture, however, materials should not only fulfil technical requirements but also appeal to the user's senses and contribute to the intended character of the building. The process of selecting the most suitable materials for a new design project is therefore based on sensorial descriptions. This implies an assessment of the aesthetic and perceptive values of materials. The incorporation of the aesthetic performance criteria into material selection tools aims to facilitate this assessment, guiding the architect into a material selection process that can be oriented towards the perceptive values of materials, which also considers technical requirements and other criteria (such as environmental, economical and operational) for a more holistic selection approach. The recent development of specific tools for designers featuring less technical information, as evidenced in Chapter 3, are important undertakings. However, the utility of technical information must not be minimised, but rather conciliated with the other features of materials that architects and clients may find interesting. The direction is to provide more information on materials, broadening the range of performance criteria taken into consideration when making material choices. This can perform towards integrating and balancing the different factors in selection in order to ensure that the materials "will not only fulfil its functions, but produce aesthetic appeal, elicit positive user experience, and with the lowest expense of resources, energy and labour." (Zuo, 2010). Moreover, inappropriate materials selection can cause serious consequences, besides being a complex and time consuming endeavour. A systemised procedure for material selection is therefore indispensable if the choice is to be made with reduced time and efforts, but also with the assurance that no possibility is overlooked.

When collaborating with other stakeholders, the incorporation of the aesthetic performance criteria into material selection tools can also assist architects in practical issues. The systematic approach of the proposed process allows the many stakeholders involved in the design process to utilise a unified material selection tool, and come to a consensus on a direction to follow. Architects can utilise the sensory/aesthetic attributes in design briefs to communicate the perceptive values intended for a design, or to understand the client's perspective on them. In the same manner, it can assist in design briefs with engineers, contractors and consultants towards mutual understanding. Furthermore, it has the potential of contributing to the material manufacturing industry. Through the analysis of the sensory/aesthetic attributes that are appreciated by architects and clients, manufacturers may be able to produce customised materials and/or define a demand profile for new products to be developed.

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I CHAPTER 5 I

The Tool'S Foundation

The previous chapters evidenced the demand and necessary inputs for a more comprehensive and holistic material selection system to assist the stakeholders involved in the architectural design process. For this reason, a tool for assessing aesthetic performance by selecting materials according to their sensory/aesthetic attributes was proposed.

In this chapter, subsequently, the empirical approach to the development of the proposed tool is detailed as to acquire in-sight on the implications involved in the assessment of aesthetic performance criteria in multiple criteria material selection tools.

5.1 Experimental Process

The main purpose of the proposed material selection tool is to provide a support system for selecting material according to aesthetic performance which, in association with technical tools, has the potential to provide a more holistic material selection approach.

As to acquire detailed insight on the implications involved in incorporating aesthetic performance into multiple criteria selection tools, an experimental process is proposed, where samples of building materials were chosen and evaluated through instrumental measurements. The quantitative data on the physical properties that correspond to the sensory/aesthetic attributes chosen to categorise aesthetic performance will form the proposed tool's database. The purpose of this experimental process is to obtain first hand information and clarify the synthesis of the quantified data into parametric inputs. Consequently, it will enable the understanding of the implications involved in evaluating the aesthetic performance criteria of building materials.

5.1.1 Selecting materials samples

50 assorted materials were chosen to be evaluated (figure 17). They are all categorised by being planar/sheet materials and can be used for facade/wall cladding as to set a limiting parameter intended to make the experiment more equitable since all materials have the same geometric constraint and functional objective.

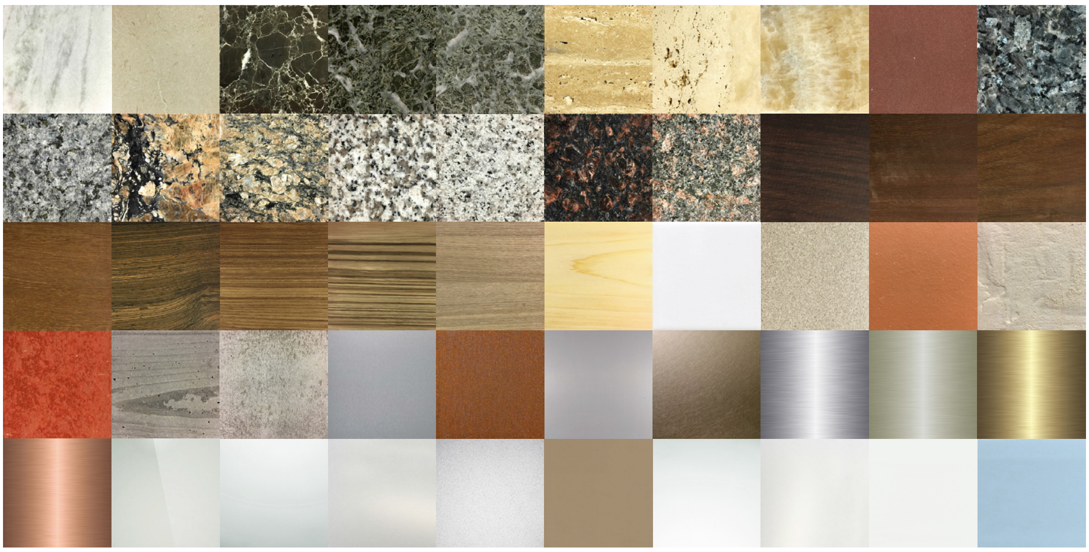
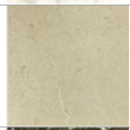
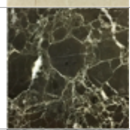
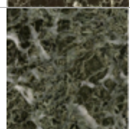
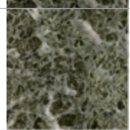
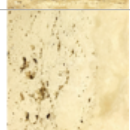
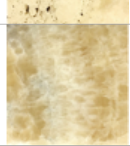
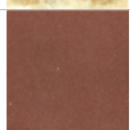
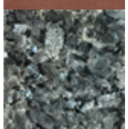
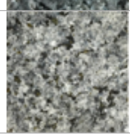


figure 17 - Collection of materials that were chosen to be evaluated

Every material family was represented to set a range of the variety of materials used by architects: stone, wood, metal, glass, polymer, ceramic and concrete. Within each family, assorted materials were selected, having undergone different manufacturing processes and surface finishes. This diversification was crucial to analyse, since these aspects have direct influence in the material's properties and attributes.

table 6 - Material samples used in the experimental process to compose the proposed tool's database

material family	material name/type finish	image
Stone	White Smoke marble / polished	
	Crema Marfil marble / honed	
	Savona Dark Brown marble / polished	
	Djamon marble / polished	
	Djamon marble / honed	
	Noce travertine / polished	
	Romano Classico travertine / honed	
	Alabastro onyx / polished	
	Red sandstone / honed	
	Blue Pearl granite / polished	
	Blue Pearl granite / flamed	

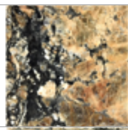
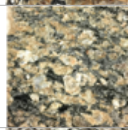
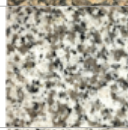
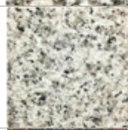
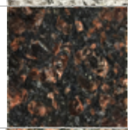
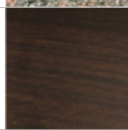
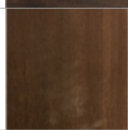
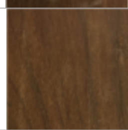
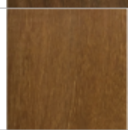
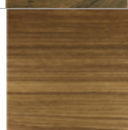
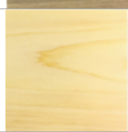
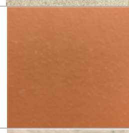
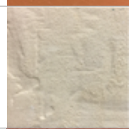
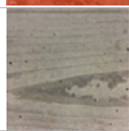
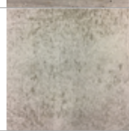
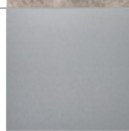
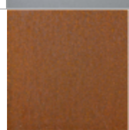
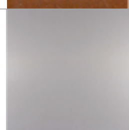
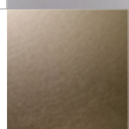
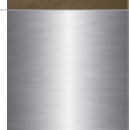
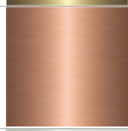
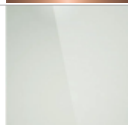
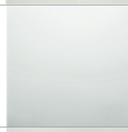
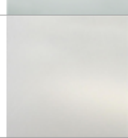
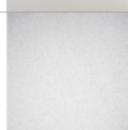
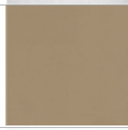
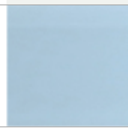
Stone	Golden Black granite / polished	
	Golden Black granite / flamed	
	Inada granite / polished	
	Inada granite / flamed	
	Tan Brown granite / polished	
	Tan Brown granite / flamed	
Wood	East Indian Rosewood / natural	
	Massaranduba / natural	
	Brazilian Ipe / natural	
	Selangan Batu / natural	
	Bocote / natural	
	Teak / natural	
	Zebrano / natural	
	Ash / natural	
	Cypress / natural	

table 6 (continuation) - Material samples used in the experimental process to compose the proposed tool's database

material family	material name/type finish	image
Ceramic	White / glazed	
	Grey / unglazed	
	Terracotta / unglazed	
	Offwhite / unglazed	
	Rosso / unglazed	
Concrete	mortar / wooden formwork	
	mortar / plastic formwork	
Metal	Zinc / #3 finish	
	Weathered steel / Cor-Ten A natural	
	Stainless steel / #2D finish	
	Stainless steel bronze / #4 finish	
	Stainless steel / #4 finish	
	Titanium / #4 finish	

Metal	Brass / #4 finish	
	Copper / #4 finish	
Glass	clear laminated 6mm	
	float 4mm / acid etched	
	float 5mm / soft frosted	
	float 5mm / medium frosted	
	bronze laminated 6mm	
Polymer	ETFE clear 250µm	
	ETFE frosted 250µm	
	ETFE white 250µm	
	ETFE blue 250µm	

The samples of stone, wood, ceramic, metal, glass and polymer were acquired through various vendors, and the concrete samples were fabricated in a laboratory. The area set to be tested and analysed within each sample was standardised to $36cm^2$.

5.1.2 Collecting Physical Properties Data

Experimental research was carried out for obtaining first-hand information on the physical properties of materials that correlate to every sensory/aesthetic attribute chosen to assess aesthetic performance. Objective tests were carried out in a controlled environment, with specialised equipment, and following industrial standards of measurement for each attribute as described (for results refer to appendix 1).

Texture: Texture concerns tactual smoothness or coarseness of a given material. In sensory perception, texture produces an uneven pressure distribution on the skin when touched statically, and vibrations when stroked (Bergmann Tiest, 2010), rendering the surface of a material to be perceived as smooth when these vibrations are imperceptible, and of increasing coarseness as the vibrations become more distinguished.

figure 18 - The tactual sensory perception of texture varies from smooth to coarse in materials https://ak7.picdn.net/shutterstock/videos/11173547/thumb/1.jpg?i10c=img.resize(height:72)

Physically, materials have topographical deviations that compose miniature peaks and valleys on their surface profiles, which are characterised by properties of lay, roughness and waviness (figure 19). The size and spatial distribution of these deviations influence the surface's properties, and can be measured using equipments and expressed quantitatively within specific parameters.

According to industrial standards, surface profile values can either be calculated linearly or by area. Since area roughness gives more significant values, they were adopted in this experiment and measured using Keyence 3D Digital Microscope

VR 3100 (figure 20). This equipment is a non-contact, wide area 3D measurement system that scans the entire topography of the sample at once by using three, double-telecentric lenses in multi-triangulation technology of displacement gauges. For each material sample, the arithmetical mean roughness (*Sa)* was measured. *Sa* expresses the difference in height of each point in comparison to the arithmetical mean of the surface within a defined area - in the samples it was the total area of 36cm². It is a basic industrial roughness parameter used for detecting variations in the overall surface profile height (Z), which is quantified in µm (micrometers) units using the equation (1). The height measurement resolution used was 0.1 µm, and the protocol followed the standards established by the ISO 25178 Surface Texture (Areal Roughness Measurement).

$$S_a = \frac{1}{A} \iint_A \left| Z_{(x,y)} \right| dxdy \qquad (01)$$

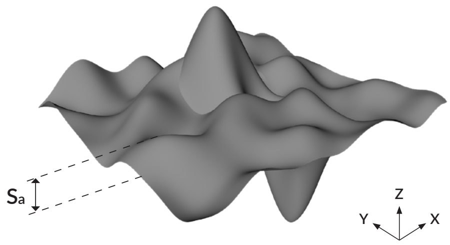


figure 19 - texture corresponds to physical properties of lay, roughness and waviness

figure 20 - 3D digital microscope used to measure the arithmetical mean roughness of material samples

table 7 - Texture attribute and corresponding properties, measuring aid and parameter

SENSORY/ AESTHETIC ATTRIBUTE	*correspondent set of* PHYSICAL PROPERTIES	MEASURING AID	MEASURED PARAMETER
TEXTURE (smooth/coarse) ◄·····►	lay, roughness, waviness ·····►	digital microscope ·····►	arithmetical mean roughness (*Sa*)

Translucidity: Three visual phenomenas occur when light interacts with a material - transmittance, absorption and reflection - causing different visual effects related to translucidity: light may be transmitted through the bulk of the material, making it transparent; it may be partially absorbed and/or partially reflected by the material, making it translucent; and it may be fully reflected by the material's surface, making it opaque.

figure 21 - The visual sensory perception of translucidity varies from opaque to transparent in materials - http://digitaldealer.com/wp-content/uploads/2014/01/transparency2.jpg

Physically, depending on the material's thickness and on the amount and angle of the incident light (figure 22), translucidity is measured by total transmittance (*T*), which is the ratio between the intensity of light entering the sample (*Io*) and the intensity of light leaving the sample without being scattered (*I*) as shown in the equation (2), and expressed in percentage. For example: incident light = 100% - (absorption = -2% + reflection = -7%) = Total Transmittance = 91%. These factors will define quantitatively the light transmitting properties of a material to determine whether it is transparent, translucent or opaque.

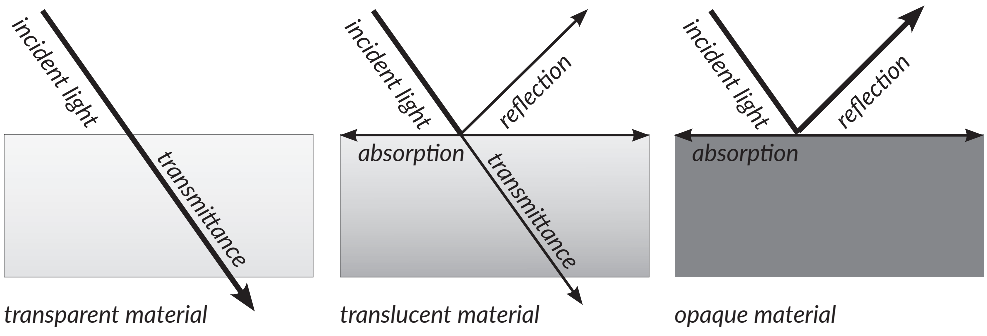


figure 22 - translucidity corresponds to physical properties of total light transmittance

Total transmittance (*T*) must be evaluated in the wavelength range of 380 to 780 nm, which is the range capable of passing through our visual sensory organs and cause visual effects. A Shimadzu UV-3150 Spectrophotometer (figure 23), with a double-monochromator system, was used to collect the data within this wavelength range. Measurements were taken in three different locations of the samples (figure 24) and were averaged exponentially for a final result.

$$T = \frac{I}{I_o} \qquad \%T = \frac{I}{I_o} \times 100 \qquad (02)$$

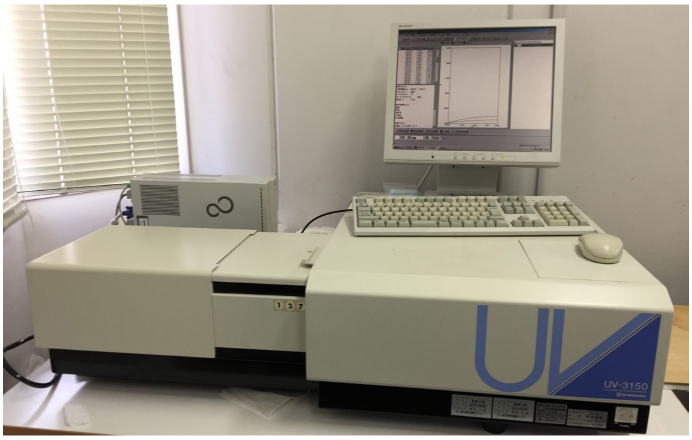


figure 23 - Spectrophotometer used to calculate total light transmittance (*T*)

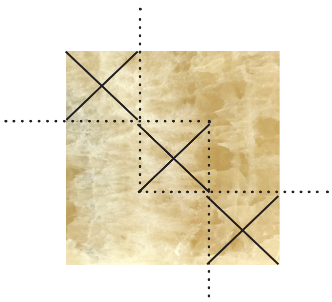


figure 24 - image of the Alabastro onyx and the indicated location from where the *T* measurements were collected

table 8 - Translucidity attribute and corresponding properties, measuring aid and parameter

SENSORY/ AESTHETIC ATTRIBUTE	*correspondent set of* PHYSICAL PROPERTIES	MEASURING AID	MEASURED PARAMETER
TRANSLUCIDITY (opaque/translucent/transparent) ◂·······▸	total transmittance ·······▸	spectrophotometer ······▸	transmittance (*T*)

Brillancy: Brillancy concerns the amount of light that reflects from the material's surface and the angle of this reflection. When light incidence on a material's surface reflects in an equal amount and in a symmetrical angle, the visual effect of gloss occurs. However, as the light reflection decreases and disperses in other directions the gloss also decreases.

figure 25 - The visual sensory perception of brillancy varies from matte to glossy - http://www.marketwire.com/library/MwGo/2017/3/14/11G133083/Images/cambria_high_gloss-cd07a9c5b8f8addbbd8d09c6848fdea7.jpg

Physically, it is an optical phenomenon which depends on illumination angle, surface profile, and observation conditions, and is related to properties of specular reflection and surface roughness (figure 26). It is defined by the ratio of the specularly reflected light flux (*Fx*), from a surface for a specified angle of incidence (*θ*), to the specularly reflected light flux (*Fs*), from a standard surface for the same angle of incidence as shown in the equation (3). These factors will define quantitatively the amount of light reflected by the material, which is designated on a numerical scale in Gloss Units (GU). Materials with a smooth surface appear glossy to the eye and have higher GU values due to the large amount of light being reflected back in an orderly mirror-like specular direction. As surface roughness increases, the amount of reflected specular light decreases as it is scattered in all directions, making the gloss effect constantly fade ranging from semi-gloss to matte, and have decreasing GU values.

The material samples were measured according to the Japanese Industrial Standards JIS Z 8741 Method of Measurement for Specular Glossiness, using a Suga UGV-6P Variable Angle Glossmeter (figure 28). The equipment has a ø45mm aperture, and measures gloss by directing a light beam - of constant intensity and at a fixed angle - and monitors the amount of light that is reflected back at the same angle.

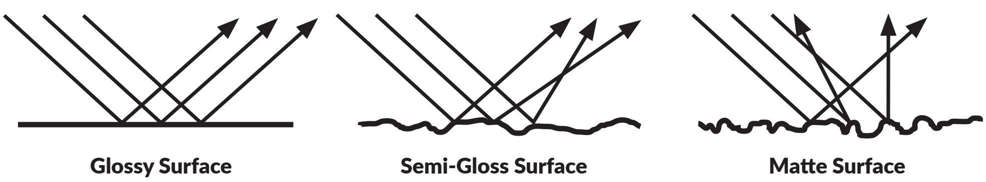


figure 26 - Brillancy corresponds to physical properties of specular reflection and surface roughness

Different type of material surfaces require to be measured at different reflective angles. The 60° geometry is the universal standard geometry used to measure specular glossiness, and is used a priori to determine the appropriate measuring angle for each sample. The 85° geometry is used to measure low gloss samples - when results at 60° are below 10 GU - and the 20° geometry is used to measure high gloss samples - when results at 60° are above 70 GU (figure 27). However, as results can only be compared when measured within the same geometry, all samples were measured with 60° geometry, and averaged over three locations within their 36cm² area (figure 29). The measurement ranges between 0–1000GU for 60°.

$$GU = (F_x / F_s)_{\theta, \theta'}, \qquad (03)$$

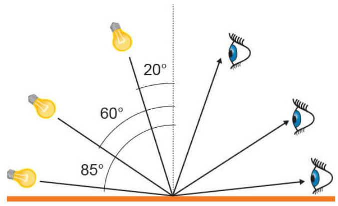


figure 27 - Geometries used for calculating gloss

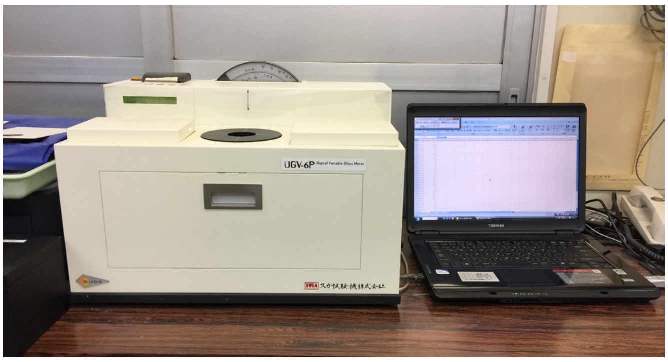


figure 28 - Glossmeter used to calculate gloss 60°

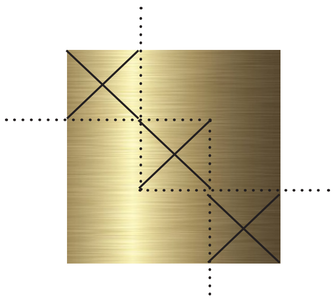


figure 29 - Image of the Brass sheeting (#4 finish) and the indicated location from where the gloss 60° measurements were collected

table 9 - Brillancy attribute and corresponding properties, measuring aid and parameter

SENSORY/ AESTHETIC ATTRIBUTE	*correspondent set of* PHYSICAL PROPERTIES	MEASURING AID	MEASURED PARAMETER
BRILLANCY (matte/semi-gloss/glossy)	specular reflection, roughness	glossmeter	gloss 60° (GU)

Pattern and Color: Pattern and color are intrinsically related. The visual perception of color derives from the stimulation of cells in the human eye by a range of waves carrying electromagnetic radiant energy. Color, or spectrophotometric characteristics, is determined by its wavelength distributions. The wavelengths that are visible to us range near 400 and 700 nm of the electromagnetic spectrum, between the violet and the red color (figure 30).

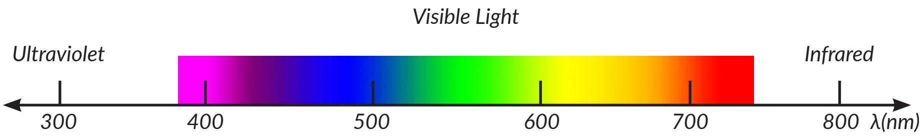


figure 30 - The visible spectrum

Physically, wavelengths that are not absorbed by the material are reflected back, thus making them visible to observers. These reflections can be either specular or diffuse, each affecting how the human eye perceives a material's color, and are influenced by gloss and surface roughness. Many systems have been developed to organise colors numerically as coordinates in a color space that allow their physical profiling. Usual reference standard is the CIELAB color space, developed by the Commission Internationale d'Eclairage CIE in 1976. It is a three dimensional system, designed to include all colors an average person can see (figure 31).

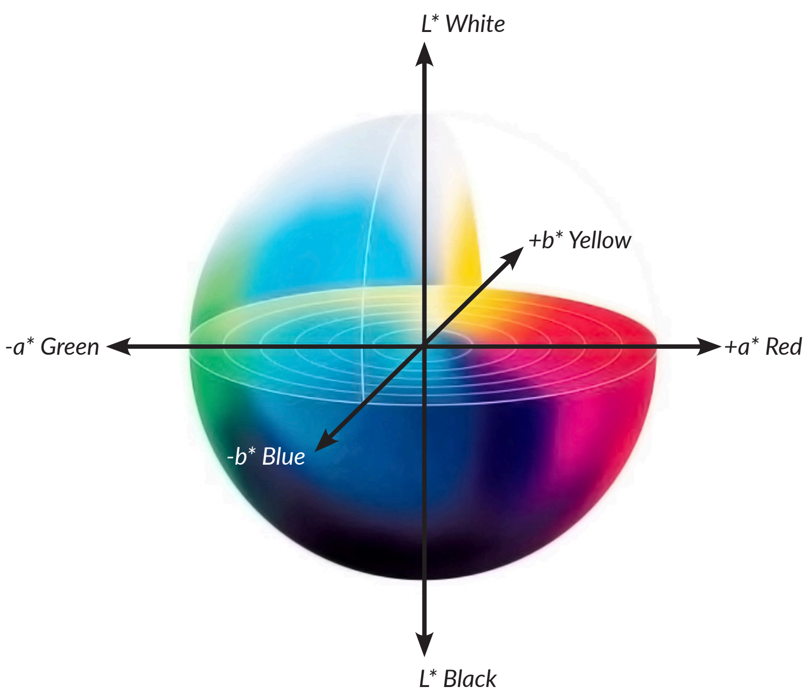


figure 31 - The three-dimensional CIELAB color space

The CIELAB color space describes colors using cartesian coordinates: L*, *a** and *b**. *L** is the lightness factor and varies from white (100) to black (0). *a** and *b** are the chromaticity coordinates: where *-a** values are in the green direction, *+a** values in the red direction, *-b** in the blue direction, and *+b** in the yellow direction, varying from -127 and +127. The center is achromatic - neutral grey - and as a* and b* values increase in both directions, the saturation of the color also increases (figure 32).

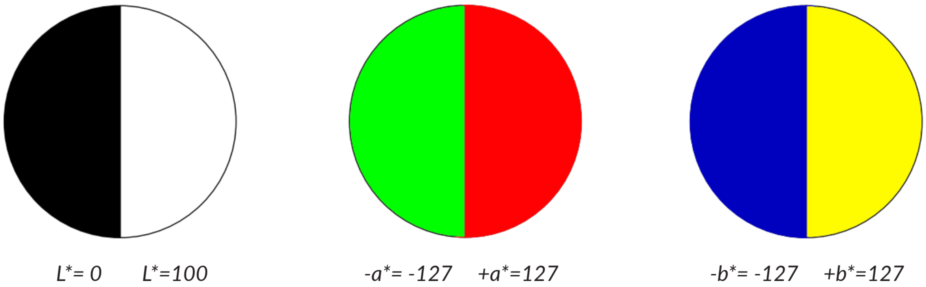


figure 32 - The three cartesian coordinates of the CIELAB color space

As to evaluate the visual aspects of materials related to color, first a material should be appraised for its sensory/aesthetic attribute of pattern, since almost none of the materials in nature have completely uniform color. Materials are usually composed of different color hues in either a microscopic scale, or as patterns - which are discernible optical markings on materials that can be identifiable through vision. Materials can be made to have a uniform color through processing or surface finishes such as coating, but most materials found in nature have a discernible pattern. Pattern parameters ranges from seamless to distinct, where a seamless pattern concerns a monochromatic material - where only one color can be perceived - moving gradually to distinct, as more than one color becomes noticeable with increasing color contrast between them.

figure 33 - The visual sensory perception of pattern varies from seamless to distinct
https://stock.adobe.com/stock-photo/sun-light-portrait-outdoor-over-marble-background/76002942?prev_url=detail

To determine the distinctiveness of pattern, a Minolta CM-508d Spectrophotometer with a diffuse/8° geometry was used (figure 35). D65/2° illuminant parameters according to the Japanese Industrial Standards JIS Z 8722 "Methods of colour measurement - Reflecting and transmitting objects" was adopted as the measuring standard. The spectrophotometer has a ø8mm measuring aperture, and was used in the SCE mode, where the specular reflection is excluded from the measurement and only the diffuse reflection is measured, producing a color evaluation which correlates more to the way the observers categorise color. Following a protocol described for measuring the color of granite stone (Prieto et al., 2010) - which is the material with the most diverse color hues - 14 measurements taken within the 36cm2 area of each material sample is required to characterise color when using a spectrophotometer with a ø8mm aperture head (figure 34). As for the translucent and transparent samples, their color was measured over a white background as the standard required procedure.

Following, the resulting data was used to calculate total color difference of each material as to determine whether it is composed with only one color or more. Total color difference has to be calculated from two reference colors (*L**, *a**, *b**) in the CIELAB space by the CIEDE2000 color difference equation (4). Differences in color are expressed as a single numerical value, ΔE^*_{00}, which is the Euclidian distance between the color points in the CIELAB space, with values ranging from 0 to 100.

$$\Delta E^*_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C}\frac{\Delta H'}{k_H S_H}} \qquad (04)$$

$$\Delta L' = L_2^* - L_1^* \quad \bar{L} = \frac{L_1^* + L_2^*}{2} \quad \bar{C} = \frac{C_1^* + C_2^*}{2}$$

$$a_1' = a_1^* + \frac{a_1^*}{2}\left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right) \quad a_2' = a_2^* + \frac{a_2^*}{2}\left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right)$$

$$\bar{C}' = \frac{C_1' + C_2'}{2} \text{ and } \Delta C' = C_2' - C_1' \quad \text{where } C_1' = \sqrt{a_1'^2 + b_1^{*2}} \quad C_2' = \sqrt{a_2'^2 + b_2^{*2}}$$

$$\bar{C}' = \frac{C_1' + C_2'}{2} \text{ and } \Delta C' = C_2' - C_1' \quad \text{where } C_1' = \sqrt{a_1'^2 + b_1^{*2}} \quad C_2' = \sqrt{a_2'^2 + b_2^{*2}}$$

$$h_1' = \text{atan2}(b_1^*, a_1') \mod 360°, \quad h_2' = \text{atan2}(b_2^*, a_2') \mod 360°$$

$$\Delta h' = \begin{cases} h_2' - h_1' & |h_1' - h_2'| \leq 180° \\ h_2' - h_1' + 360° & |h_1' - h_2'| > 180°, h_2' \leq h_1' \\ h_2' - h_1' - 360° & |h_1' - h_2'| > 180°, h_2' > h_1' \end{cases}$$

$$\Delta H' = 2\sqrt{C_1' C_2'} \sin(\Delta h'/2), \quad \bar{H}' = \begin{cases} (h_1' + h_2' + 360°)/2 & |h_1' - h_2'| > 180° \\ (h_1' + h_2')/2 & |h_1' - h_2'| \leq 180° \end{cases}$$

$$T = 1 - 0.17\cos(\bar{H}' - 30°) + 0.24\cos(2\bar{H}') + 0.32\cos(3\bar{H}' + 6°) - 0.20\cos(4\bar{H}' - 63°)$$

$$S_L = 1 + \frac{0.015\left(\bar{L} - 50\right)^2}{\sqrt{20 + \left(\bar{L} - 50\right)^2}} \quad S_C = 1 + 0.045\bar{C}' \quad S_H = 1 + 0.015\bar{C}'T$$

$$R_T = -2\sqrt{\frac{\bar{C}'^7}{\bar{C}'^7 + 25^7}} \sin\left[60° \cdot \exp\left(-\left[\frac{\bar{H}' - 275°}{25°}\right]^2\right)\right]$$

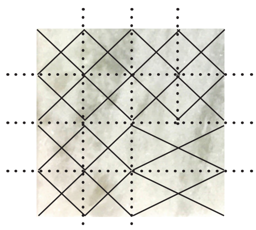
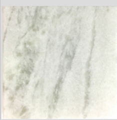
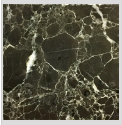


figure 34 - Image of the white smoke marble polished and the indicated location from where the 14 measurements for pattern and color were collected

figure 35 - Portable spetrophotometer used to collect measurements for pattern and color

The 14 measurements taken from every sample were used to calculate the ΔE*00 of each material, where the first reference color were the minimum average values measured for *L* a* b**, and the second reference color were the maximum average values for *L* a* b**, as in table 10:

table 10 - Partial table showing results from experimental process with the 14 values of the collected data from white smoke marble and savona dark brown marble, with their minimun average, maximum average and ΔE*00. (full table is available in the appendix)

		value 1	value 2	value 3	value 4	value 5	value 6	value 7	value 8	value 9	value 10	value 11	value 12	value 13	value 14	max	min	Δ	ΔE*00
	STONE																		
	White Smoke Marble polished																		
	L*=	79.3	78.6	70.8	73.1	75.8	79.5	78.3	80.6	80.4	81.4	74.7	77.5	77.3	79.1	81.4	70.8	77.6	7.7
	a*=	-0.7	-1.0	-1.5	-1.3	-1.2	-0.8	-1.0	-0.8	-0.8	-0.8	-1.0	-1.3	-1.0	-0.8	-0.7	-1.5	-1.0	
	b*=	-0.7	-0.7	-0.9	-1.2	-1.2	-0.7	-1.0	-0.9	-0.7	-0.8	-0.8	-1.2	-1.0	-0.7	-0.7	-1.2	-0.9	
	Savona Dark Brown Marble polished																		
	L*=	72.3	32.5	30.4	34.6	31.2	32.9	33.0	35.6	31.8	36.3	37.8	27.5	65.8	73.3	73.3	27.5	41.1	46.0
	a*=	1.1	1.6	1.0	1.2	1.3	1.1	1.0	0.8	0.7	1.1	1.0	1.1	1.1	-0.0	1.6	-0.0	1.0	
	b*=	6.5	6.1	4.9	5.4	7.0	5.7	4.7	5.2	4.5	4.9	5.0	5.0	6.0	6.8	7.0	4.5	5.5	

From then, the colors that compose each material could be determined. The *L* a* b** values for materials with seamless pattern could already be established by averaging the data acquired from the spectrophotometer measurements - Δ*L**, Δ*a**, Δ*b**. For the materials with distinct pattern, high quality digital photographs were taken and analysed using the software Color Summarizer (version 0.77). The software is able to distinguish and determine the *L* a* b** values that are more representative in an image by clustering and averaging the *L* a* b** values of its pixels (figure 36). Resulting images show the material's predominant color and second dominant color. Results for other materials can be found in the Appendix.

table 11 - Pattern and Color attributes and corresponding properties, measuring aid and parameter

SENSORY/ AESTHETIC ATTRIBUTE	*correspondent set of* PHYSICAL PROPERTIES	MEASURING AID	MEASURED PARAMETER
PATTERN (seamless/distinct)	*L*, a*, b**	spectrophotometer	color difference ΔE*00
COLOR	*L*, a*, b**	spectrophotometer	*L*, a*, b**

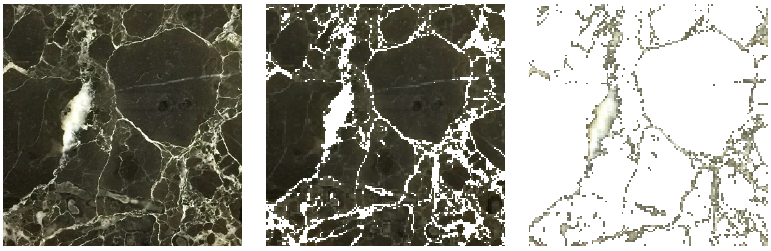


figure 36 - Image of savona dark brown marble (left), image of predominant color (center), and image of second dominant color

Tone: Tone concerns lightness, being a representation of the variation in the perception of a color or color space's brightness. It is one of the color appearance parameters of any color appearance model. In the CIELAB color space, lightness is represented by L^* (figure 37), where the darkest black at $L^* = 0$, and the brightest white at $L^* = 100$, calculated using the equation (5). The 14 measurements, taken with the portable spectrophotometer (figure 39), from every material sample to determine the sensory/aesthetic attribute of color were used to determine the materials' tone ranging from dark to light, where L^* values were averaged.

$$L^* = 116\, f\left(\frac{Y}{Y_n}\right) - 16 \qquad (05)$$

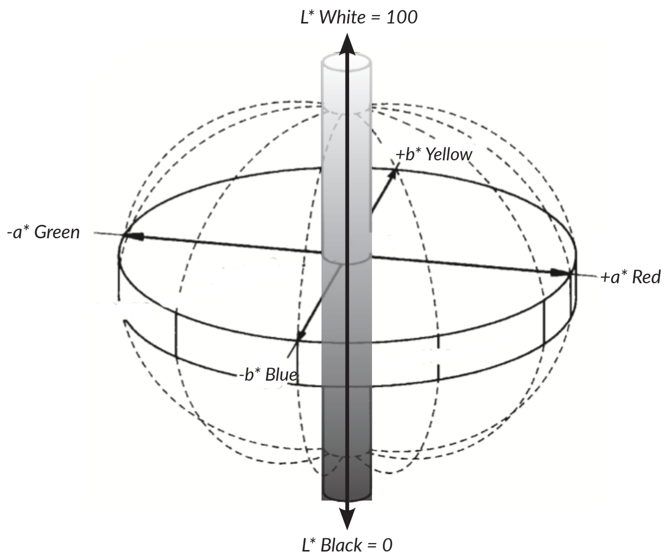


figure 37 - The lightness L^*coordinate in the three-dimensional CIELAB color space

table 12 - Tone attribute and corresponding properties, measuring aid and parameter

SENSORY/ AESTHETIC ATTRIBUTE	correspondent set of PHYSICAL PROPERTIES	MEASURING AID	MEASURED PARAMETER
TONE	lightness L^*	spectrophotometer	L^*, a^*, b^*

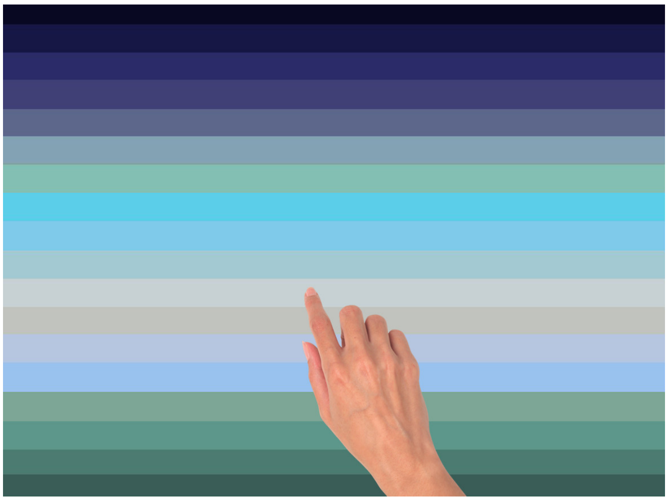


figure 38 - The visual sensory perception of tone varies from dark to light
http://hdblackwallpaper.com/wallpaper/2015/05/green-and-black-color-palette-17-high-resolution-wallpaper.jpg

figure 39 - Portable spetrophotometer used to collect measurements for tone

5.2 - Data Synthesis - Correlating Material's Physical Properties and Sensory/ Aesthetic Attributes

The following step was to synthesise the collected data in order to make it available as parametric inputs for determining the selection criteria of the materials within the proposed tool. The correlation of the measured properties of the samples to the criteria of appraisal of the sensory/aesthetic attributes was achieved through the parameters of interpretation. Standards and information found in literature were the source for establishing these parameters between the quantitative data on the physical properties and the qualitative appraisal of the sensory/aesthetic attribute.
The following graphs illustrate the results that will constitute the tool's database and the criteria of material selection. Their X axis display the quantitative range of the physical property and the gradient shows the correlation to the qualitative range of the sensory/aesthetic attribute. Their Y axis shows the numerical data collected from the experimental process and the bars distinguish their attribute appraisal.

Texture: Scientific studies render the perception of smoothness/coarseness as subjective and individual (Tiest & Kappers, 2006), where roughness is always established between references as a parameter of comparison. Also, industrial standards exist to specify roughness values of materials, however, there are no parameters to distinguish values as being smooth/coarse. Therefore, in this study, the parameter of interpretation for tactual texture was established by comparison among the measured samples (table 13). The material with the highest Sa value set the absolute coarse parameter in the texture scale, and the lowest Sa value set the absolute smooth parameter.

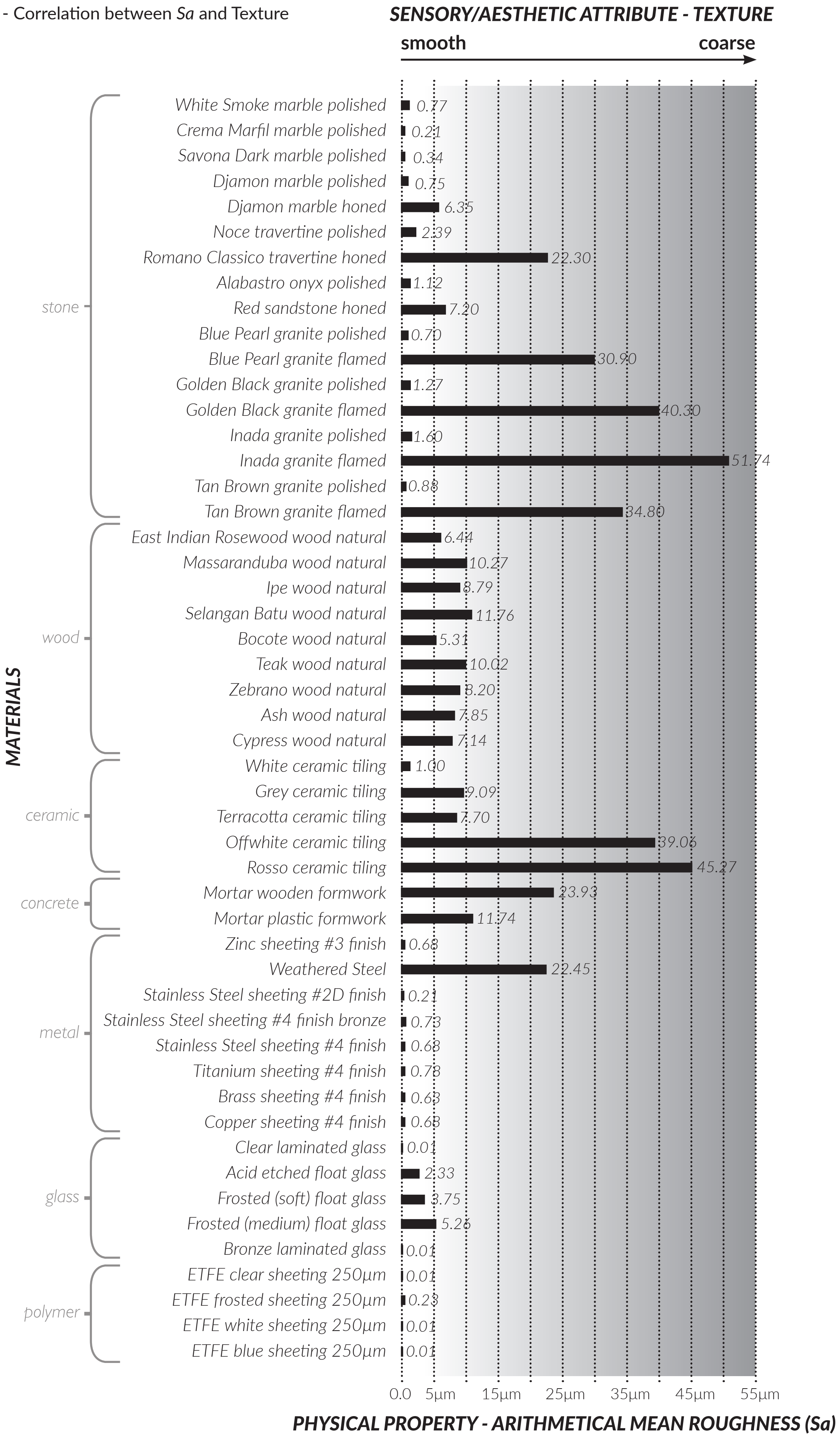
The flamed Inada granite, measuring 51.7 µm set the parameter for absolute coarse. For the absolute smooth parameter, there were five materials measuring 0.01 µm: the clear laminated glass, bronze laminated glass, ETFE clear sheeting, ETFE white sheeting and ETFE blue sheeting. Other values in between were considered exponentially along the texture attribute gradient scale.

Clear evidence of the influence of surface properties on arithmetical mean roughness (*Sa*) values were demonstrated, as expected, specially with the stone samples that are from the same material, but went through difference manufacturing processes in terms of surface finish. Stones that have a polished finish had very low values for *Sa*, and therefore are correlated as smooth. Stones that have a honed finish and flamed finish had increasing Sa values and consistently progressed along the texture attribute gradient scale towards coarse. The influence of surface properties was also evident with the data collected from the glass samples - with the glass with etched and frosted surface finishes having increased Sa values when compared to the ordinary laminated glass finish. Furthermore, the metal samples with the same #4 finish consistently showed approximate *Sa* values.

The data collected from the wood samples also showed that the material's bulk properties influences their *Sa* values. All the selected wood samples have a natural finish, meaning they went through the same manufacturing process and have no surface finish - such as coating or varnishing. However, *Sa* values differed depending on the type of wood, evidencing that it is dependent on its structure - its cells relative size and variation of size, and the width and abundance of its rays. This directly influences the difference between smooth-textured woods - which have small cells and thin rays - and coarse-textured woods - which have wide vessels and broad rays.

The difference in the *Sa* values of the concrete demonstrated how the formwork influences its surface properties and consequently the sensorial attribute of texture. The concrete, with its bulk properties, additionally acquires the texture attributes of the formwork in which it was produced, with the wooden formwork rendering it to be coarser and the plastic to be smoother.

table 13 - Correlation between *Sa* and Texture

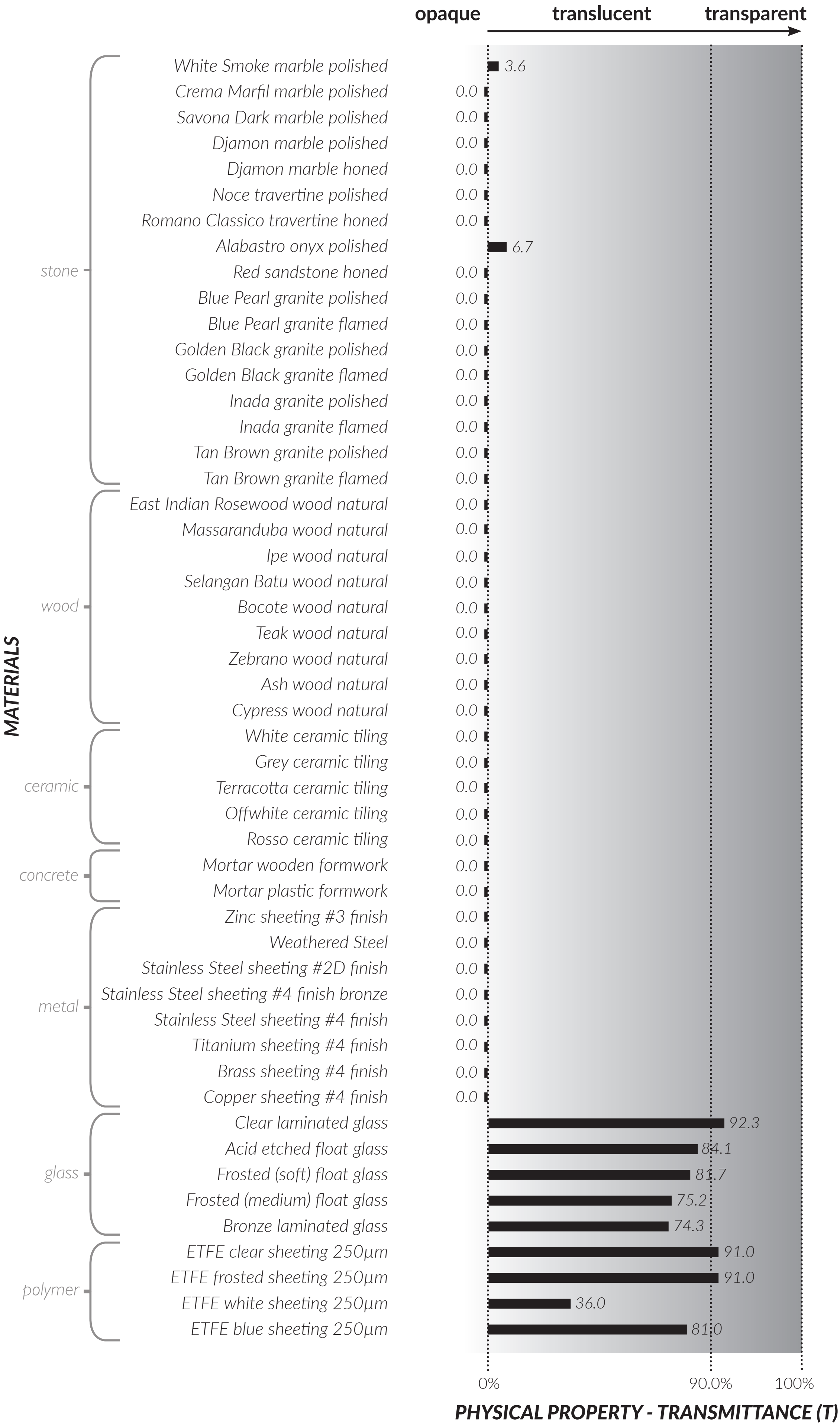


Translucidity: Parameters of interpretation for translucidity were based on information found on handbooks (Kenneth et al., 1997; Harper et al., 2003). Materials that have total transmission values over 90% are considered to be transparent, percentages between 90 and 0.1 are considered translucent, and 0 is considered opaque.

- >90% = transparent
- 0.1% ~ 90% = translucent
- 0 = opaque

Table 14 evidences, as expected, that glass and polymer samples have high transmittance values. The clear laminated glass, the ETFE clear 250mm sheeting and the ETFE frosted 250mm sheeting measured quantitative values for transmittance (*T*) above 90%, and therefore being considered transparent. All other glass and polymer samples have quantitative values ranging from 36%*T* to 84.1%*T*, being considered translucent. For the rest of the materials, only two types of stone have values above 0.1%: White Smoke marble with 3.6%*T*, and Alabastro onyx with 6.7%*T*. The light transmitting properties of stone are related to its bulk properties and its crystalline structure, and also with the influence of the material's thickness. As both samples have the same thickness (2cm) and polished surface finish, complimentary tests would be necessary to verify if surface properties would influence *T* values.

table 14 - Correlation between *T* and Translucidity



Brillancy: Parameters of interpretation for brillancy are established by international industry standards, where gloss measurements below 10 GU at 60° are considered to have low glossiness, or matte, and measurements above 70 GU at 60° are considered to have high glossiness, or glossy. Measurements in between 10 GU and 70 GU are considered semi-gloss.

- If <10 GU = Low Gloss/Matte
- If 10 ~ 70 GU = Semi-Gloss
- If >70 = High Gloss/Glossy

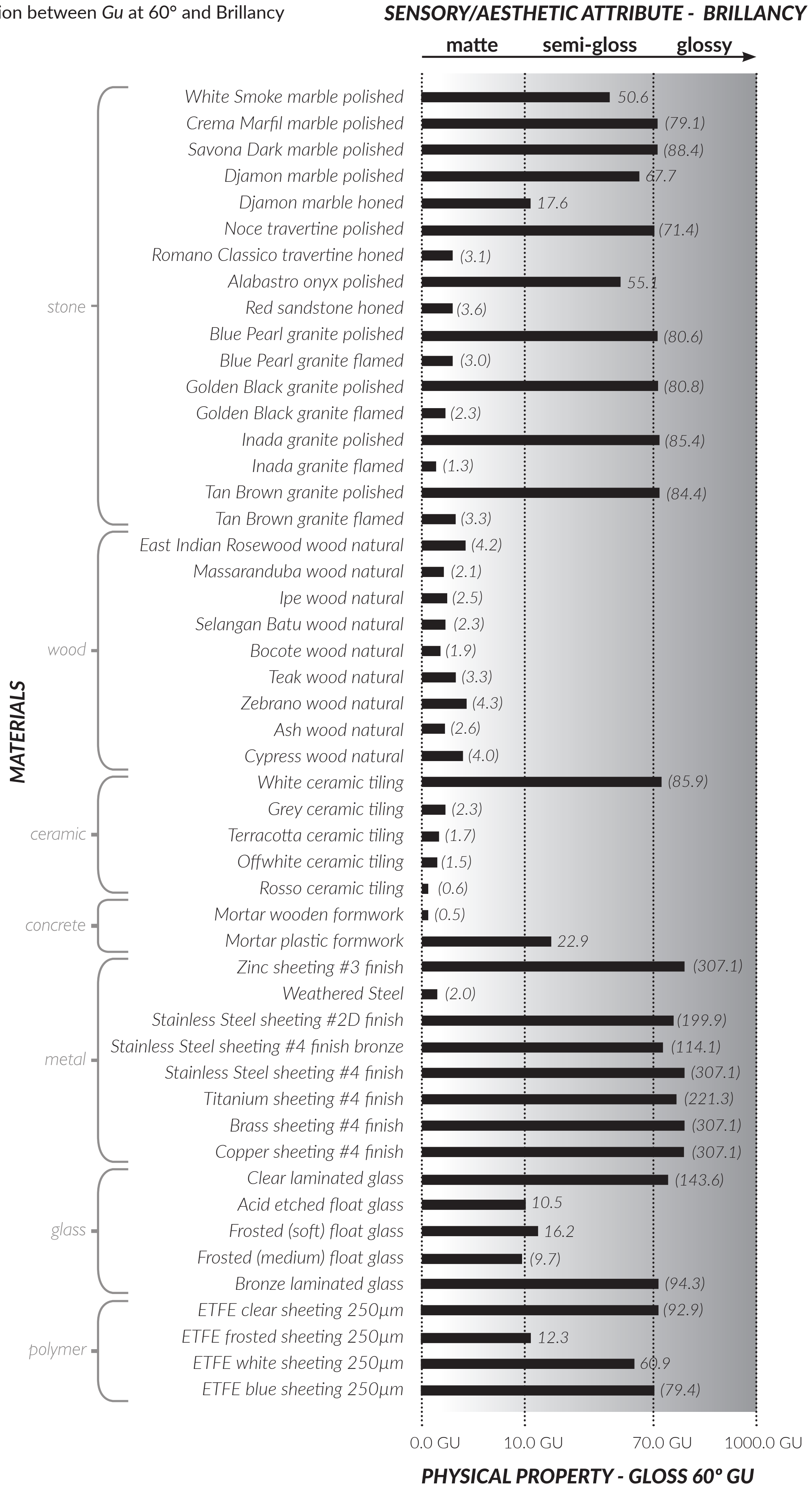
Table 15 shows results in of measurement of specular gloss according to the 60° geometry, for the reason that results need to be compared within the same geometry. The values placed between parenthesis in the table indicate that the 60° geometry is not the optimal geometry for the material sample, however, it still reveals the appropriate parameters for evaluating the sensory/aesthetic attribute of brillancy.

Clear evidence of the influence of surface properties on gloss (*GU*) values were demonstrated, as expected, specially with the stone samples that are from the same material, but went through difference manufacturing processes in terms of surface finish. Stones with a flamed and honed surface finish had *GU* values below 10 at 60°- evidencing that a 85° geometry would be more appropriate to measure these low gloss materials - and were correlated as being matte. As for the stones with a polished surface finish, some were within the threshold of the 60° geometry measure - between 10 *GU* and 70 *GU* - and were correlated as being semi-gloss (White Smoke marble, Djamon marble and Alabastro onyx). However, most stones with a polished surface finish had *GU* values above 70 - evidencing that a 20° geometry would be more appropriate to measure these high gloss materials - and were correlated as being glossy.

The *GU* values for the wood samples also showed that a 85° geometry would be more appropriate to measure them since all values were below 10 at 60°, and were correlated as being matte. The opposite is true for the metals: all samples - except the Weathered Steel - showed that a 20° geometry would be more appropriate to measure them since all values were above 70 at 60°, and were correlated as being glossy.

The difference in the *GU* values of the concrete demonstrated how the formwork influences its surface properties and consequently the sensorial attribute of brillancy. The concrete, with its bulk properties, additionally acquires the brillancy attributes of the formwork in which it was produced, with the wooden formwork rendering it to be matte and the plastic to be semi-gloss.

table 15 - Correlation between *Gu* at 60° and Brillancy



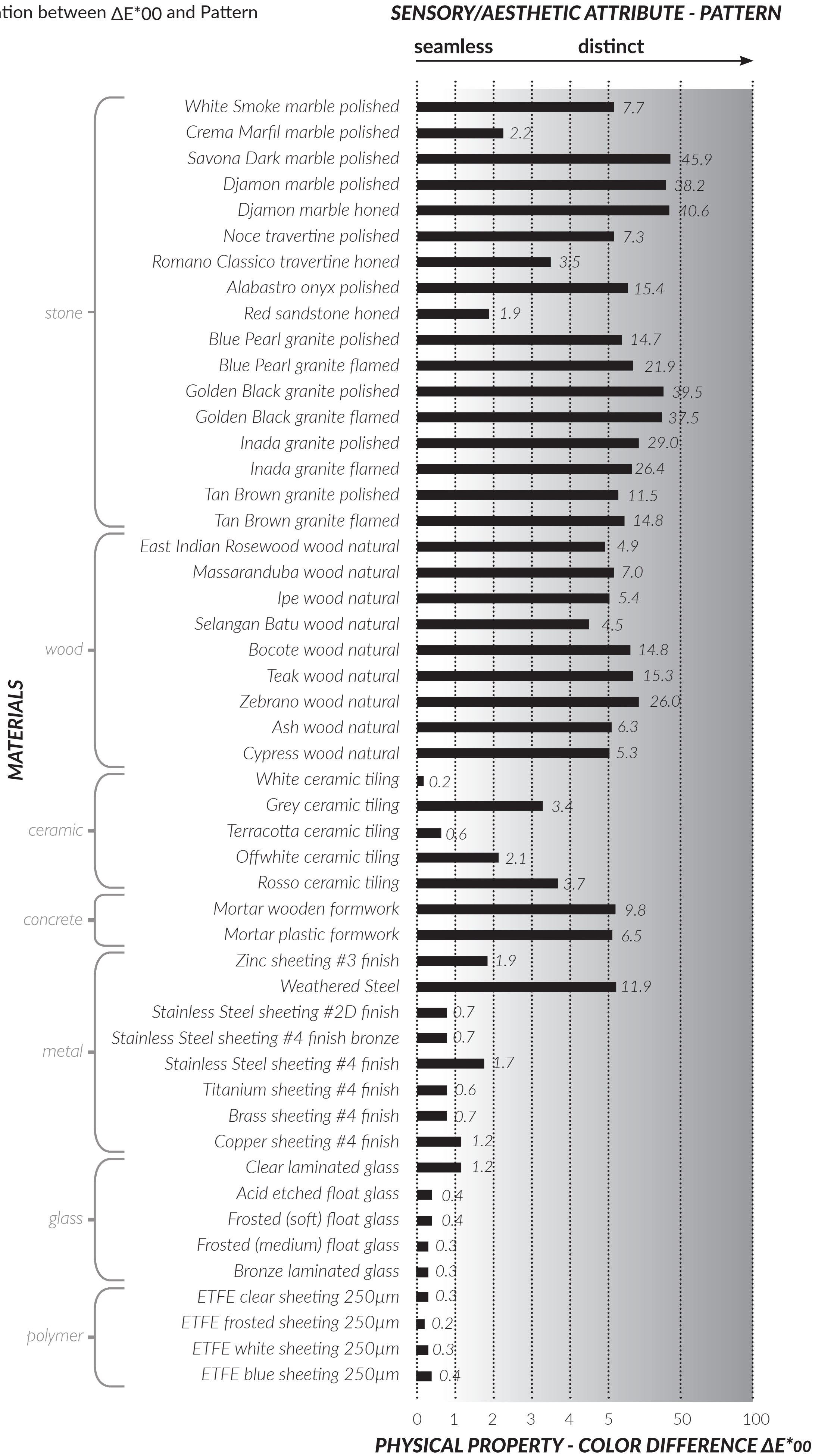
Pattern and Color: First, the interpretation for distinction of pattern follows the parameters set by the research conducted by Mokrzycki & Tatol (2011), where the ΔE^*_{00} value for total color difference are interpreted as:

- $0 < \Delta E^*_{00} < 1$ - the observer does not notice the difference in colors
- $1 < \Delta E^*_{00} < 2$ - only an experienced observer can notice the difference in colors
- $2 < \Delta E^*_{00} < 3.5$ - an unexperienced observer also notices the difference in colors
- $3.5 < \Delta E_{00} < 5$ - a clear difference in color is noticed
- $5 < \Delta E^*_{00}$ - the observer notices two different colors
- $\Delta E^*_{00} = 100$ - colors are exact opposites

Therefore, when the ΔE^*_{00} value is below 2, there is no noticeable color difference within the material, rendering it a seamless pattern. When ΔE^*_{00} value is above 2, color differences within the material becomes increasingly noticeable, reaching an absolute distinct pattern when the ΔE^*_{00} value is 5 or above.

Table 16 evidences that all granite stone samples have ΔE^*_{00} value above 5, as expected, due to its structure composed of different minerals, which renders its multicolored bulk, and therefore, a distinct pattern. As for the metal (except the weathered steel), glass and polymer samples, they all have a seamless pattern. Presumably, this is due to their manufacturing requirements and quality control.

table 16 - Correlation between ΔE*00 and Pattern



Consequently, as ΔE^*_{00} values have been established for every material sample, quantitative values for each color hue can also be determined. It was straightforward to specify the *L* a* b** value of the materials that have a seamless pattern ($0 < \Delta E^*_{00} < 2$), as only one color hue is noticeable (Table 17). All metals (except the weathered steel), glass and polymer samples are constituted of one color hue. In the stone family, only the red sandstone was measured with one color hue, and in the ceramic family, the white and the terracotta ceramic tiling were measured with one color hue.

For the other materials with distinct pattern ($\Delta E^*_{00} > 2$), first, the predominant *L* a* b** value was determined (Table 18), followed by the *L* a* b** value of the second dominant color (Table 19).

table 17 - Correlation between *L* a* b** and Color

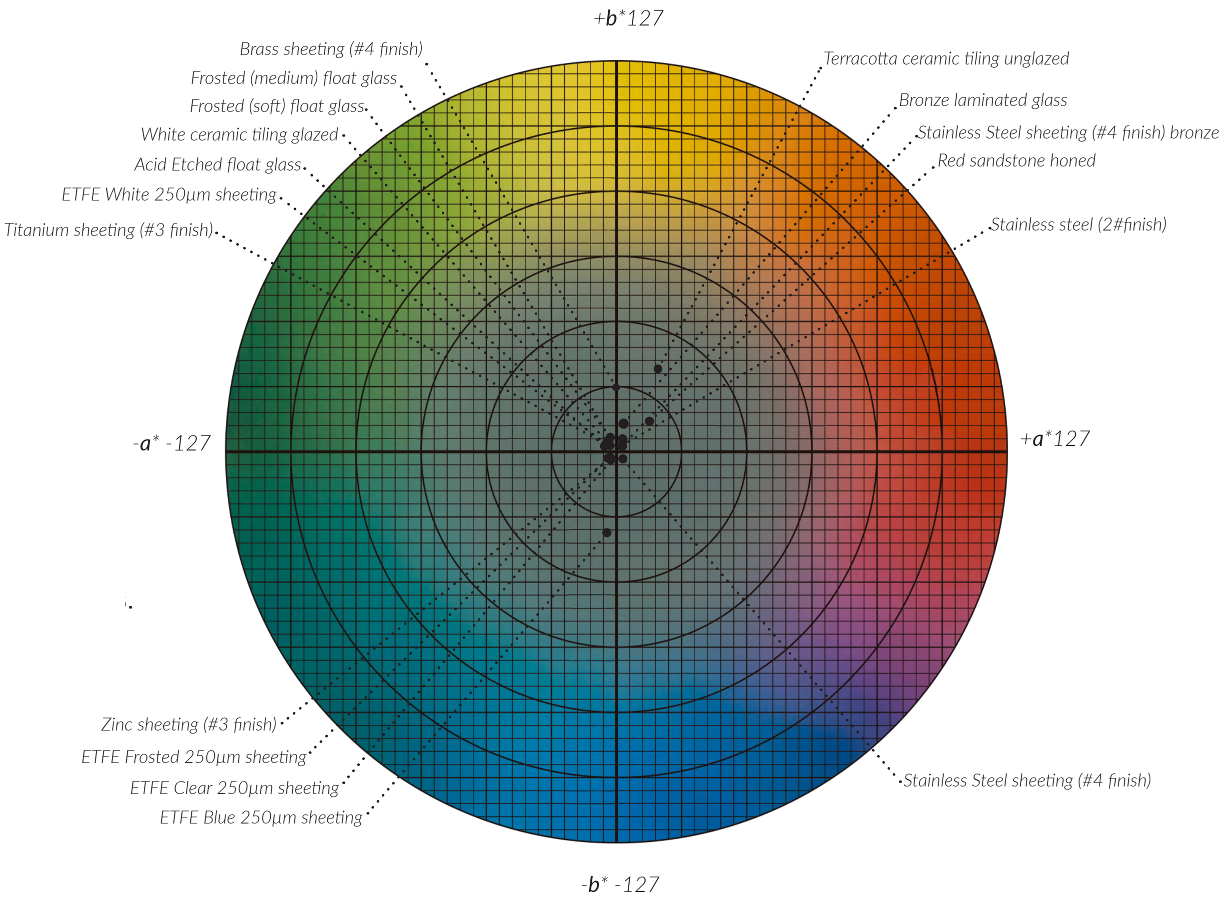
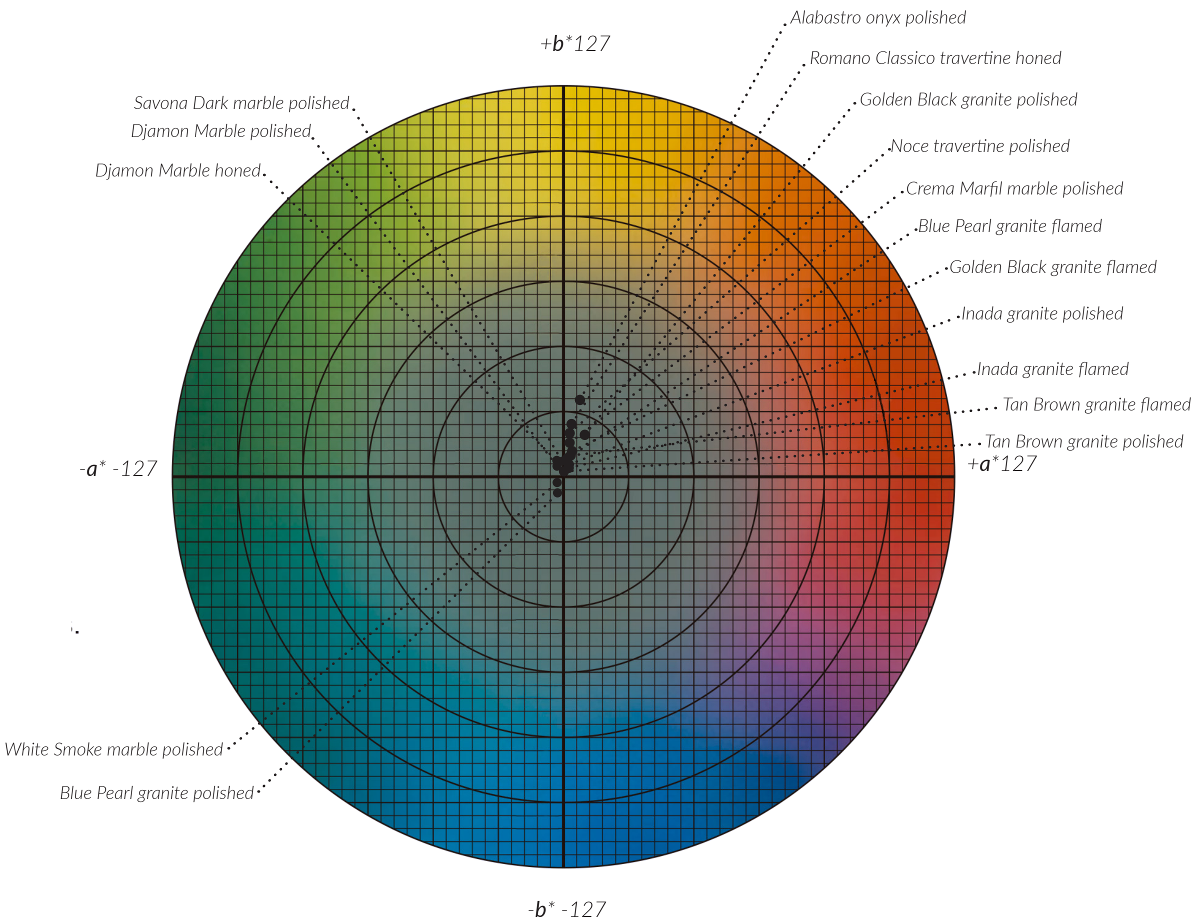


table 18 - Correlation between *L* a* b** and Predominant Color



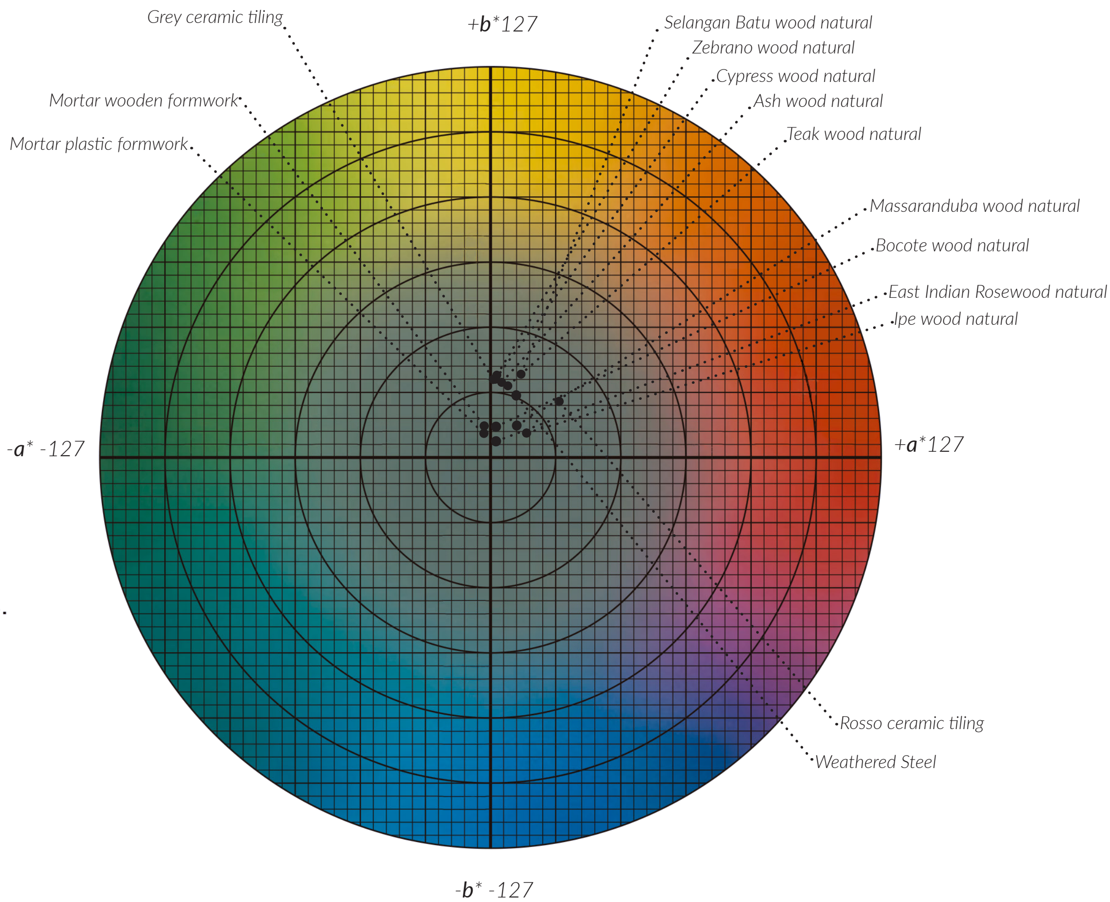
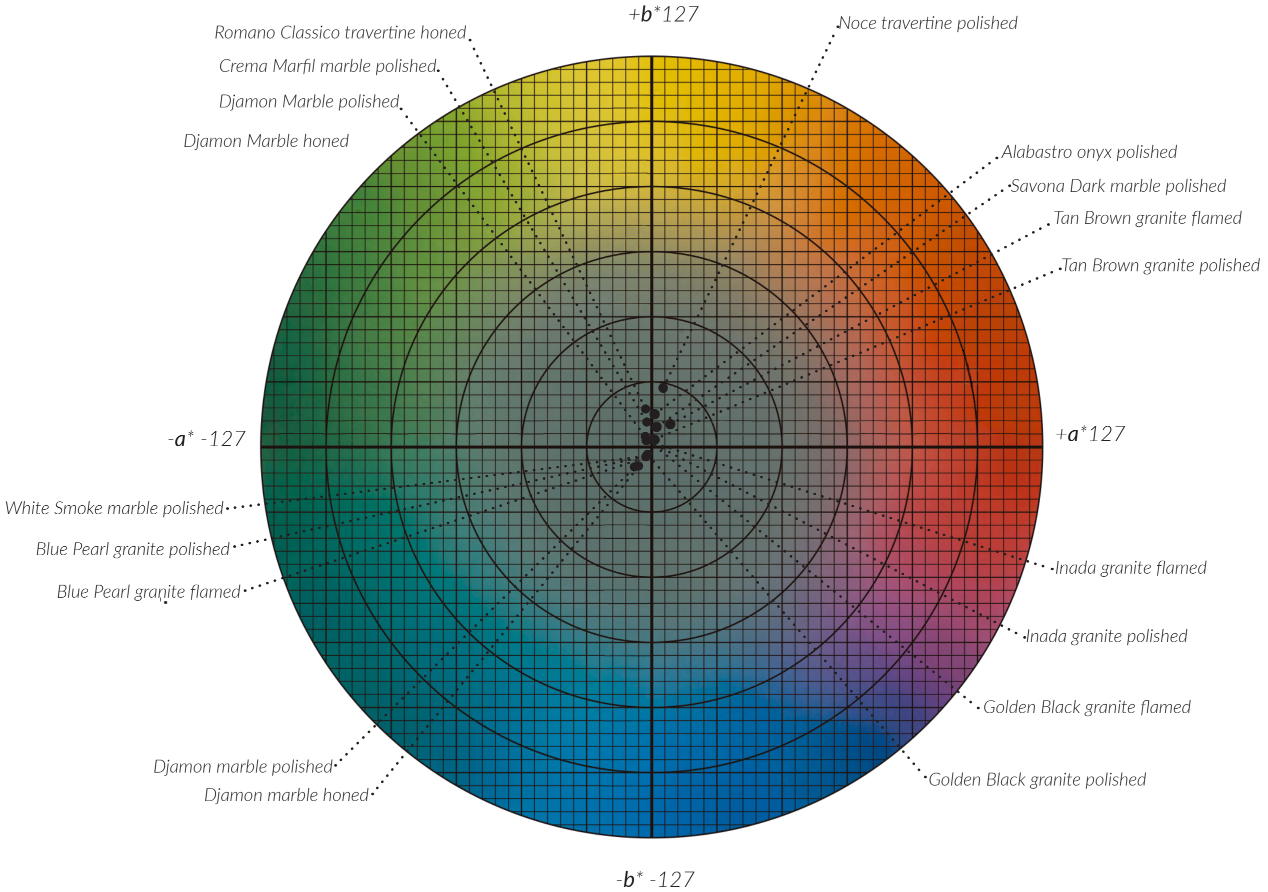
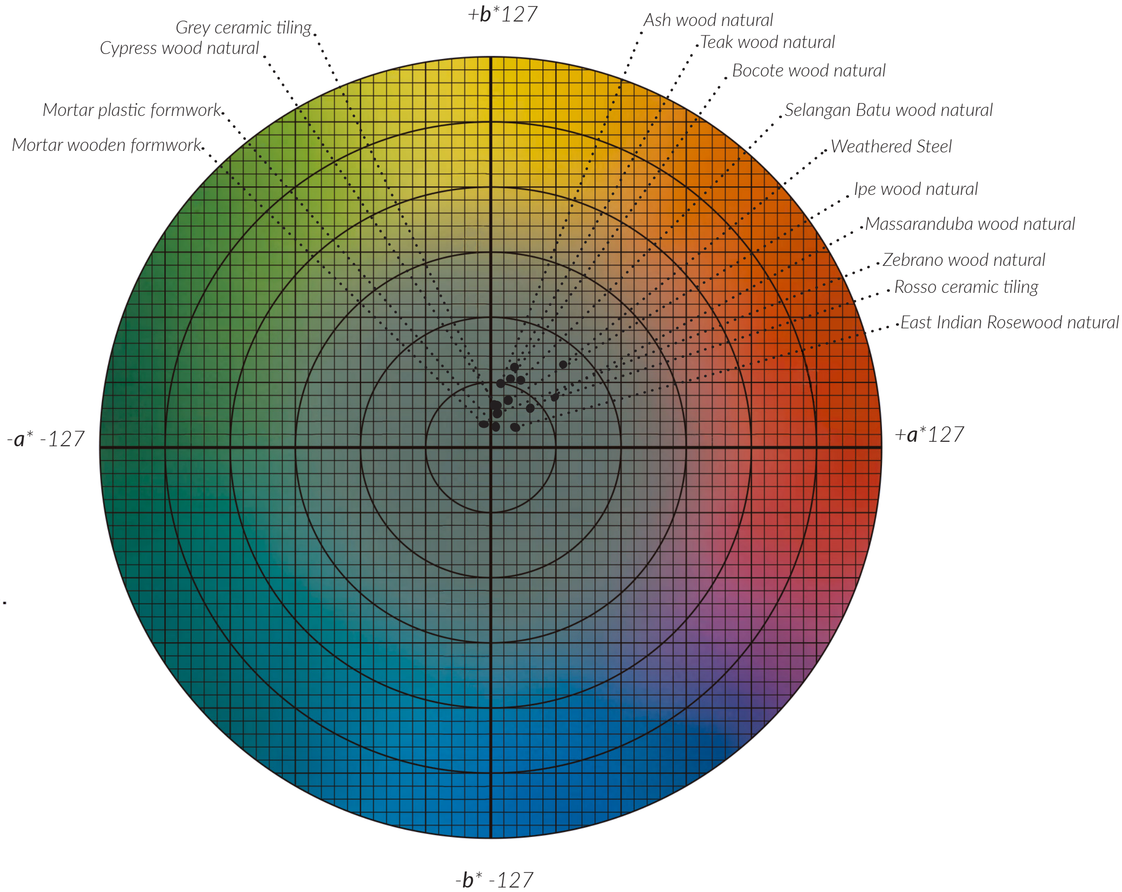


table 19 - Correlation between *L* a* b** and Second Dominant Color

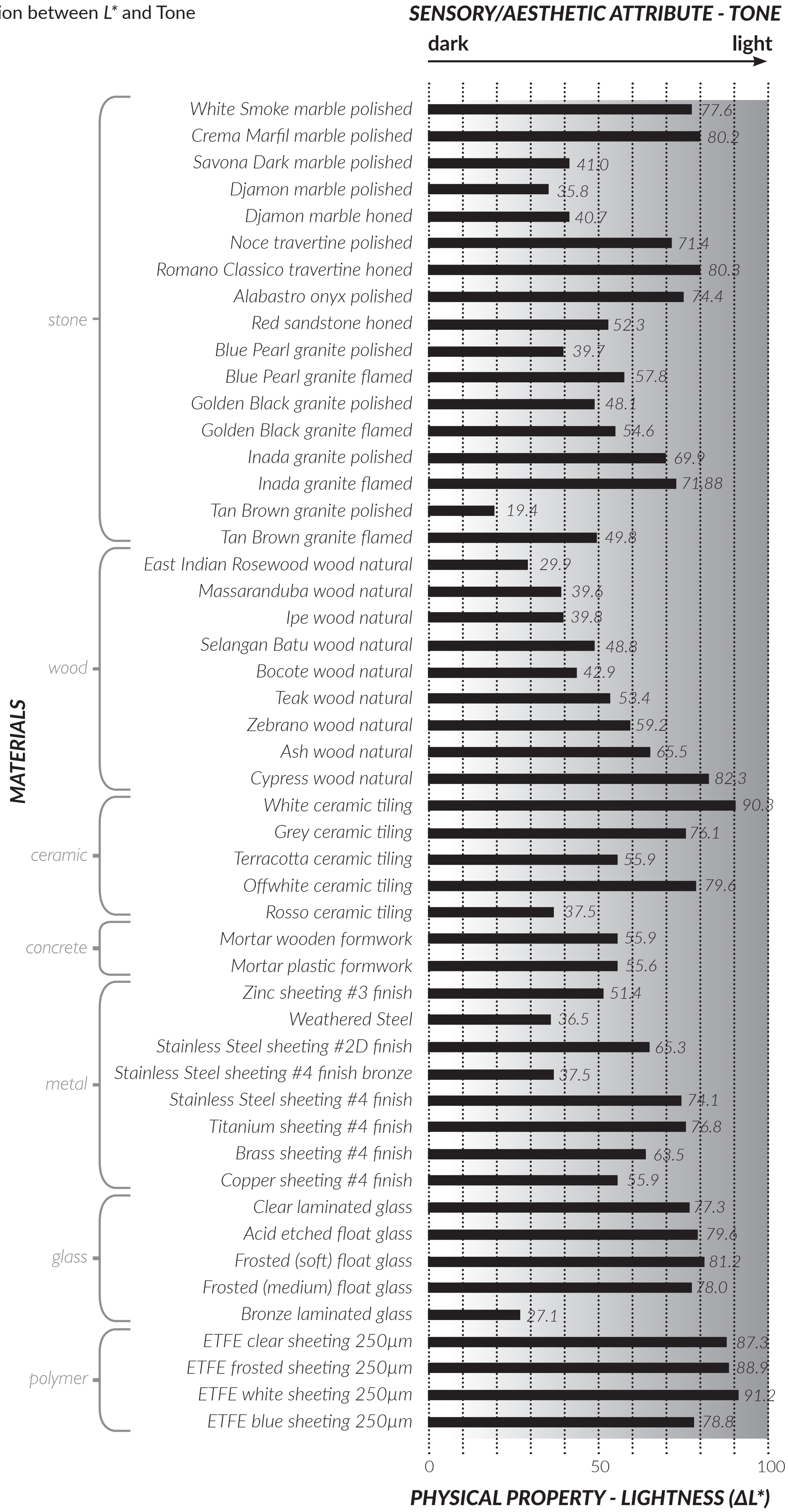




Tone: In the CIELAB color space, lightness is represented by L^*, where the darkest black value is $L^* = 0$, and the brightest white value is $L^* = 100$. Hues of gray lie along the vertical axis between black and white.

A material's color is determined by its structure and bulk properties. Furthermore, the averaged values for L^*- based on the 14 measurements of every sample - show the influence of surface properties on tone values as well (table 20). This was evidenced in the case of the stone samples that are from the same material, but went through difference manufacturing processes in terms of surface finish. Stones that have a polished finish had lower values for L^*, being darker than the stones with a honed finish and flamed finish. Stones that have a honed finish and flamed finish had increased L^* values when compared to their polished versions, with their tone attribute advancing towards light in the gradient scale. It would be interesting, in further research, to compare measurements of the same material with more than two types of surface finish - e.g. polished, honed and flamed - to evaluate if the L^* values increase consistently.

table 20 - Correlation between *L** and Tone



Conclusion

The first advancements towards the proposed tool were accomplished. The experimental process conducted through analysis and measurement of the physical properties of chosen building material samples that correlate to the sensory/aesthetic attributes was relevant to gather the necessary quantitative data in order to establish the proposed tool's database. It was also important as to gain insight on the implications involved when appraising the sensory/aesthetic attributes. As for the process of synthesising the data, the parametric inputs determined for the evaluation of the materials according to the correspondence of the sensory/aesthetic attributes and the physical properties will allow the proposed tool to operate and be evaluated.

A major implication involved when appraising aesthetic performance concerns the importance of surface properties data to enable the correlation to the sensory/aesthetic attributes. Bulk properties are intrinsic to material's micro and macrostructure, and are a major focus of material science and engineering. Consequently, most informational data on material selection tools are based on bulk properties. Surface properties can also be intrinsic to a material. However, they are mostly extrinsic and conditioned by the material's manufacturing techniques. As materials are manufactured into products to be used in building construction applications - e.g. ceramic tiles, wood boards, marble slabs, glass panels - they can acquire a variety of different surface properties depending on surface finishing processes. For material products that follow standard grading and classification - e.g cement and concrete, wood timber and lumber, metal sheeting - surface properties should not be a problem to be included in material selection tools. However, material products that do not follow standard grading and classification - like certain types of ceramics and composites - may present a problem as to include their technical information into databases, since they present product-based properties. This may be an obstacle for incorporating aesthetic performance into existing material selection tools.

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| Part 3 |
STRUCTURE FOR IMPLEMENTATION

Part 3 depicts the structure for implementation of the proposed tool. The implications of the tool as an operational system are discussed, and an evaluation is proposed for assessing its validation. This assessment aimed at understanding the situation in which the tool would be effective for improving the framework of material selection in architecture (Chapter 6).

I CHAPTER 6 I

The Tool's Operation

The previous chapter explained the foundation of the proposed tool: how the experimental process of composing its database evolved, and how the parameters for appraising aesthetic performance were set based on the correlation between the acquired data on the physical properties of the material samples and the sensory/aesthetic attributes.
In this chapter, the development of the dummy tool is explained. The crucial issues to ensure the tool as an operational system were addressed - its data systemisation, visualisation, interactivity and practicality. Furthermore, its functionality was simulated. This assessment aimed at understanding the situation in which the tool would be effective.

6.1 Functionality

A dummy operational system was developed to explore the relevant aspects to be considered in the proposed tool and to test its functionality. In the real application, the purpose is for the tool to have an add-on format. It would add its features of appraising aesthetic performance to an existing computer aided multiple criteria material selection tool oriented for engineering. It would operate by utilising the existing tool's database on the physical properties of materials in order to correlate it to sensory/aesthetic attributes parameters. In the dummy tool, the 50 material samples that were analysed compose its database. This aimed at providing a variety of examples and enough content that would be sufficient to allow the dummy tool's evaluation as an operating system.

The dummy tool required basic software programming in order to operate as a computer application, where a triangulation algorithm was created to link the correlational parameters of the quantitative data, the qualitative data and the material. Furthermore, computational softwares and interface templates that contemplate graphical representations for materials' physical properties were analysed with the objective of formulating a systematic and comprehensive design for the tool.

The tool should work as an assistant to identify which materials have particular aesthetic and sensory qualities are important for a design or that the user is looking for. This identification intends to clarify the aesthetic performance requirements for material's search, where minimum steps of interpretation should be needed to find the materials that fit the requirement. Important issues to ensure the tool's functionality as a multiple criteria material selection system were related to data systemisation and visualisation, and the tool's interactivity and practicality.

6.1.1 Data Systemisation

Data systemisation concerns the structure of the information that is processed and provided by the tool. It should assist to identify which materials have particular aesthetic and sensory qualities that are important for a design or that the user is looking for. This identification intends to clarify the aesthetic performance requirements for material's search, where minimum steps of interpretation should be needed to find the materials that fit the requirement. The tool's structure is based on the sets of parameters determined by the correspondence between quantitative data on material's physical properties and qualitative appraisal of sensory/aesthetic attributes in Chapter 5. Figure 40 shows the diagrammatic structure of the tool's work flow, where the selection criteria inputs are based on qualitative scales of appraisal, the evaluation process is based on a automatic correlational search of the database, and the result is a suggestion of the suitable material/materials that fit the specified selection criteria.

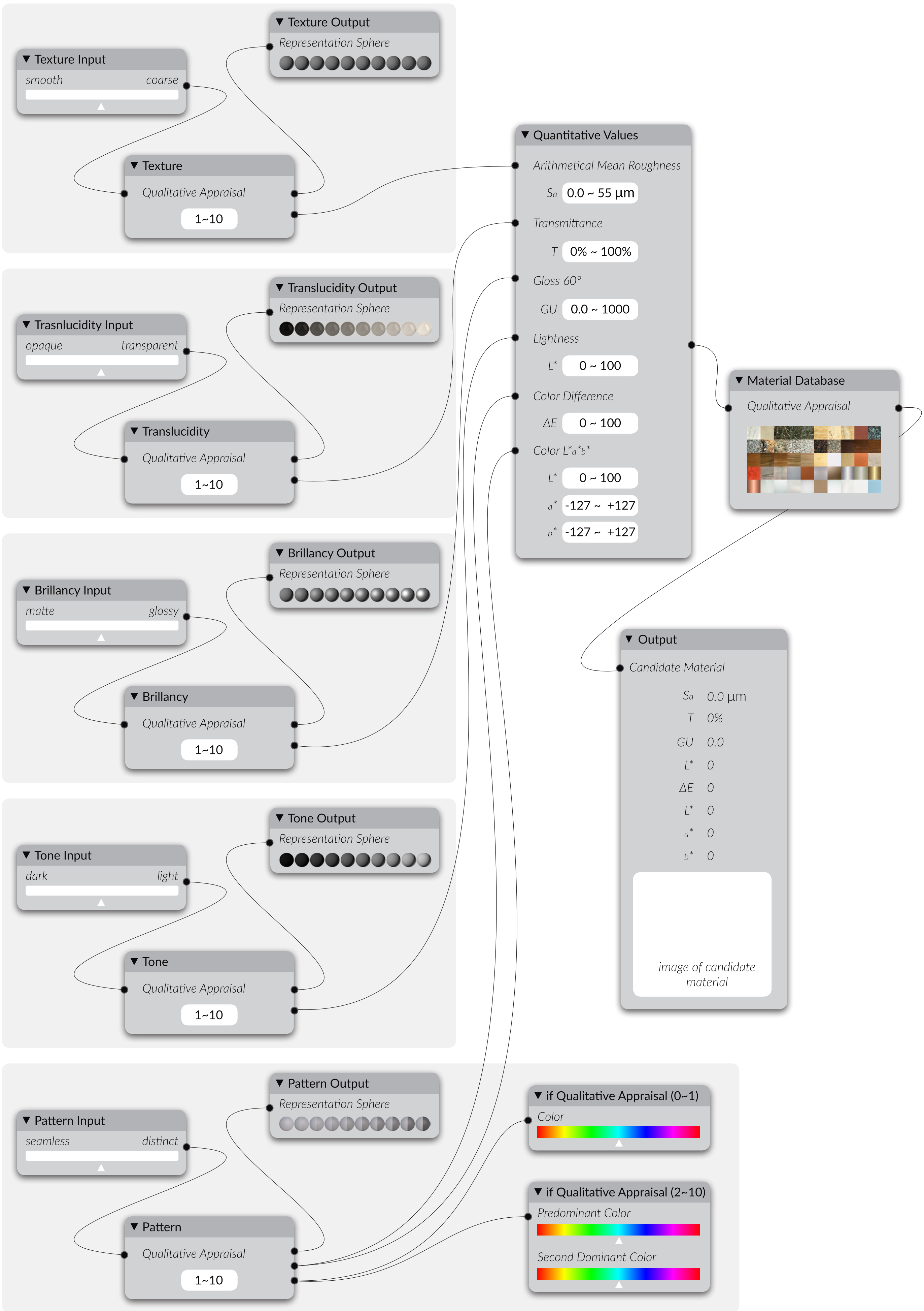


figure 40 - Diagramatic structure of the tool's work flow

However, in order for the tool to have an operational system based on multiple criteria selection, first, a common metric between data sets needed to be established. Most sensory/aesthetic attributes appraised by the tool are denominated semantically by a pair of antonym adjectives, expect for color. This criteria, where selection is defined by qualitative objectives/requirements through the definition of opposing parameters, is suitable to be rated in a point scale. Therefore, a comparable metric system to rank the sensory/aesthetic attributes was determined (Table 21). It is based on a 0 to 100 units scale, with 10 units integers, that represent efficacy scores for the selection criteria.

table 21 - Definition of metric system in 10 point scale

10 point scale	Texture	Translucidity	Brillancy	Pattern	Tone
	smooth	opaque	matte	seamless	dark
0	0 ~ 0.1 μm	0 ~ 0.09%	0 ~ 1 *GU*	0 ~ 0.4	0 ~ 1
10	0.2 ~1 μm	0.01 ~ 10%	1.1 ~ 5 *GU*	0.5 ~ 2	1.1 ~ 10
20	1.1 ~ 2 μm	10 ~19.9%	5.1 ~ 10 *GU*	2.1 ~ 3.5	10.1 ~ 20
30	2.1 ~ 5 μm	20 ~ 29.9%	10.1 ~ 20 *GU*	3.6 ~ 5	20.1 ~ 30
40	5.1 ~ 13 μm	30 ~ 39.9%	20.1 ~ 30 *GU*	5.1 ~ 15	30.1 ~ 40
50	13.1 ~ 20 μm	40 ~ 49.9%	30.1 ~ 40 *GU*	15.1 ~ 25	40.1 ~ 50
60	20.1 ~ 30 μm	50 ~ 59.9%	40.1 ~ 50 *GU*	25.1 ~ 35	50.1 ~ 60
70	30.1 ~ 37 μm	60 ~ 69.9%	50.1 ~ 60 *GU*	35.1 ~ 50	60.1 ~ 70
80	37.1 ~ 45 μm	70 ~ 79.9%	60.1 ~ 70 *GU*	50.1 ~ 65	70.1 ~ 80
90	45.1 ~ 50 μm	80 ~ 89.9%	70.1 ~ 150 *GU*	65.1 ~ 80	80.1 ~ 90
100	50.1 ~ 55 μm	90 ~ 100%	150 ~ 1000 *GU*	80 ~ 100	90.1 ~ 100
	coarse	translucent	glossy	distinct	light

This comparable metric system for assessing the appraisal of the sensory/aesthetic attributes was graphically represented as ten-point one-dimensional scales that separate the two antonym adjectives that represent the extremes of each attribute. The user sets the score points range in the sliding scale to input the parameters he/she wants for the material candidate. This range is also shown as percentage, as to make the selection parameters more clear (figure 41).

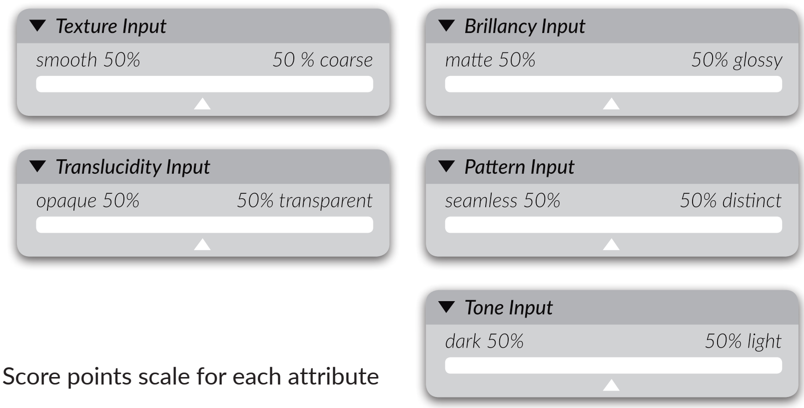


figure 41 - Score points scale for each attribute

As for color attribute, which is dependent on the determination of pattern, one-dimensional scales with all color coordinates of the CIELAB space are used to set the parameters for defining the desired color of the material to be selected, as well as a numerical denomination of its *L* a* b** values (figure 42).

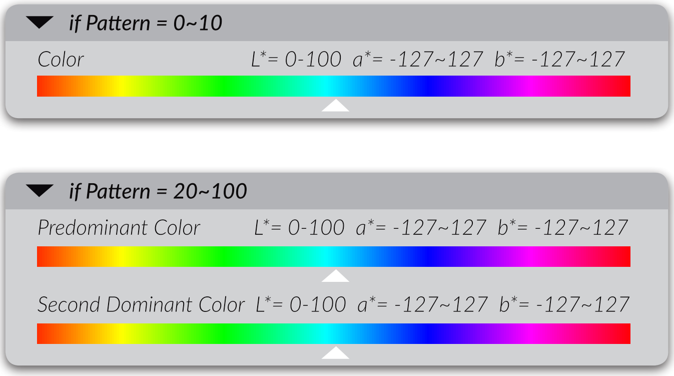


figure 42 - One-dimensional scales for defining color attributes

In order to configure an appraisal that is systematic for its users, aesthetic performance can be assessed by setting parameters of appraisal to sensory/aesthetic attributes in a order of preference/requisite. The desired material characteristic follows the order of prioritisation defined by the user, since some attributes are critical and need to be met exactly, whereas other material aspects can have any value and do not effect the criteria of the selection process.

When all parameters of appraisal deemed important and/or necessary by the user have been input, the image of the material or materials that match the selection criteria will be displayed on the tool's interface. By clicking on the image, all technical data related to its physical properties that correspond to its aesthetic performance becomes accessible (figure 43). This feature intends to clarify the correlation between the qualitative and quantitative appraisal of materials and make all data available for further selection purposes.

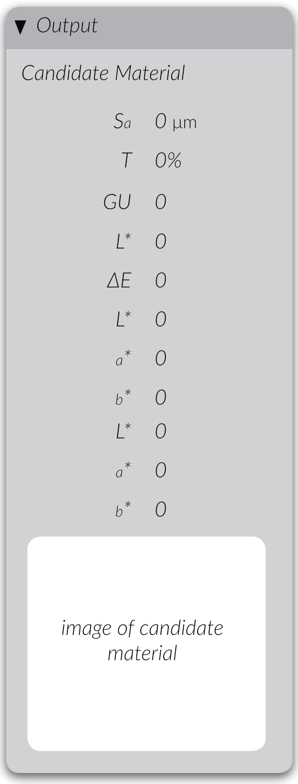


figure 43 - Image and technical details of candidate materia

6.1.2 Data Visualisation

Visual communication is a crucial aspect of computer applications, where the design of the interface can affect significantly its functionality. As the proposed tool's selection criteria is based on a qualitative appraisal, its primary interface was designed to embody less technical features, and to create a more intuitive - yet descriptive - narrative of this selection criteria. All data were made to be displayed as symbols, scales and images, and with minimum text, in order to make the tool's employment more accessible. As the selection process is completed, a secondary interface becomes available, where the user is able to access detailed quantitative data on the material or materials that correspond to the chosen selection criteria (figure 43).

A big concern is that people may have different interpretations of the sensory and aesthetic aspects of materials that the tool evaluates - which could lead to miscommunication and influence the effectiveness of the selection method when the candidate materials fail to match the users expectation. Therefore, the data visualisation aimed to be a comprehensive and dynamic graphical representation of the criteria appraised by the tool. Computer softwares for generating photorealistic images of 2D and 3D models most often use texture maps - bitmaps or procedural textures - to represent materials. These maps are able to simulate various perceptual characteristics of materials. The software Cinema4D was used for the simulation of each attribute assessed by the tool, and the resulting images were used to illustrate them in the dummy tool.

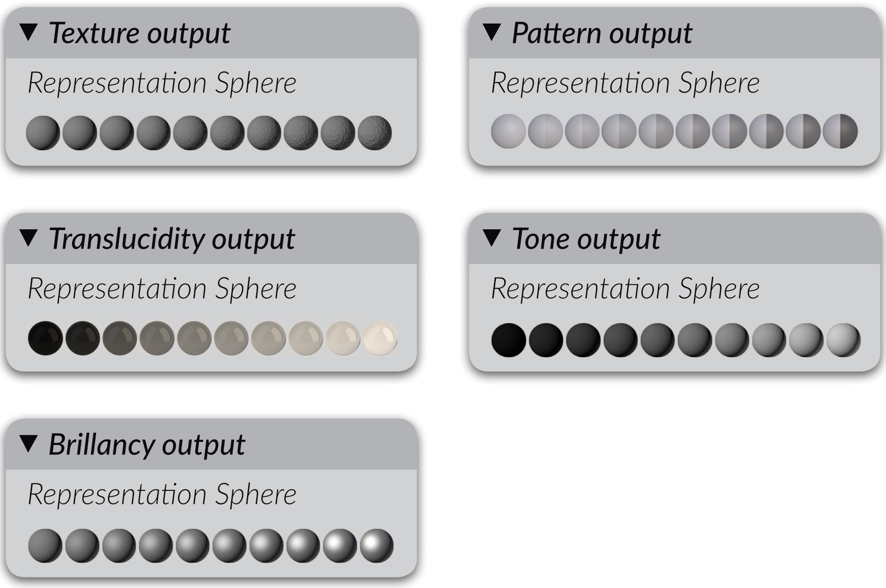


figure 44: Spheres representing the 10 point scale assessment of each attribute

The perceptual characteristics of the sensory/aesthetic attributes are represented as spheres that change simultaneously as the users adjusts their points rating scale (figure 44). Ten different perceptual characteristics for the spheres represent each score point assigned for texture, translucidity, brillancy, pattern and tone. For appraising color, the sphere changes according to the coordinates of the CIELAB space. These features intend to facilitate the assignment of the proper parameters of the material the user is aiming for, where all variants of a certain attribute can be considered whilst evaluating the materials selected based on that attribute.

The proposed interface of the dummy tool is illustrated in figure 45.

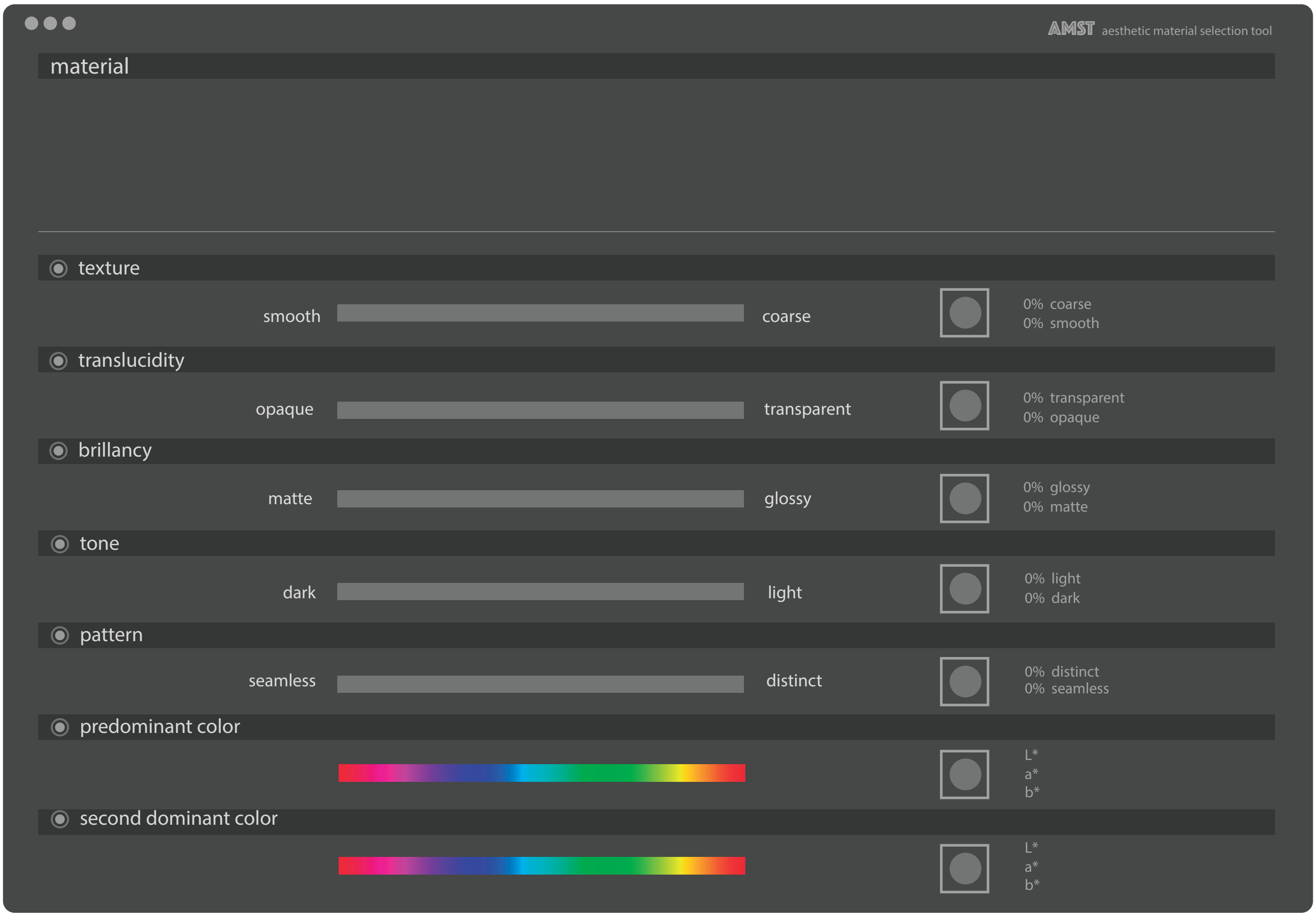


figure 45: The proposed interface of the dummy tool

6.1.3 Interactivity and Practicality

Interactivity refers to the tool's interactive behaviour as experienced by the user, and is best perceived by operating the tool. It concerns how the information within its database is responsive to the user's inputs. For example, whenever there is a change in the input parameter of the attributes, the final selection output is likely to be different.

The tool's practicality concerns its easy usability. The tool should be able to provide practical and clear guidance to its users when assessing the desired sensory/aesthetic attributes to select materials. Furthermore, when more than one material matches the selected criteria, the accessible technical data intends to provide means for intelligent judgements in the selection of different materials with the same sensory/aesthetic attributes.

6.2 Simulation

A series of simulations of the material selection process were conducted to evaluate the tool's functionality in terms of its data systemisation and visualisation, and in terms of its interactivity and practicality. For these simulations, an alpha version of the dummy tool was developed in Android mobile operating system, and was made available on a tablet computer. Three volunteers participated in the simulations, and no instructions about how to operate the dummy tool were given to them.

The first volunteer, a practicing architect with more than 10 years experience in housing design, participated in a simulation to select a material for façade of a building he is presently working on. The project is early on the concept design phase, and the client gave him complete freedom to appoint the materials to be used in the project.

After briefly analysing the tool's interface, the volunteer initiated to input his selection criteria in accordance to his design requirements. The following figures 46 ~ 51 show the sequence of his selection inputs, and figure 52 shows the resulting candidate material with its respective quantitative information.

The volunteer started the selection process by setting the qualitative appraisal for the Pattern attribute to 60% distinct/40% seamless. Within the 50 materials of the database, the dummy tool identified 13 materials that fit that criteria (figure 46).

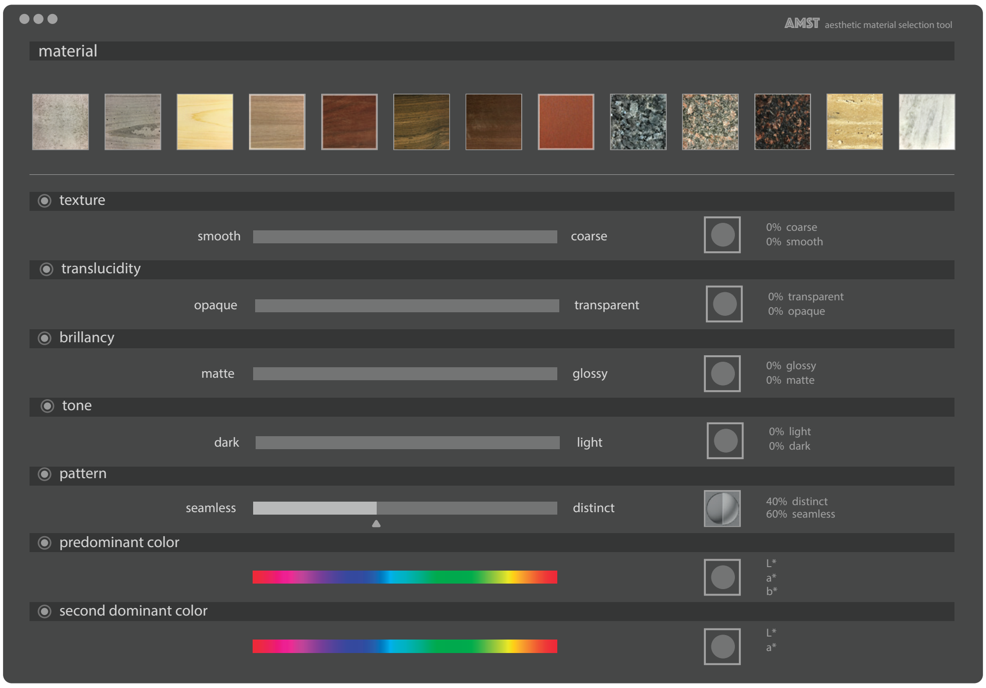


figure 46: Interface of the dummy tool with the input for the qualitative appraisal of Pattern attribute

Next, the qualitative appraisal for Transludicity attribute was set 100% opaque/0% transparent. The dummy tool updated to 12 candidate materials that fit the criteria (figure 47).

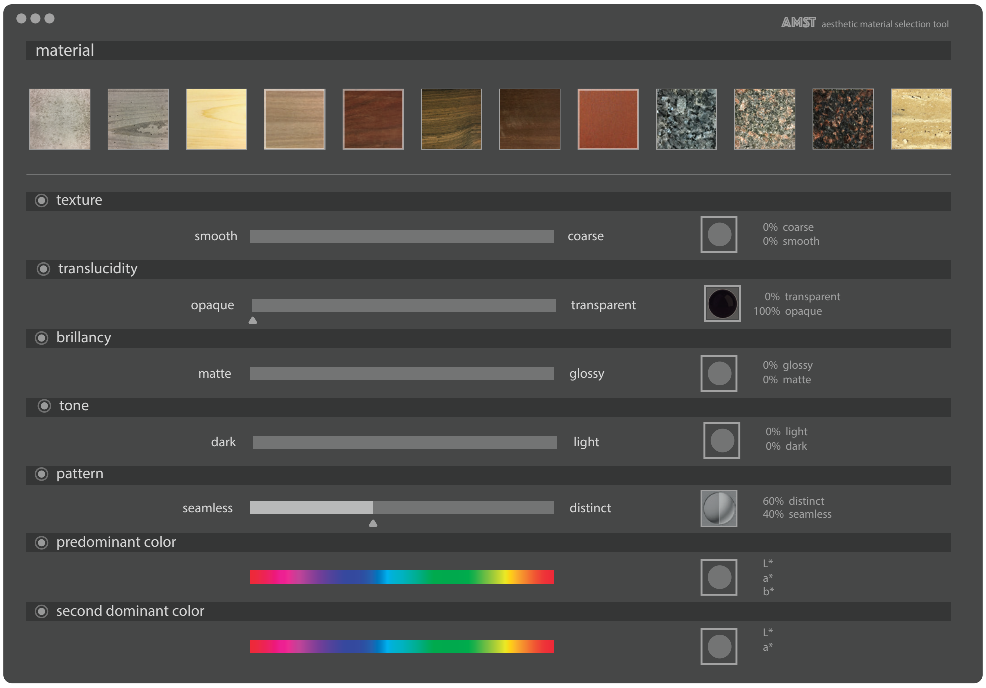


figure 47: Interface of the dummy tool with the input for the qualitative appraisal of Translucidity attribute

Next, the qualitative appraisal for Brillancy attribute was set to 90%matte/10%glossy. The dummy tool updated to 7 candidate materials that fit the criteria (figure 48).

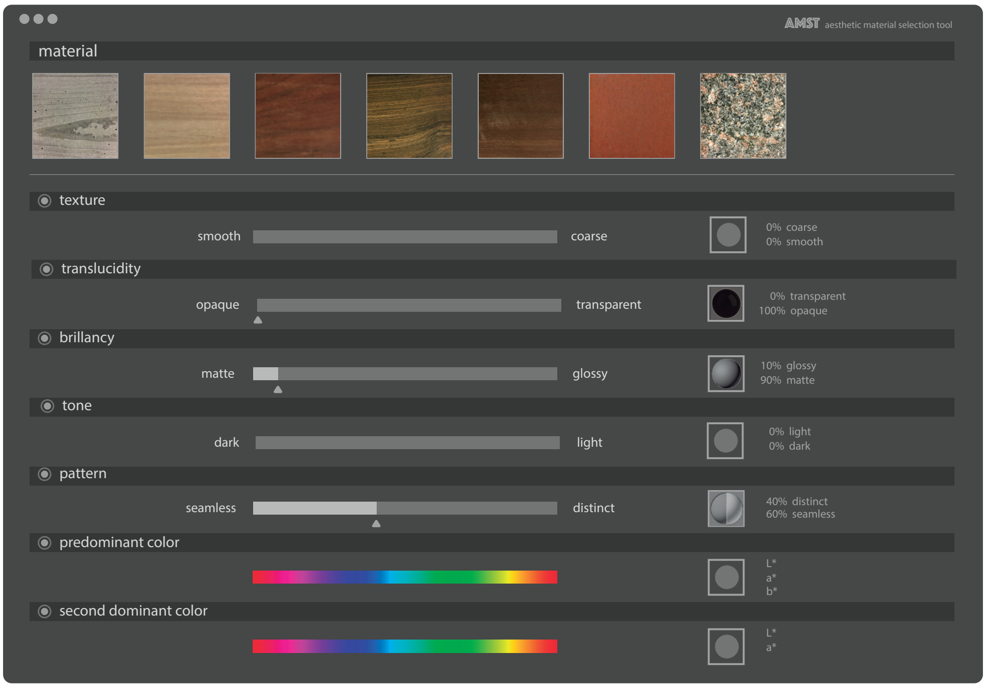


figure 48: Interface of the dummy tool with the input for the qualitative appraisal of Brillancy attribute

Next, the qualitative appraisal for Texture attribute was set to 70% smooth/30% coarse. The dummy tool updated to 2 candidate materials that fit the criteria (figure 49).

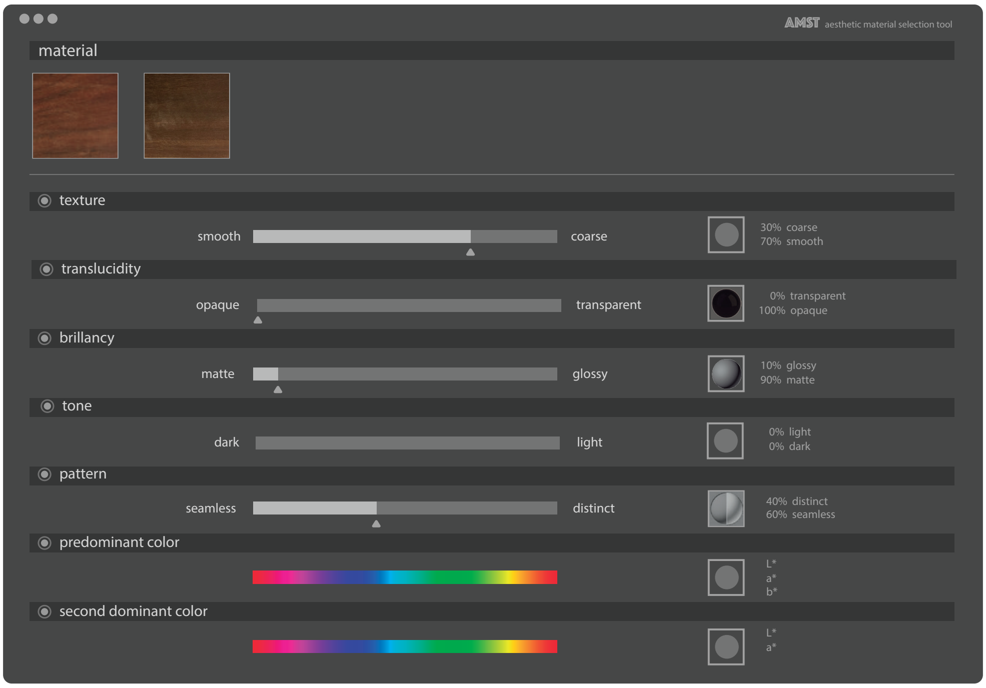


figure 49: Interface of the dummy tool with the input for the qualitative appraisal of Texture attribute

Next, the qualitative appraisal for Tone attribute was set to 60% dark/40% light. The dummy tool updated to 2 candidate materials that fit the criteria (figure 50).

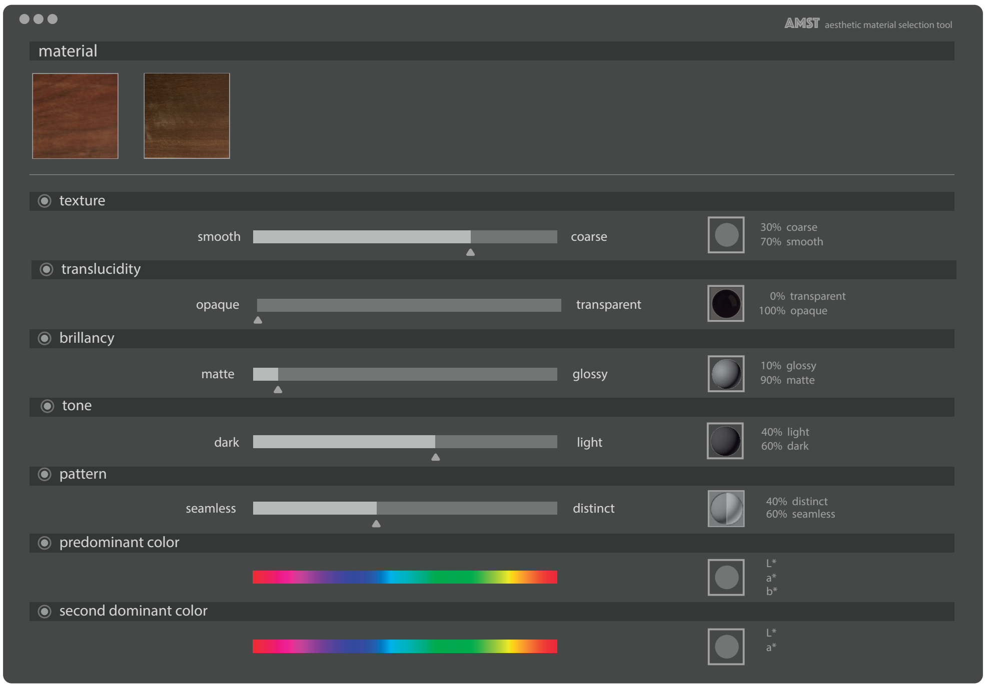


figure 50: Interface of the dummy tool with the input for the qualitative appraisal of Tone attribute

Next, the qualitative appraisal for Predominant Color attribute was set, followed by the Second Dominant Color. The dummy tool updated to 1 optimal candidate materials that fit the criteria (figure 51).

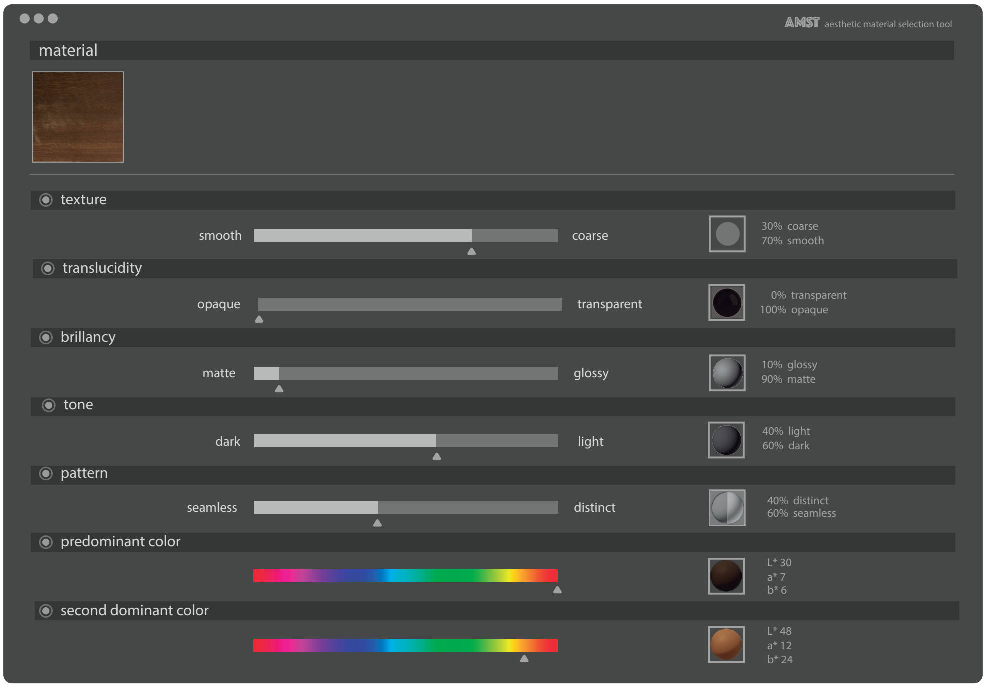


figure 51: Interface of the dummy tool with the input for the qualitative appraisal of Predominant Color and Second Dominant Color attributes

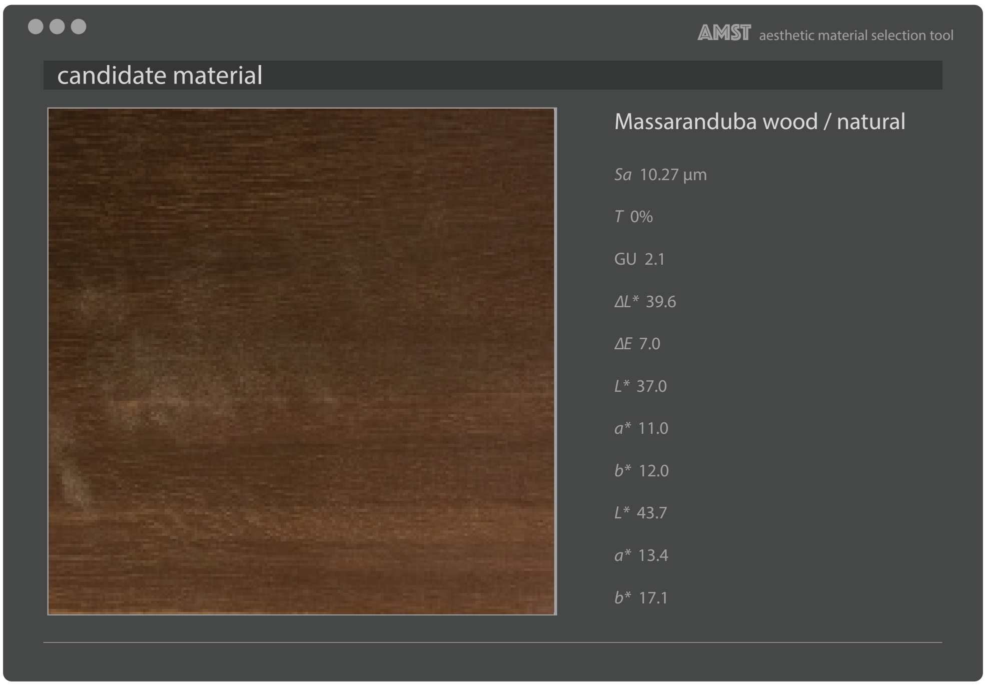


figure 52: Secondary interface of the dummy tool with quantitative data of the optimal candidate material established by the inputs of selection criteria

At the end of this selection process, one material was considered optimal for fitting all the criteria input by the volunteer. The dummy tool then displays a secondary interface with the respective quantitative information on the optimal material candidate (figure 52).

The second volunteer, a 3rd year undergraduate architecture student, participated in a simulation to select a material for a project that she is proposing for a design studio at university. It is conceptual design for a small pavilion.

After taking some time to analyse the tool's interface, the second volunteer initiated to input her selection criteria in accordance to her design requirements. The following figures 53 ~ 55 show the sequence of her selection inputs, and figure 56 shows the resulting candidate material with its respective quantitative information.

The second volunteer started the selection process by setting the qualitative appraisal for the Translucidity attribute to 10% opaque/90% transparent. Within the 50 materials of the database, the dummy tool identified 3 materials that fit that criteria (figure 53).

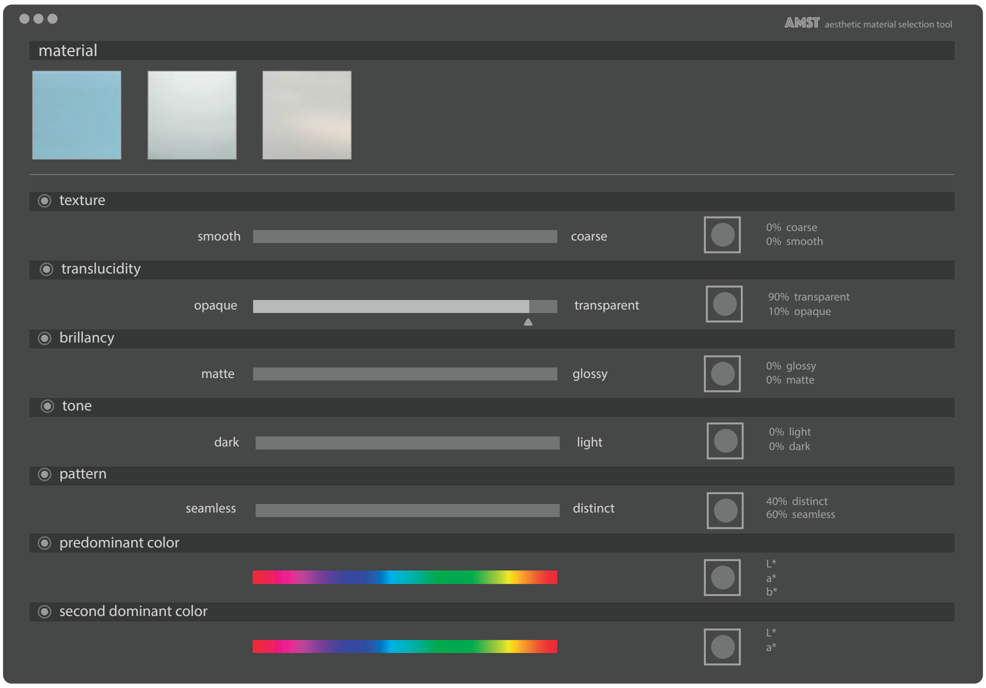


figure 53: Interface of the dummy tool with the input for the qualitative appraisal of Translucidity attribute

Next, the qualitative appraisal for Pattern attribute was set 100% seamless/0% distinct. The dummy tool updated to 2 candidate materials that fit the criteria (figure 54).

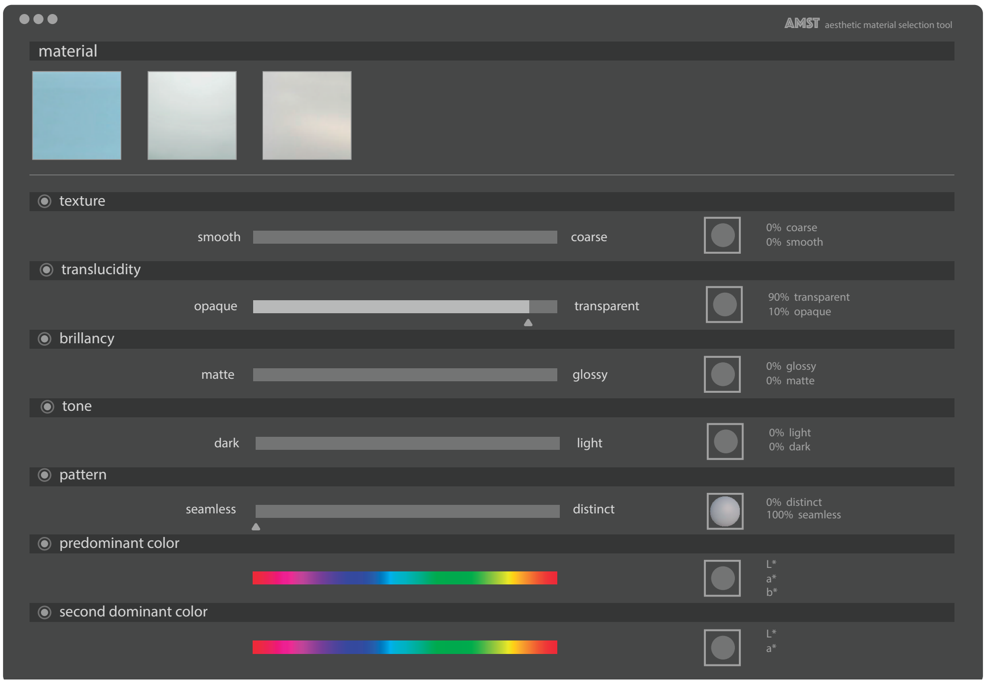


figure 54: Interface of the dummy tool with the input for the qualitative appraisal of Pattern attribute

Next, the qualitative appraisal for Predominant Color attribute was set. The dummy tool updated to 1 optimal candidate materials that fit the criteria (figure 55).

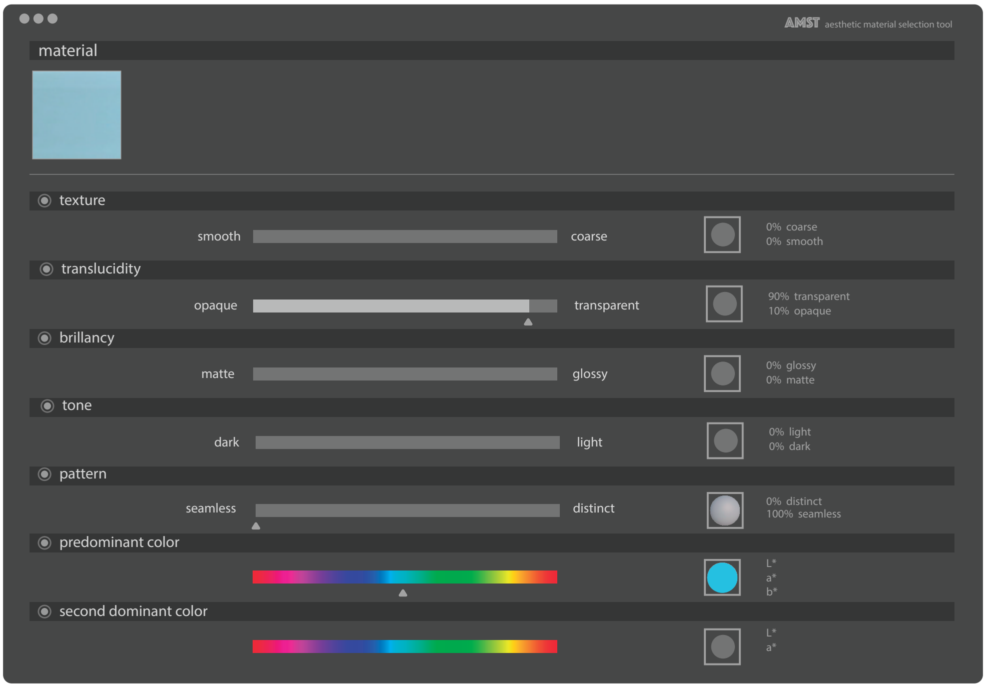


figure 55: Interface of the dummy tool with the input for the qualitative appraisal of Predominant Color attribute

The volunteer intended to set the qualitative appraisal for other attributes. However, since the selection process had already come to an optimum material according to previous qualitative inputs, no other parameters could be added. The dummy tool then displays the secondary interface with the respective quantitative information on the optimal material candidate (figure 56).

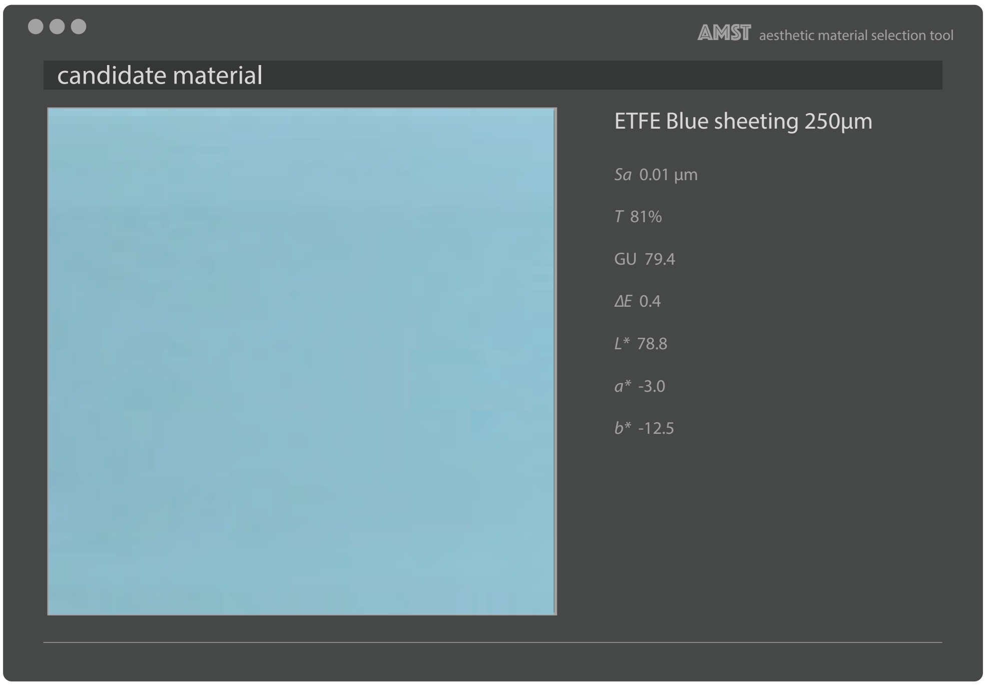


figure 56: Secondary interface of the dummy tool with quantitative data of the optimal candidate material established by the inputs of selection criteria

The third volunteer, a university researcher, participated in a simulation to select a material for the façade of his future house, assuming the position of a client. The idea was to test the material selection process within the tool with someone not in the field of architecture or design. This volunteer took some time to analyse how the tool worked before initiating the selection process. The following figures 57 ~ 60 show the sequence of her selection inputs, and figure 61 shows the resulting candidate material with its respective quantitative information.

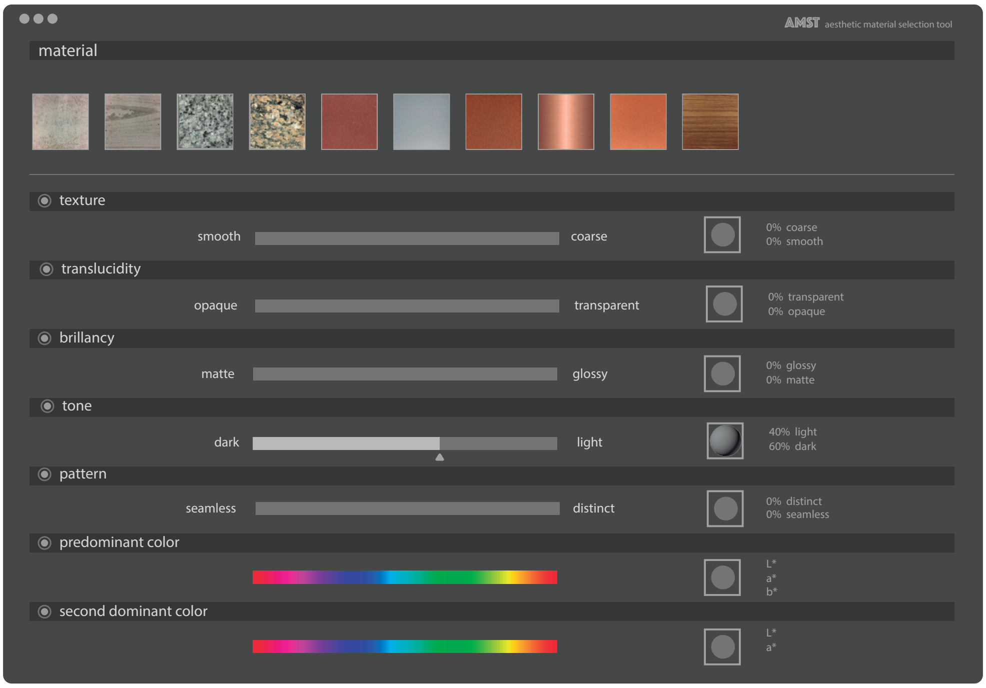


figure 57: Interface of the dummy tool with the input for the qualitative appraisal of Tone attribute

The third volunteer started the selection process by setting the qualitative appraisal for the Tone attribute to 60% dark/40% light. Within the 50 materials of the database, the dummy tool identified 10 materials that fit that criteria (figure 57).

Next, he intended to set an input for Translucidity. However, realising that all of the materials selected so far were opaque, he chose the next attribute that would fulfil his requirements.

Next, the qualitative appraisal for Pattern attribute was set to 90% seamless/10% distinct. The dummy tool updated to 8 candidate materials that fit the criteria (figure 58).

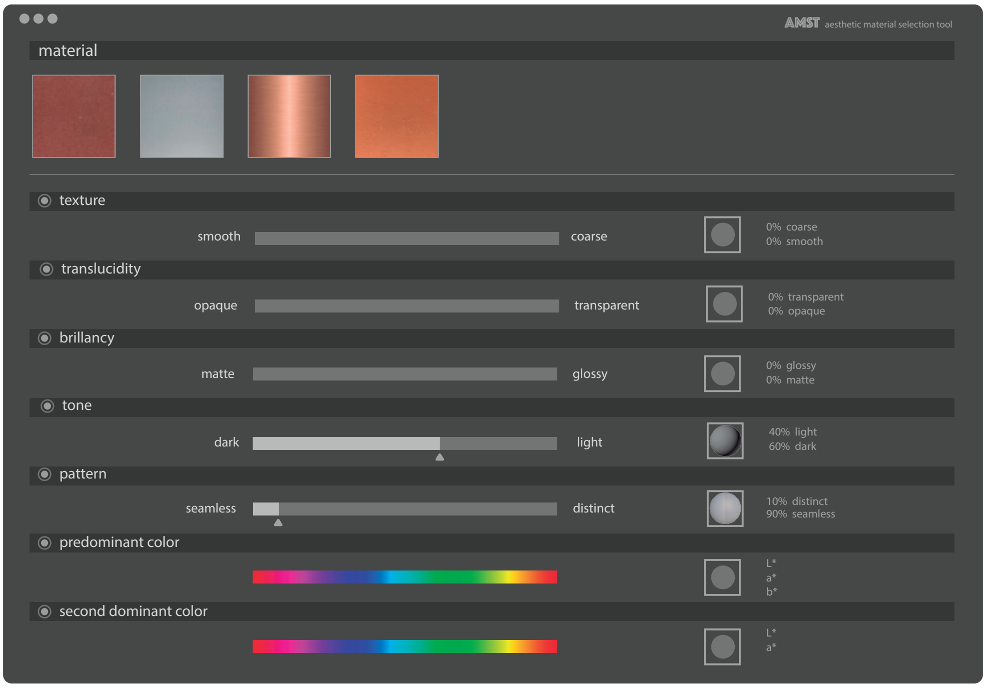


figure 58: Interface of the dummy tool with the input for the qualitative appraisal of Pattern attribute

Next, the qualitative appraisal for Brillancy attribute was set to 90% matte/10% glossy. The dummy tool updated to 2 candidate materials that fit the criteria (figure 59).

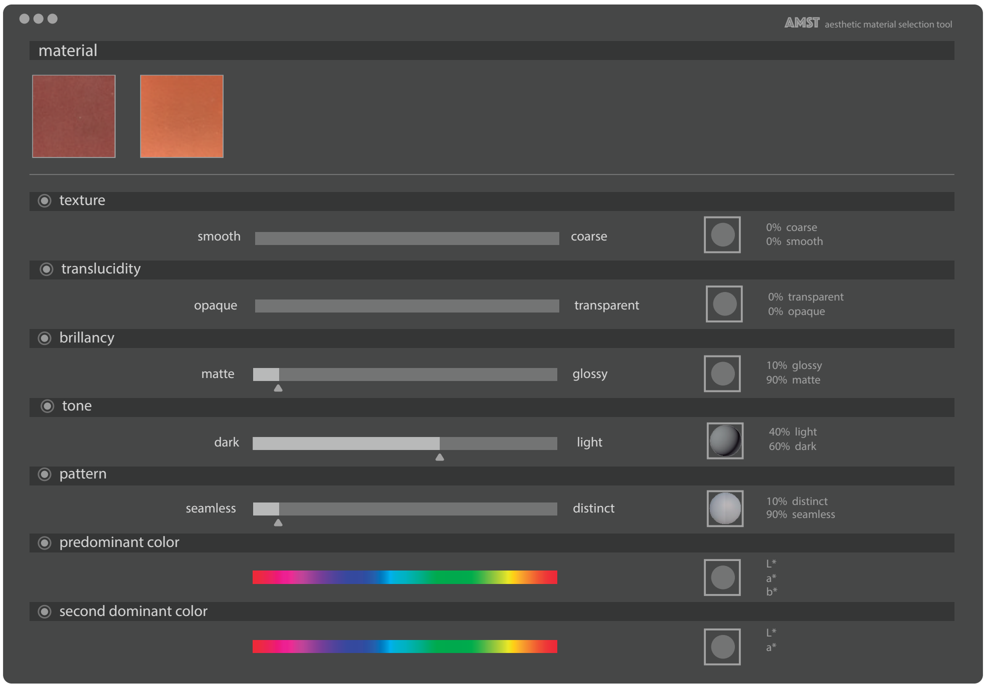


figure 59: Interface of the dummy tool with the input for the qualitative appraisal of Brillancy attribute

Next, the qualitative appraisal for Texture attribute was set to 60% smooth/40& coarse. The dummy tool updated to 1 candidate materials that fit the criteria (figure 60). One material was considered optimal for fitting all the criteria input by the third volunteer.

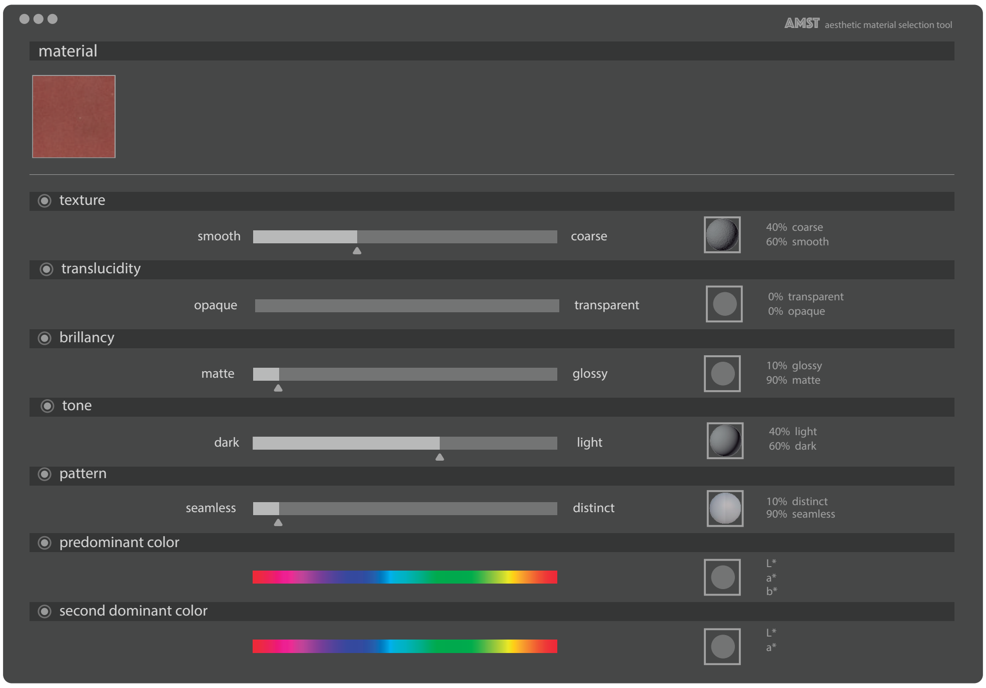


figure 60: Interface of the dummy tool with the input for the qualitative appraisal of Texture attribute

The dummy tool then displays a secondary interface with the respective quantitative information on the optimal material candidate (figure 61).

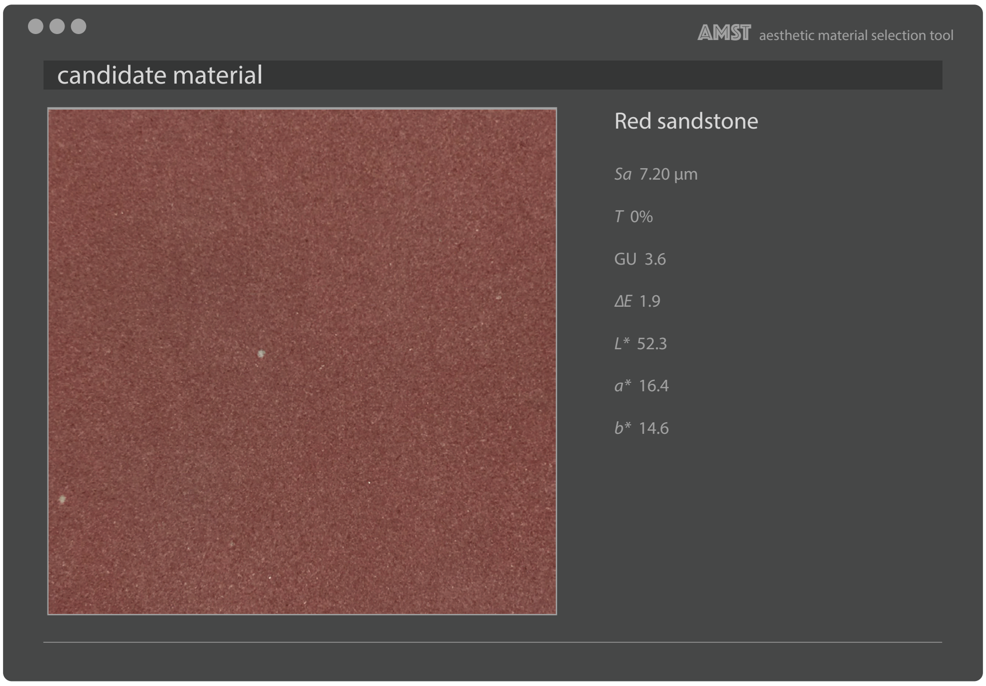


figure 61: Secondary interface of the dummy tool with quantitative data of the optipal candidate material established by the inputs of selection criteria

6.3 Conclusion

The material selection simulation with the dummy tool was able to validate its functionality in terms of its data systemisation and visualisation, and in terms of its interactivity and practicality. The volunteers' feedback was that the tool was easy and comprehensible to use, and that the selection criteria were made clearer with the aid of the representational spheres to illustrate the sensory/aesthetic attributes. This evidences the initial concern that people may have different interpretations of the sensory and aesthetic aspects of materials that the tool evaluates. The volunteers also expressed that the secondary interface with the detailed quantitative data of the candidate material was interesting as to comprehend the correlation between qualitative and quantitative appraisals. This revealed and educational feature of the tool, demonstrating that it might be useful for other purposes than selecting materials. Architects might take advantage of this operational system to learn more about how material's physical properties affect our sensory perception of them, and how this can beneficial for considering materials during the design process.

The simulation of the material selection process by the volunteers was able to demonstrate that the dummy tool, as an operational system, is able to identify the materials in its database to match the input criteria. In the case of the first volunteer, his sequence was able to match materials to every input values for all six sensory/aesthetic attributes, resulting in an optimal material candidate at the end of the selection process. In the case of the second volunteer, her sequence of inputs was able to match materials to the input values of only three sensory/aesthetic attributes - Translucidity, Pattern and Color - resulting in an optimum material prematurely. The second volunteer wished there were more options of materials so that she could input values for other attributes. In the case of the third volunteer, his sequence of inputs was able to match materials to the input values of four sensory/aesthetic attributes - Tone, Pattern, Brillancy and Texture. After setting the first input of Tone, he wanted to set an input for Translucidity, but realized that all the output materials were opaque. Even not having set inputs for all six sensory/aesthetic attributes, this volunteer did not feel the need to set an input for color, and was satisfied with the optimum material output.

This dummy operational system was developed to explore the relevant aspects to be considered in the proposed tool and to test its functionality. In the real application, the purpose is for the tool to have an add-on format. It would add its features of appraising aesthetic performance to an existing computer aided multiple criteria material selection tool oriented for engineering. It would operate by utilising the existing tool's database on the physical properties of materials in order to correlate it to sensory/aesthetic attributes parameters. The dummy tool's database is composed of the 50 material samples analysed in the experimental process. This aimed at providing a variety of examples and enough content that would be sufficient to allow the dummy tool's evaluation as an operating system. The simulations that were carried out with the volunteers evidenced that the dummy tool's database consisting of 50 materials cannot accommodate all the options of input criteria it has to offer. Table 22 shows the allocation of each of the 50 materials within the sensory/aesthetic attributes 10 point scale metric system. It evidences that not all selection input can be fulfilled with a correspondent match. This indicates that, within the concept of having an add-on format functioning inside an existing computer aided multiple criteria material selection tool, the proposed tool could become more proficient benefiting from a larger database. Consequently, this would increase the selection process' success.

table 22 - Allocation of each material within the defined 10 point scale metric system

I CHAPTER 7 I

Findings and Implications

How to incorporate aesthetic performance into material selection support tools? This was the question that oriented this thesis. The theme involves many issues that were raised along the previous chapters. It offered insight to how material selection is not a common subject in architecture research, and how systematic methods and tools could be of more assistance to the field.
The outcome was a proposal for a method and a tool aimed at appraising materials more holistically. This chapter discusses the findings and implications of this endeavour, and recommends relevant points for further research.

7.1 Results

Aesthetic performance is an important factor to be considered when appointing materials for architecture. The materials that compose a building will largely influence its perception within the city, and how the users interact with the spaces it generates. This thesis proposes that sensory/aesthetic attributes of materials are important to be assessed in the selection process in order to make it more effective and suitable for the design process of architecture. The main research question was, therefore, how to incorporate aesthetic performance into material selection support tools. The objectives of this research were to explore the issues that should be considered for making the material selection process more effective, and to improve the methods by including aesthetic performance as a criteria of material appraisal.

The adopted research approach intended to clarify the context of the material selection methods and processes, and the specific requirements within the field of engineering and product design as to set parameters of comparison and improvements to be considered when selecting materials in the architecture field. The practical results are the proposition of a concept for an improved material selection process to better assist architects - and other stakeholders involved in the design process of architecture - to make more informed decisions when appointing materials for their projects. The proposed concept includes a method and a tool. The method describes the sequence of steps for a material selection based on performance criteria. Consequently, the tool was proposed in order to support this method.

Existing material selection tools have thorough information on physical properties useful for specifying material's technical and functional performance related to environmental, economical and operational issues (Mangonon, 1999; Ashby, 2005). However, when regarding material's aesthetic performance, they lack an objective approach that could be more useful for architects. The proposed tool, therefore, aimed at selecting materials according to aesthetic performance. It was envisioned to operate by utilising an existing tool's database on the physical properties of materials in order to correlate it to sensory/aesthetic attributes parameters, resulting in a practical resource of information and in a holistic material selection system.

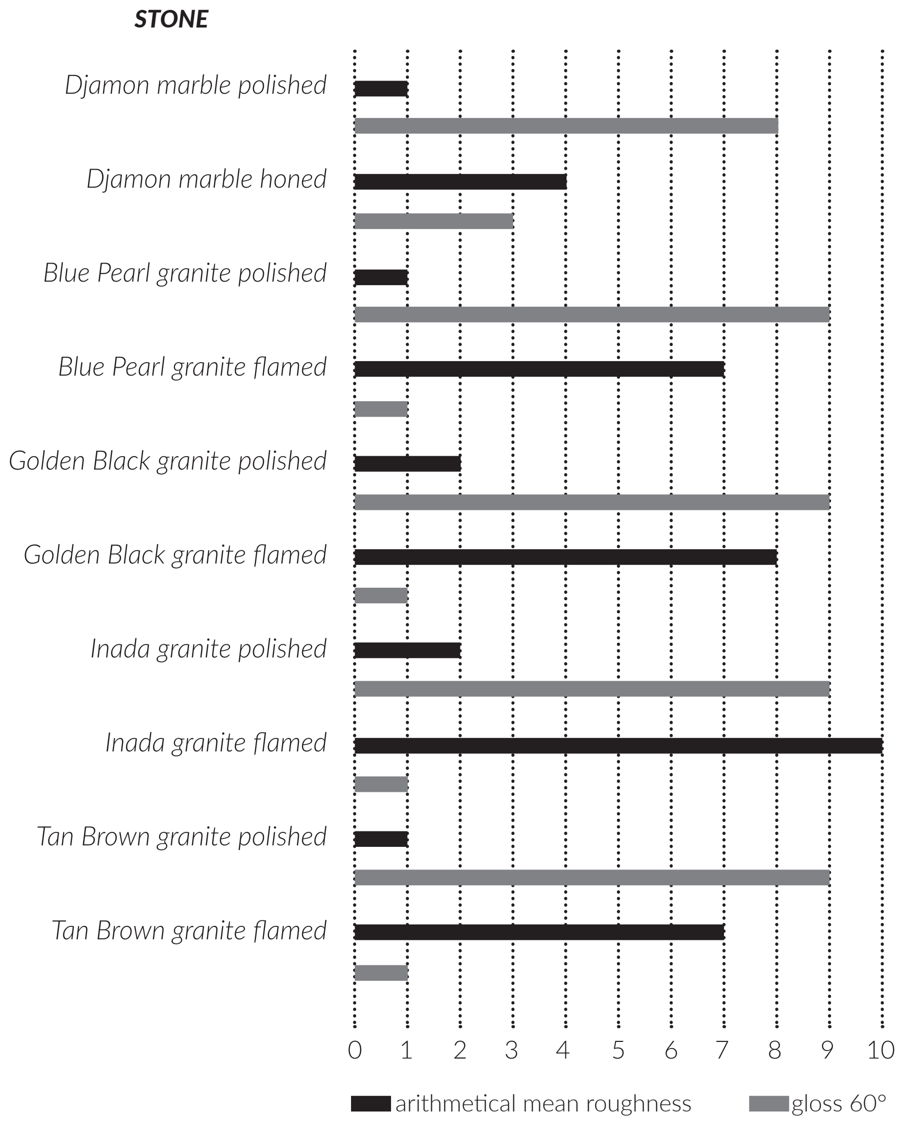
A dummy tool was, therefore, developed as an operational system to select materials according to aesthetic performance requirements, as to match peoples' expectations regarding materials' aesthetic in relation to sensory perception in an objective and systematic manner. The objective, which was to acquire detailed insight on the implications involved in incorporating aesthetic performance into multiple criteria selection tools, was fulfilled. The experimental process provided the foundation for the academic findings that are discussed in the following section.

7.1.1 Academic Findings and Implications

The existing material selection tools and databases can be divided into two different types: tools for selecting materials according to technical information and tools for inspiration. The majority of the available tools fit into the technical information type. These tools most often classify materials by name, in general material's families, and in specific classes and/or subclass. The selection is carried out most commonly through quantitative evaluation of material's bulk, physical, mechanical, thermal and electrical properties (Ramalhete et al., 2009), which is also used to define the material's profile. Only few tools and databases are the inspiration type. They present information about sensory/aesthetic characteristics and surface properties of materials, usually as qualitative data, which lessens them to inspiration sources, and limits their use when other aspects become essential for selecting materials.

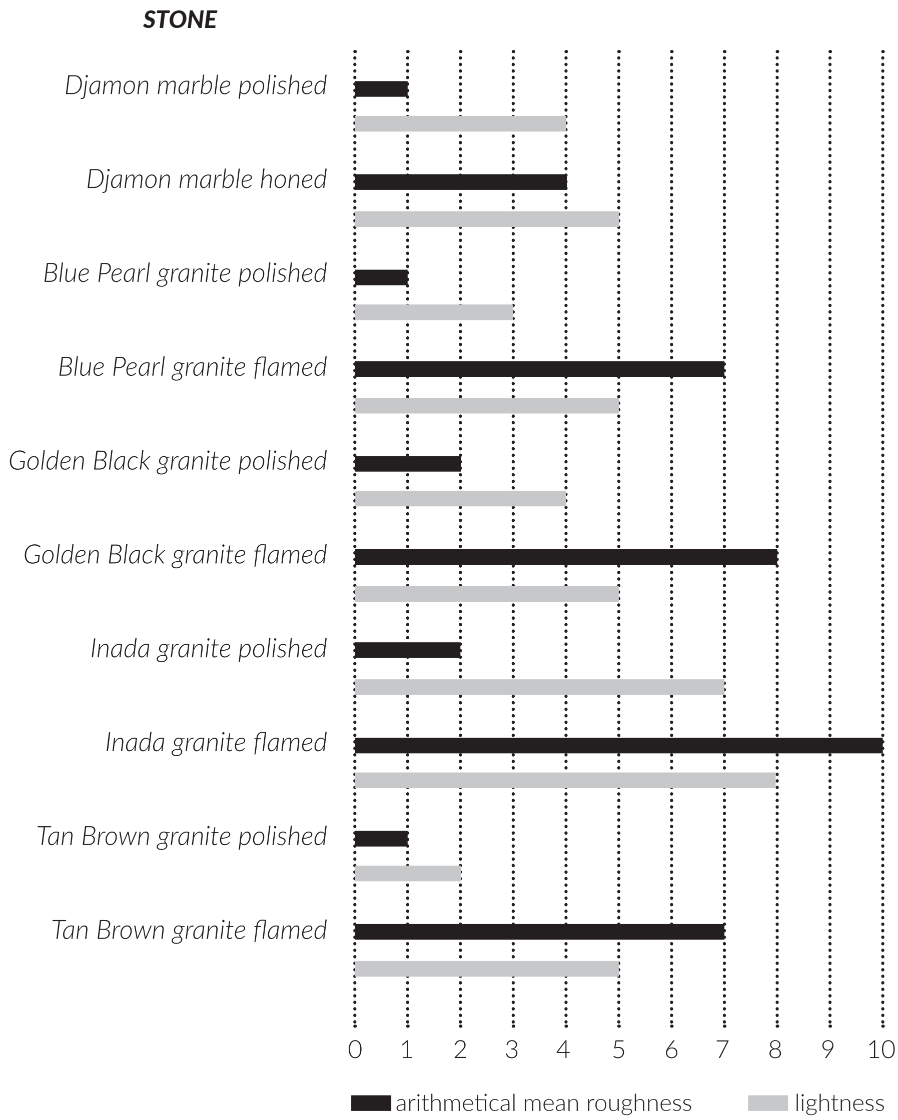
The concept of incorporating aesthetic performance into material selection tools aims at combining these two different types of tools. In this thesis, the proposition of the tool to select materials according to aesthetic performance empirically demonstrated that it is possible to correspond the data on material's physical properties into sensory/aesthetic attributes of appraisal. What is essentially necessary for this correspondence is technical information not only on the bulk properties of materials, but also information on surface properties, since most sensory/aesthetic attributes are related to it. However, surface properties are usually not fully available in the existing technical-information-type tool's databases. The experimental process described in Chapter 5 attested the influence of surface characteristics when evaluating the sensory/aesthetic attributes of materials, with surface roughness being the most affecting. Several studies have proved that surface roughness is a physical property that directly influences material's texture, brillancy and tone, and the relationship among them (Thomas, 1999; Dalal & Natale-Hoffman 1999; Benavente, 2003). The data analysis in this thesis also evidenced this influence. Besides defining a material as having a smooth or coarse feel, the data collected from the stone samples of different surface finishes evidenced the inverse relationship between roughness and gloss. As roughness values increase, gloss values decrease and vice-versa (table 23).

table 23 - Inverse relationship between roughness and gloss in stone samples with different surface finishes



The lightness (*L**) values of the material's color also varies with the interaction of roughness. The different surface finish of the stone samples clearly demonstrate that: as roughness values increase, so do the lightness *L** values (table 24).

table 24 - Similar relationship between roughness and lightness in stone samples with different surface finishes

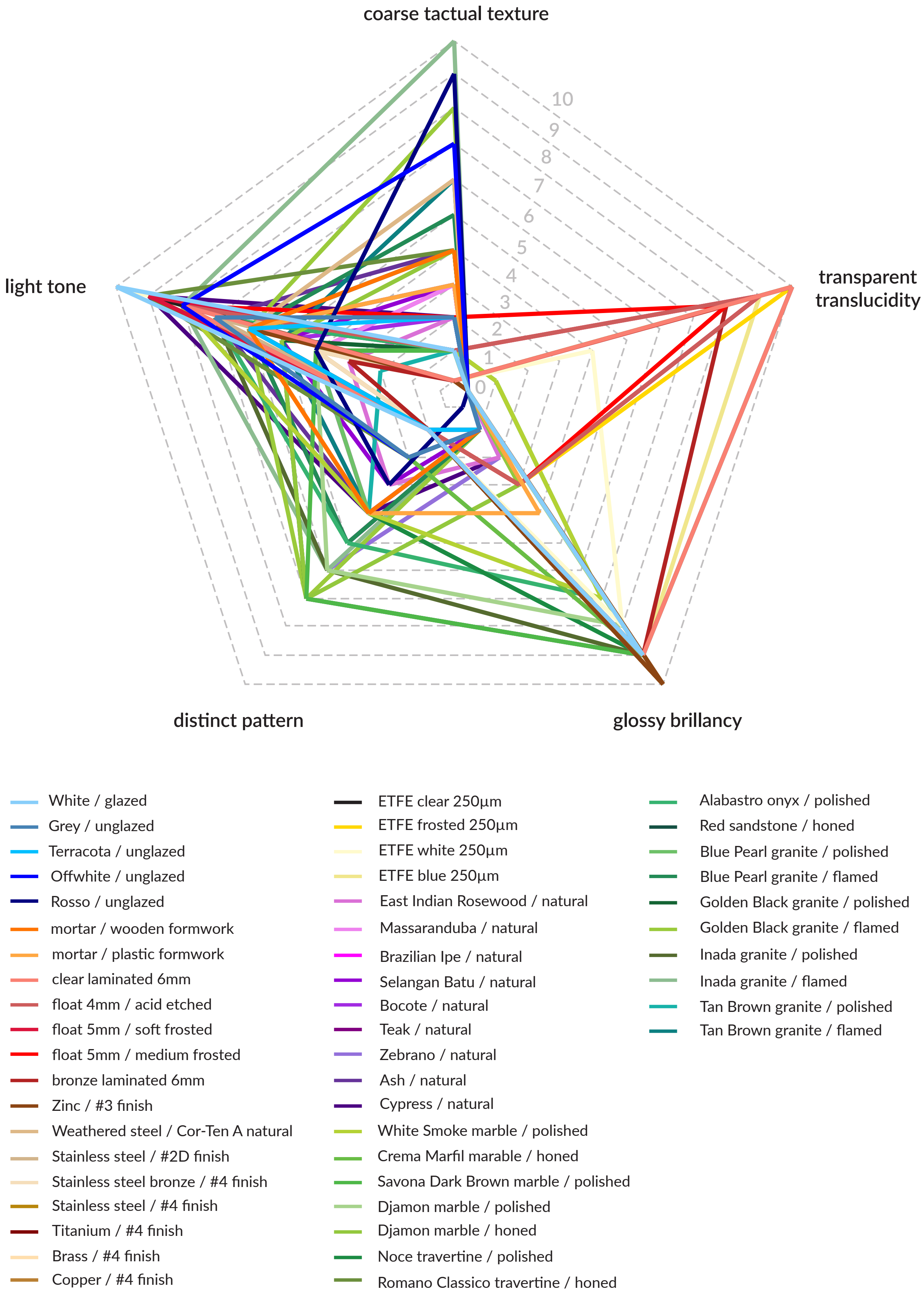


Therefore, in order for the incorporation of aesthetic performance into material selection tools to be feasible, this research acknowledged that adequate data on material's surface properties must also be included on databases. Since many materials have product-based properties and do not follow standard grading and classification, a solution would be for the manufacturers to make the technical information on their products more readily available. This would facilitate the incorporation of such data into material selection tools, and consequently the assessment of the required performance criteria that needs to be evaluated.

Furthermore, the proposition of the tool was important to demonstrate the possibility to formulate new material profiles in terms of sensorial and aesthetic appraisal of material. The classification of materials into families - e.g. wood, stone, metal - is a common verbal standard when referring to materials. However, scientifically, this classification is defined by material's technical appraisal, which formulates its accepted material science and engineering-based profile. If we classify materials defined by their sensory/aesthetic attributes, which relates to their visual and tactile aspects, new material profiles emerge. Table 25 shows the summary of appraisal of all material samples. It is possible to recognise the materials that share the same qualitative parameters for the sensory/aesthetic attributes.

These data show that members of the different families may sometimes be more similar in terms of sensory/aesthetic attributes than to members of the same family. For example: stones can have the same texture values as weathered steel, and that ceramics, stone, metal, glass and polymers may share approximate brillancy values.

table 25 - Summary of the aesthetic performance appraisal attained in this thesis



Tables 26~32 additionally show that some qualitative parameters of the sensory/aesthetic attributes may vary substantially within material families, and that shared parameters for sensory/aesthetic attributes can be independent from material family.

table 26 - Aesthetic performance summary of stone family

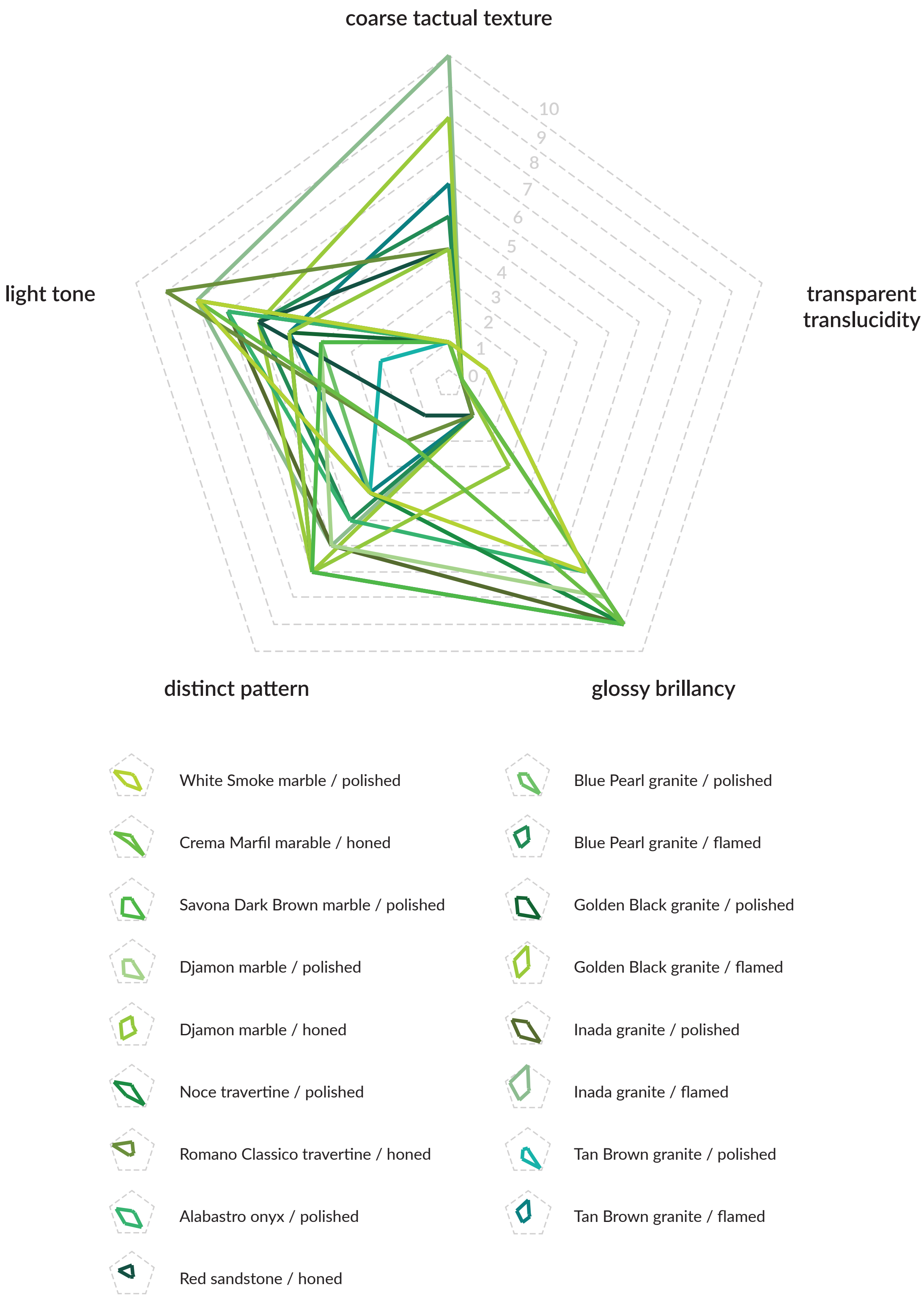


table 27 - Aesthetic performance summary of wood family

table 28 - Aesthetic performance summary of ceramic family

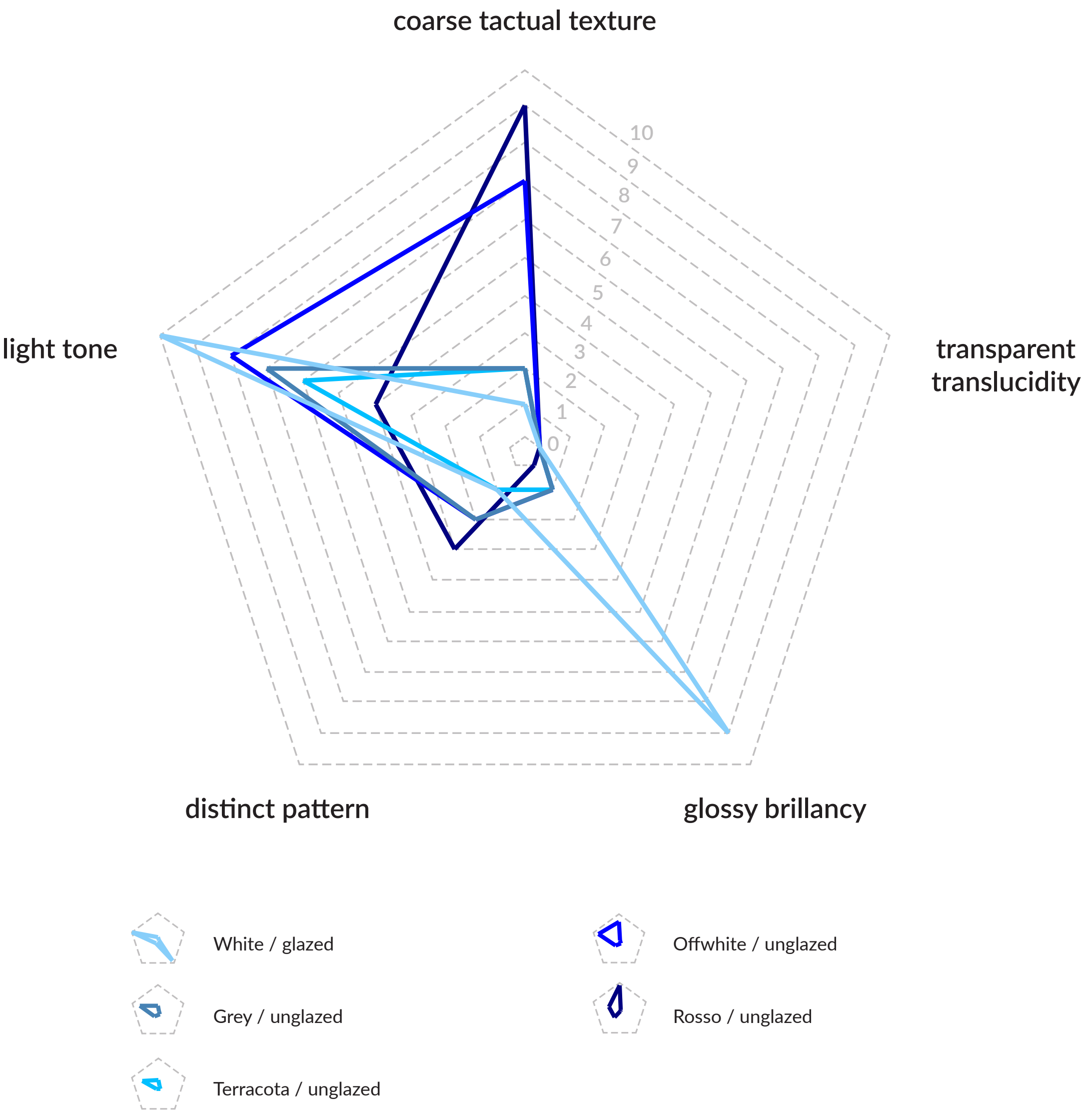


table 29 - Aesthetic performance summary of concrete family

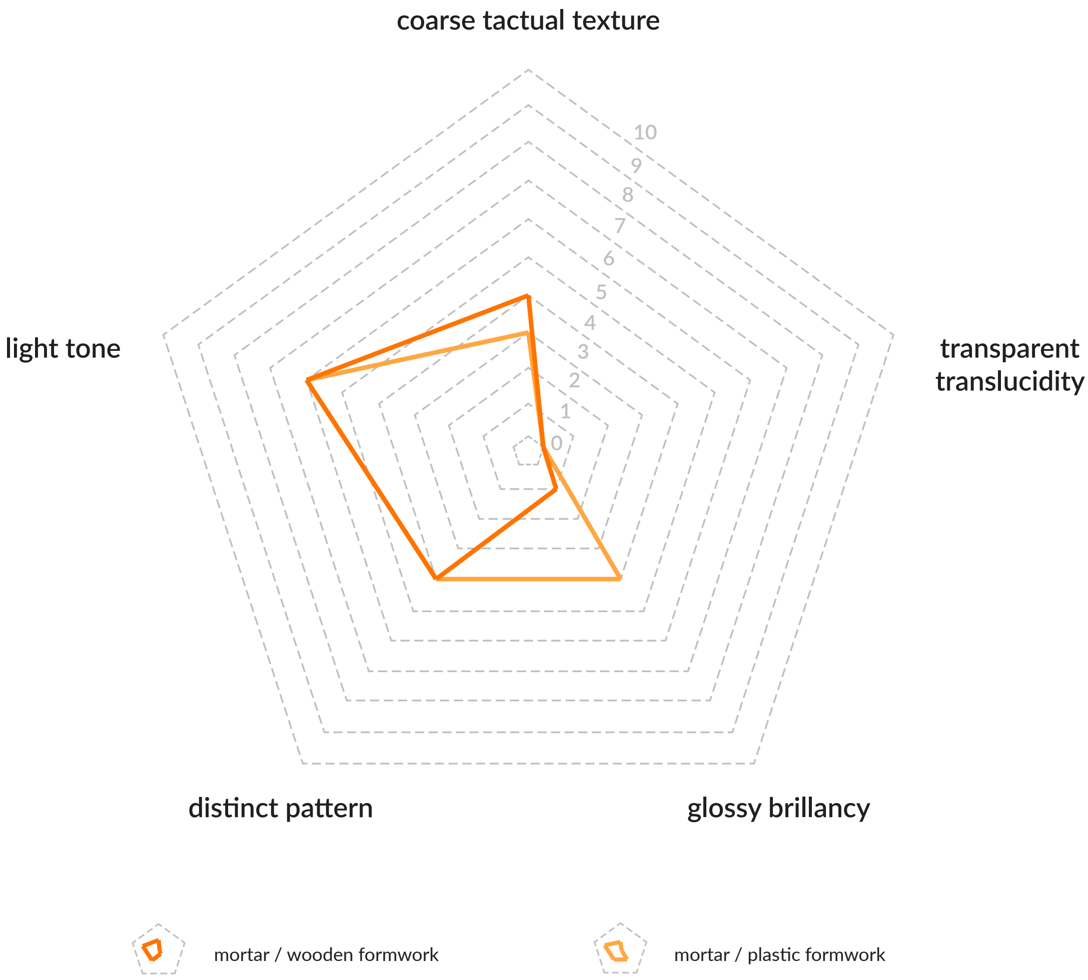


table 30 - Aesthetic performance summary of metal family

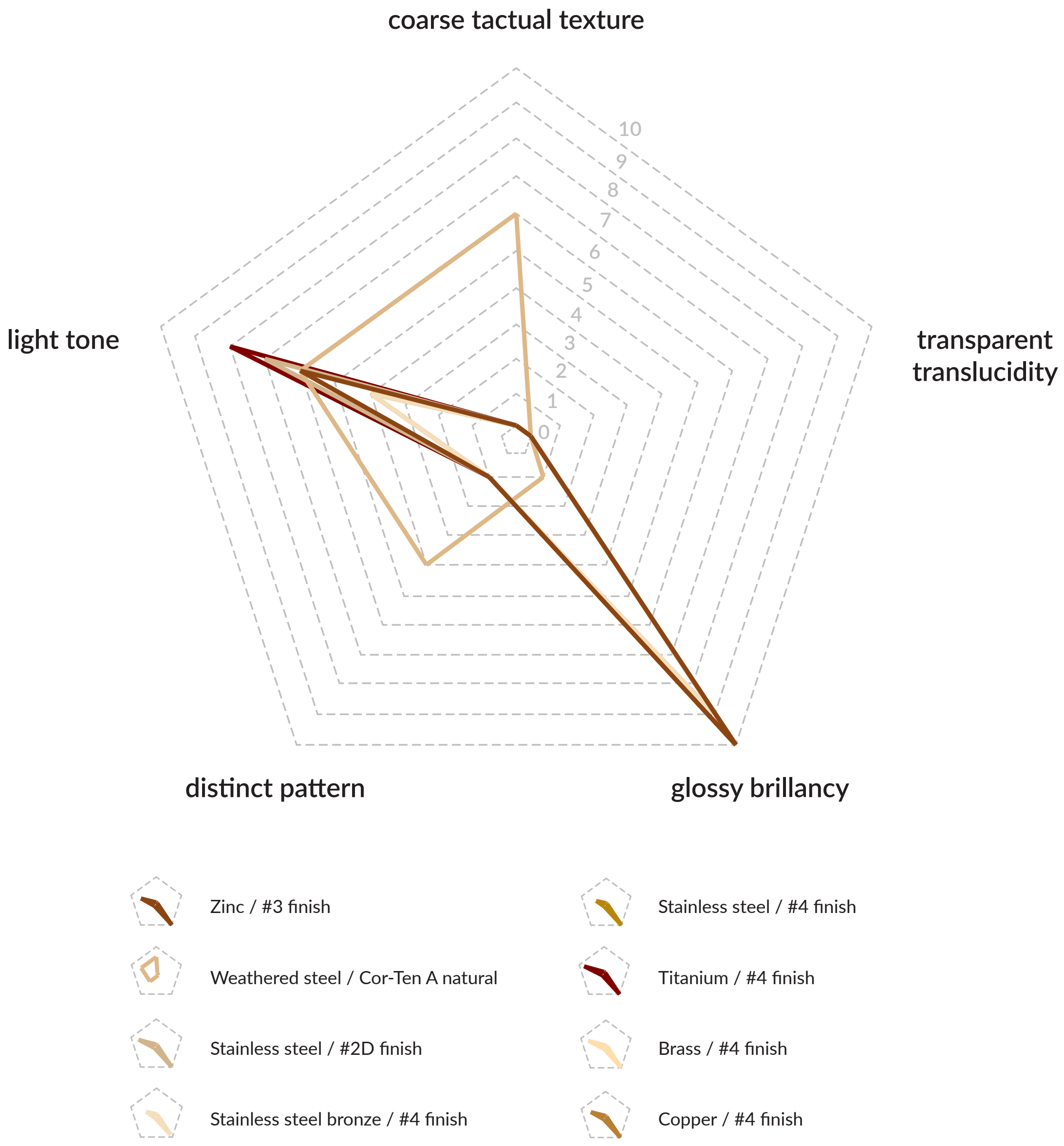


table 31 - Aesthetic performance summary of glass family

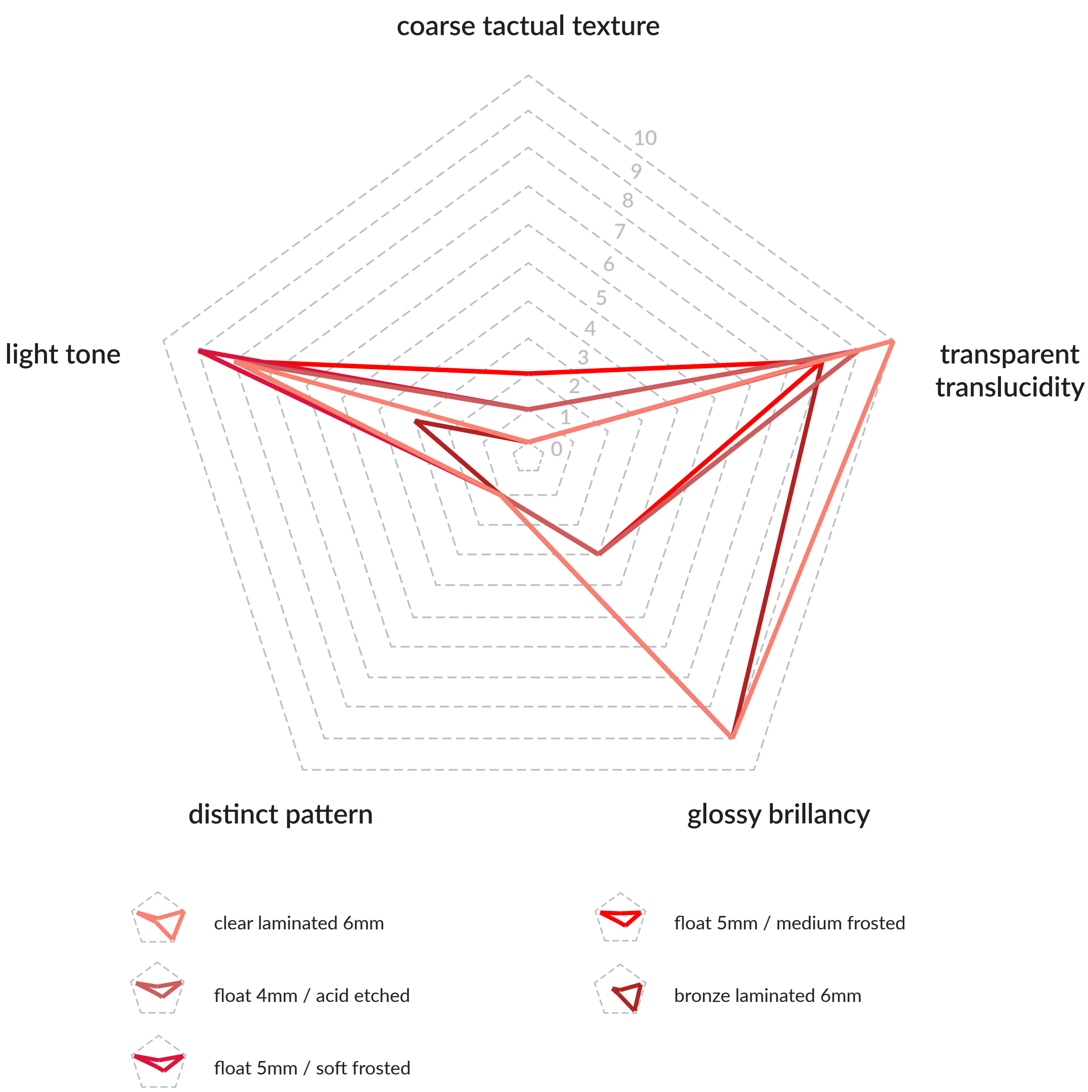
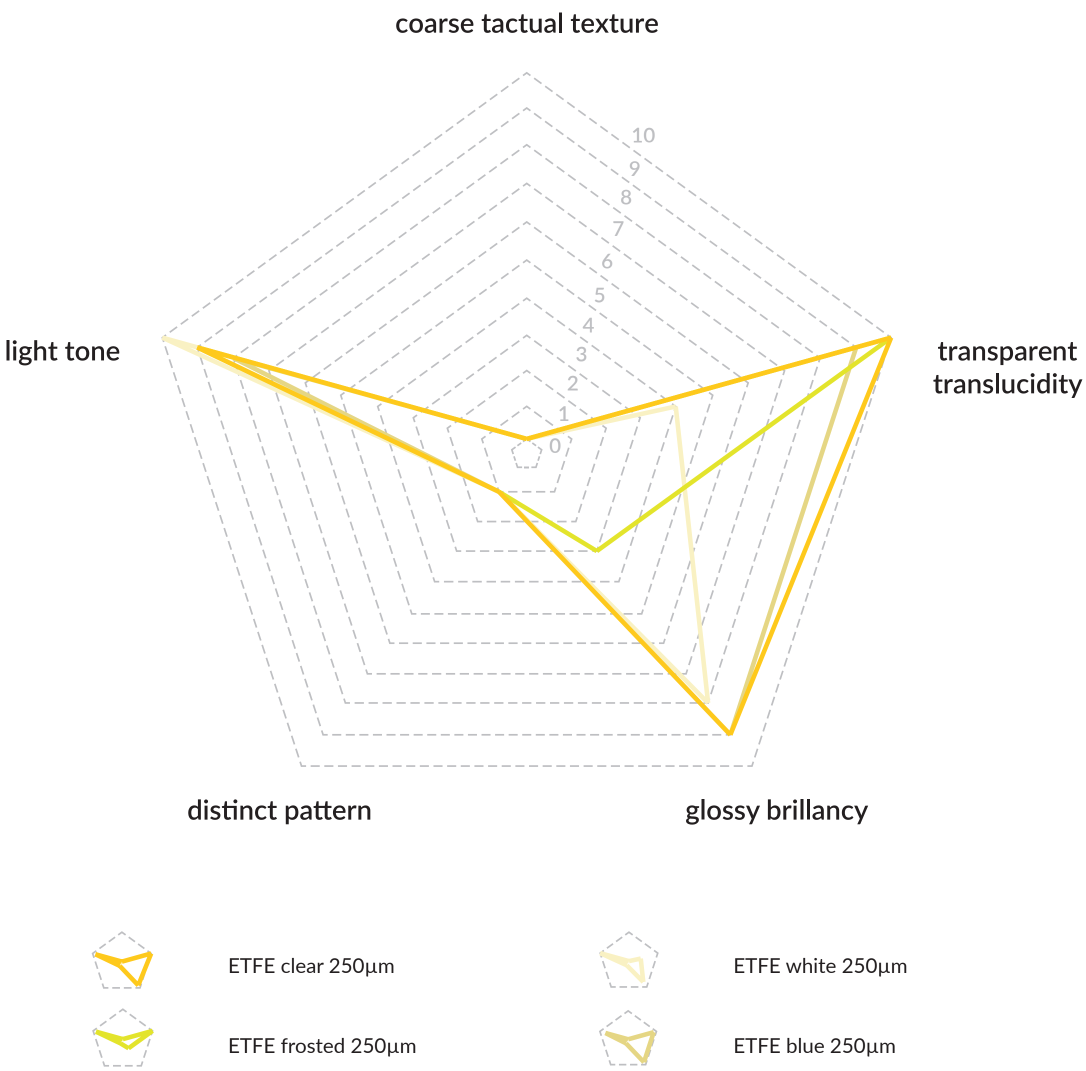


table 32 - Aesthetic performance summary of polymer family



Tables 25 ~ 31 show the interaction between material classification and parameters of sensory/aesthetic attributes. It is interesting to note that these results demonstrate the possibility of a different classification of materials into groups with the same design-based profile - as opposed to the material science and engineering-based profile (figure 62 and 63). This can consequently lead to alternative selection strategies, as the one developed in this thesis. This concept was previously explored by Johnson et al. (2002), and the present research confirms its prospect. A design-based material profile may stimulate alternatives and suggest substitutions by allowing architects to assess materials with similar sensory/aesthetic attributes. The establishment of a well-defined design-based material profile may also ensure that information about a material is communicated in a clearer manner. As materials' accepted material science and engineering-based profile provide semantic and quantitative descriptions of their technical behaviour, design-based material profile also has the same capability.

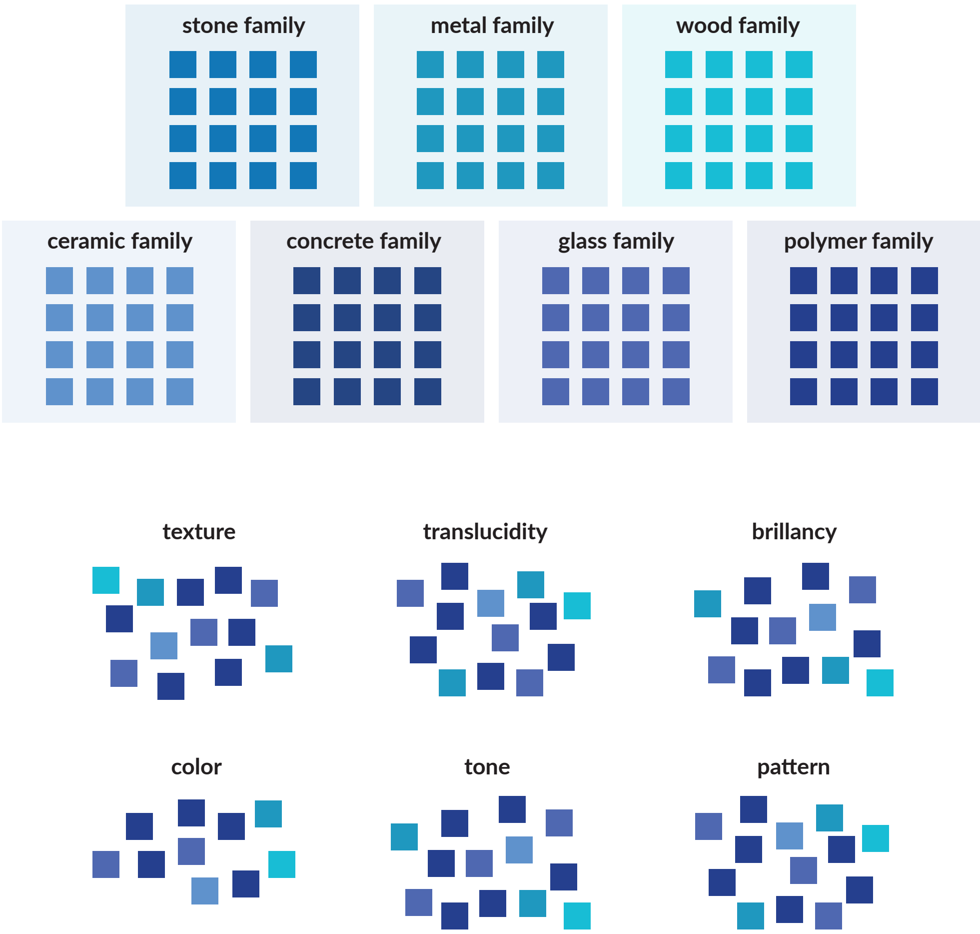


figure 62 - Groups of materials according to engineering-based profile versus design-based profile

figure 63 - Groups according to material's design-based profile

Color is an important attribute for appraising the aesthetic performance of materials. However, it was the most challenging attribute to classify for its broad scope of assessment. Materials like marble, granite, and wood have always been appreciated for their variety of colors hues. However, this feature also makes it difficult to classify color of these natural occurring materials. For this reason, the pattern attribute was important to be appraised. By discriminating pattern between seamless and distinct, this thesis established a singular protocol to appraise multicolored materials. Materials that have a low value for total color difference have seamless patterns and therefore, are comprised of a single color hue. As total color difference values increment, the pattern becomes increasingly distinct, constituting of more than one color hue. Following the appraisal of pattern, the color values of materials can consequently be defined.

7.1.2 The Tool's Validation

As no defined systematic material selection method or procedure exists within the field of architecture, common ways to search for materials used by architects consist in researching through editorials, reaching for material samples through material consultants or material libraries, or searching material databases for the best material for a particular application. These practices compromise many factors, making for a selection method that is complex, time consuming and that could cause serious consequences in a design project.

The recent development of inspirational tools - like Material ConneXion (materialconnexion.com) and Materia (materia.nl) - which present limited technical information and have more accessible interfaces, are important efforts to assist architects when appraising sensory and aesthetic attributes of materials. However, these tools diminish the purpose of material selection, which should contemplate all aspects of material information. As material's properties and characteristics are interrelated, they should not be considered separately. Furthermore, it is unnecessary to set limits between the type of information and materials that might be useful for professionals in the field of architecture, design or engineering. The direction is to create tools with databases with a holistic approach to material information, and that may respond to the universal designer.

The concept for the proposed tool aims at filling that informational gap. By embodying the correlation between materials's sensory/aesthetic attributes and their physical properties, this thesis intended to demonstrate the feasibility of incorporating the appraisal of aesthetic performance into technical information tools, rendering a more holistic approach to material information. In doing so, a seamless appraisal of aesthetic and other functional and technical performance requirements could be accomplished, leading to a single and holistic materials selection tool. Such a materials selection tool could contribute to practical benefits in the field of architecture, where each stakeholder involved in the design process may use it specifically and obtain multiple benefits, as described in table 33:

table 33 - The Tool and the Stakeholders - uses and benefits

Stakeholder	How should make use of the Tool	How can benefit from the Tool
Architects	• as a substitute to the common sources of material information (listed in table 3) for initial screening, when material's objectives and constraints have not been formulated, and for selecting materials, when clear objectives and constraints have been formulated	• a straightforward material selection approach towards electing materials according to issues that have more weight within the design process of architecture
	• before formulating the material's objectives and constraints, the tool aids in browsing materials according to their aesthetic performance in relation to the sensory/aesthetic attributes criteria in a dynamic manner	• assist in client's briefs where architects can utilise aesthetic performance criteria to communicate the perceptive characteristics intended for the materials within their design proposal, or to understand the client's perspective on them
	• after formulating the material's objectives and constraints, the tool assists in comparing and electing materials according to their aesthetic performance in relation to the criteria set by the sensory/aesthetic attributes	• assist in engineers, contractors, and consultants' briefs, towards integrating and balancing different factors in material selection
	• the tool can be used to communicate and support the selection according to their aesthetic performance in relation to the criteria set by the sensory/aesthetic attributes	• instead of relying in non-structured sources of material information, the tool presents readily and structured materials' information during the design process, consequently reducing the time and effort in this activity
	• utilise the tool to elect materials according to their aesthetic performance can be done primarily or after other performance criteria have been prioritised	• accommodating change in design, legislation, or material unavailability by providing options for substitution of a material with the same requirements
		• enabling innovation in design by stimulating the use of new materials through introducing other options to the ones the professional is familiar with
Clients	• before formulating the material's objectives and constraints, the tool can be used to browse materials according to their seensory/aesthetic attributes in a dynamic manner, where its interactivity allows clients to clearly establish suitable materials/ material profile	• have the opportunity to become more involvement in the formulation of the desired material profile for the design, which may result in fewer changes of candidate materials
	• after formulating the material's objectives and constraints, the tool assists in comparing and electing materials according to their aesthetic performance in relation to the criteria set by the sensory/aesthetic attributes	• assisting communication and mutual understanding during briefs with architects and other professionals within the design process
	• the tool can be used to communicate and support the selection according to their aesthetic performance in relation to the criteria set by the sensory/aesthetic attributes	• has the opportunity to clearly establish the expected outcome of the material selection
		• with the involvement in setting the objectives and constraints for materials, the need to clarify the selection criteria if changes were to be made is diminished, since the knowledge about the material profile helps to identify which materials could be suitable substitutes
Engineers/ Contractors/ Consultants and other	• the tool can be used to understand the selection according to their aesthetic performance in relation to the criteria set by the sensory/aesthetic attributes	• the add-on format of the proposed tool can assist to evaluate the aesthetic performance of materials together with the other performative criteria offered by the host multi-criteria selection tool
professionals involved in the design process		• assist in briefs, towards integrating and balancing different factors in material selection
Material Manufacturers	• the tool can be used to understand the selection according to their aesthetic performance in relation to the criteria set by the sensory/aesthetic attributes	• through analysing the sensory/aesthetic attributes that are appreciated by architects and clients, demand profile for new products can be attained
		• understanding the relationships between objective measures of physical properties and the sensory/aesthetic attributes can help to identify particular manufacturing processes as to create desirable material properties. This can be of great significance in the development process of new materials.

Furthermore, the material selection process itself may provide relevant information, such as:

• Enabling to retrace material decisions that were made throughout the design project;
• Allowing the ability to track the importance of different requirements for different applications;
• Benefiting the material manufacturing industry by identifying demand profiles for material customisation and new products.

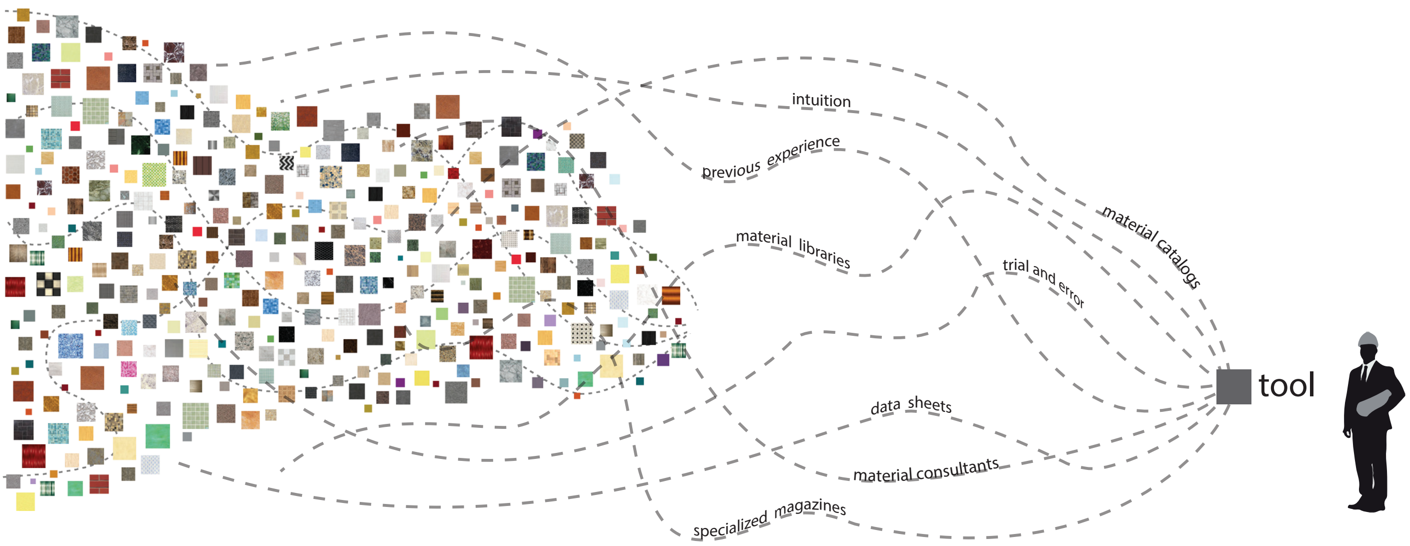


figure 64 - A holistic materials selection may present readily available materials' information during the design process

The development of the dummy tool, besides leading to important findings and implications mentioned in the previous section, also provided the means to explore relevant aspects to be considered in a system that appraises material's aesthetic performance. These aspects include important issues to ensure the tool's effectiveness in bridging and communicating the information on materials. By describing the clear correspondence between the sensorial and aesthetic aspects of materials - appraised qualitatively - and the underlying physical material properties - appraised quantitatively - professionals are expected to make more informed and inspired material selection decisions, and that can simultaneously attend to both building's functionality and expression.

The dummy tool's evaluation demonstrated a positive feedback on its ability to comprehensively display material information. This comprehension comes from the range of the information that is comprised at different levels. The material samples used to create the tool's database have notably different properties and sensory/aesthetic qualities. The qualitative point scale for each appraised attribute derives from objective material measurements. This adopted metric along with the corresponding image that represents the physical manifestation of the attribute proved to reduce the subjectiveness that can be implied in the appraisal of sensorial and aesthetic characteristics of materials. Furthermore, the accessibility to the materials' technical data was viewed as an opportunity to understand the correlation between the qualitative and quantitative appraisal of materials, and to make more informed material choices.

The add-on format of the proposed tool would be ideal to integrate into a technical materials selection tool such as the Cambridge Engineering Selector, for example. Unfortunately, material's surface properties information are not integrally included in technical material selection tools, as many are product-based properties. Furthermore, the information is not always made available by material product's manufacturers. The main challenge is to consider how information about product related aspects can be implemented in selection tool's databases. One feasible approach would be to compel the manufacturers to make technical information on their products more readily available, so that this information could then be more easily integrated into databases.

7.2 Further Research

The idea of this research was to build a framework for assessing material's aesthetic. Other than providing insight in the complexity of the relations of the aspects involved in materials' selection, the objective was to help describe and interpret material's sensorial and perceptual aspects, so that they can be appraised in measurable parameters and compared among materials. This assessment was structured around the six material attributes presented in the proposed tool: texture, brillancy, translucency, pattern, color and tone. It may be argued that to consider only six attributes may be too limited for establishing this framework. Nevertheless, that is where the opportunity for further research lies. Whereas the definition of these six attributes categories in itself was already a contribution to the understanding of the assessment to aesthetic performance, and how it can be incorporated into material selection tools, the framework can be supplemented significantly by the addition of other attributes of appraisal. Other attributes, related to materials' tactual appraisal for example, could be included, such as regularity and repetitiveness of texture. By conducting a deeper and more detailed analysis of material's properties in relation to its roughness, waviness and lay, materials could be qualified as being regular/irregular or by having a repetitive/non-repetitive texture. By analysing and correlating other sensory/aesthetic attributes to physical properties, further relationships can be determined, leading to a better understanding of sensorial and aesthetic aspects of materials which are otherwise only considered intuitively.

Another opportunity for further research lies on considerations involving the effects of environmental inputs in the appraisal of the sensory/aesthetic attributes of materials. Environmental circumstances, specially concerning lighting conditions, directly influence the sensory/aesthetic attributes in relation to their visual appraisal. For example: while a glossy material is highly reflective, its brillancy only becomes apparent when illuminated; transparent and translucent materials' bulk composition becomes evident when light passes through them; dark colors absorb more illumination than light colors. The passing of time may also have direct influence on materials' sensory/aesthetic attributes. Some materials go through physical changes as they age, which can have a direct effect on the materials' surface properties. These changes can manifest in the material's color and tone, in a increase/decrease in its brillancy, or in alterations in the materials texture. The distance from the observer and the material also influences the perception of its attributes, specially concerning color and pattern. These two attributes, as were analysed and interpreted in the proposed tool, consider as though the observer is in close range to the material, as if holding it in their hands. However, as the distance between them increases, the appraisal of these attributes can change considerably. In consequence, to include these factors would enrich the framework of appraising aesthetic performance by evidencing their influence on materials when selecting them.

7.3 Final Conclusions

This thesis demonstrates an exploratory research work aimed at finding directions to appraise aesthetic performance when selecting materials. Furthermore, the broad scope of material selection methods and tools was studied to be able to formulate an improved material selection process for architecture. Architects have specific needs and should be assisted when comparing material options on the different design aspects they need to consider. Besides attending to technical and functional requirements, materials directly influence the perceptual interaction that people have with a building via their sensorial/aesthetic attributes. Architects can consequently manipulate material use to generate coherent and multi-sensory experiences.

The evaluation of the dummy tool provided a practical overview about its usability and effectiveness. The tool was thought to facilitate the translation of ideas into a clear material profile. Based on the sensory/aesthetic attributes and their physical properties equivalents, architects were able to make informed decisions about the best material options for their selection criteria. Furthermore, the architects who participated in the evaluation mentioned that they were motivated to participate because they were interested in the topic and on how it could be approached objectively. They also expressed the desire to increase their awareness on materials selection processes.

Considering that this study only approached a small part of the scope on material's sensorial and aesthetic aspects, it nonetheless presented a framework that other research can refer to. It indicated that material selection within architecture is an underdeveloped topic, possibly for the reason that material designation is institutionally oriented towards attending building codes and standards requirements. But material selection within the design process of architecture goes beyond this scope. Materials must attend a range of performative demands within the building's system related to functional, technical, operational, economical, environmental and such aspects. Besides this complexity, where selection must consider and balance these aspects, aesthetic performance should also be highly regarded when appointing materials. This research was able to demonstrate how material attributes related to sensorial and aesthetic aspects can be linked to objective parameters. By identifying this relationship between different levels of information, the present framework is able to describe them and promote their understanding in the architectural context.

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I SUMMARY I

Materials play an essential role in architectural design. Despite being the fundamental matter for construction, materials are the medium architects use to define a building's environment and to determine its character. With today's vast diversity and availability of building materials, architects have ample means to explore their designs through materiality. However, material selection can be a complex and delicate task due to the multiple factors that have to be considered when evaluating building materials. Materials are embedded with intrinsic and attributed properties, geometric behaviour and manufacturing constraints, and they must conform to a range of performative requirements within the building's system - technical, functional, environmental, economical, operational, aesthetic, among others.

Computational tools used to assist in multiple criteria material selection processes have been a substantial development. They hinge on extensive databases on material's measurable properties related to their physical behaviour (mechanical, chemical, physical, optical, acoustical and thermal nature), attributed properties (such as life cycle cost, recyclability, safety), and manufacturing processes, and have been proven successful for selecting materials according to various performative requirements. However, when approaching requirements related to aesthetic performance, a problem has been diagnosed: most multiple criteria material selection tools take on an engineering approach, where aesthetic aspects of materials are seldom regarded.

Aesthetic performance relates to the manner in which a material successfully accomplishes the task of responding to the sensory and aesthetic requirements of a design. It is concerned with our sensorial perceptions and responses to materials - its appearance and feel - and is attributed to aspects of roughness, color, transparence and such. In the design domain, the materials' aesthetic and sensory behaviour are just as important as meeting technical requirements (Ashby & Johnson 2002; Malnar & Vodvarka, 2004; Pallasmaa, 2005; Wastiels & Wouters, 2008; Karana, 2009), thus multiple criteria material selection tools should include such aesthetic-related performance in order to establish an approach that could be more useful within the design process of architecture and, consequently, could become a more holistic material selection system. A holistic material selection concept may be able to better attend the specific needs of professionals within the design process of architecture, such as architects, engineers, contractors, consultants, clients and other stakeholders, as well as aid to increase mutual understanding and to form consensus among them when selecting materials for a project. A material selection tool that incorporates aesthetic performance is, therefore, potentially of considerable value. The question is: how to address and empirically evaluate aesthetic performance criteria of materials as to incorporate it in multiple criteria material selection tools?

A framework for establishing this incorporation is therefore proposed. The objective is to set a balance between functional and aesthetic aspects in material selection. In the methodology to achieve this objective, first there was a need to identify which sensorial aspects are attributed to the aesthetic performance of building materials. Literature review on research developed on the subject provided an extensive and diverse assessment for establishing the relevant aspects for defining what will be called the sensory/aesthetic attributes of materials. Following, the correlation of the sensory/aesthetic attributes of materials and their physical properties was studied. Since our sensory perception of materials is a combination of perceptions of numerous material properties (Chen et al., 2009, it was necessary to find the relevant and dominant physical properties that corresponds to the sensory/aesthetic attributes of building materials so that the two domains can be bridged.

Next, critical analysis of the methods used by architects to seek for information on materials, how the overall process of material selection takes place, and an investigation on the existing computational tools and databases for material selection was carried out in order to establish what issues have been overviewed and should be contemplated in a concept for an improved material selection process that incorporates aesthetic performance criteria.

Subsequently, a tool for selecting materials according to their aesthetic performance is proposed as a strategy. It was envisioned to have an add-on format - a computer software component that adds features to an existing program. The idea is that this tool can complement existing engineering-oriented material selection programs by adding on the selection criteria of aesthetic performance. It would operate by utilising materials' physical properties information available on the existing program's database to correlate with the desired parameters for the sensory/aesthetic attributes, resulting in a practical resource of information and holistic material selection system.

As to acquire detailed insight on the implications involved in the development of such a tool, an empirical procedure was developed. It entailed practical experimentation and data collection of quantitative information on physical properties of materials as to enable the categorisation of aesthetic performance. This was achieved through instrumental measurements of building material samples as to build a database to simulate the implications involved in the method of incorporating aesthetic performance into multiple criteria selection tools. The experimental process and consequent findings contributed to the establishment of correlations between quantitative and qualitative data sets. The results of this correspondence were subsequently synthesised into parametrical inputs to enable the aesthetic performance criteria of building materials to be assessed.

This methodology attempted to amplify the scope of material appraisal by using scientific methods to explore these perceptual attributes of materials that are largely ignored by the material selection tools. It contributed to demonstrate that materials can have other profiles of categorisation than of traditional engineering, which help assist in non-technical appraisal and communication between different stakeholders involved in any design project. It also contributed to demonstrate how the interaction between physical properties leads to specific sensory/aesthetic attributes, and that these could be manipulated to produce customised materials to that attend better to demand profiles for new products within the material manufacturing industry.

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APPENDIX

Tables of the collected data from experimental process

Table of collected data for arithmetical mean roughness *Sa* - values in µm

MATERIAL NAME	*Sa*
White Smoke Marble polished	0.77
Crema Marfil Marble polished	0.21
Savona Dark Brown Marble polished	0.34
Djamon Marble polished	0.75
Djamon Marble honed	6.35
Noce Travertine polished	2.39
Romano Classico Travertine honed	22.30
Alabastro Onyx polished	1.12
Red Sandstone honed	7.20
Blue Pearl Granite polished	0.70
Blue Pearl Granite flamed	30.90
Golden Black Granite polished	1.27
Golden Black Granite flamed	40.30
Inada Granite polished	1.60
Inada Granite flamed	51.74
Tan Brown Granite polished	0.88
Tan Brown Granite flamed	34.80
East Indian Rosewood natural	6.44
Massaranduba Wood natural	10.27
Ipe Wood natural	8.79
Selangan Batu Wood natural	11.76
Bocote Wood natural	5.31
Teak Wood natural	10.02
Zebrano Wood natural	8.20
Cypress Wood natural	7.85
Ash Wood natural	7.14
White Ceramic Tiling	1.87
Grey Ceramic Tiling	9.09
Terracotta Ceramic Tiling	7.70
Offwhite Ceramic Tiling	39.06
Rosso Ceramic Tiling	45.27
Mortar wooden formwork	23.93
Mortar plastic formwork	11.74

MATERIAL NAME	*Sa*
Zinc (#3 finish)	0.68
Weathered Steel	22.45
Stainless Steel (#2D finish)	0.21
Stainless Steel (#4 finish)	0.73
Stainless Steel (#4 finish) bronze	0.68
Titanium (#4 finish)	0.78
Brass (#4 finish)	0.63
Copper (#4 finish)	0.68
Clear Laminated Glass	0.01
Acid Etched Float Glass	2.33
Frosted (soft) Float Glass	3.75
Frosted (medium) Float Glass	5.26
Bronze Laminated Glass	0.01
ETFE clear 250mm	0.01
ETFE frosted 250mm	0.23
ETFE white 250mm	0.01
ETFE blue 250mm	0.01

Table of collected data for Gloss 60° - values in GU

MATERIAL NAME	value 1	value 2	value 3	Δ
White Smoke Marble polished	51.9	51.4	48.6	50.6
Crema Marfil Marble polished	76.6	80.1	80.6	79.1
Savona Dark Brown Marble polished	87.8	89.7	87.8	88.4
Djamon Marble polished	67.1	67.9	68.1	67.7
Djamon Marble honed	18.3	17.0	17.6	17.6
Noce Travertine polished	73.1	68.4	72.7	71.4
Romano Classico Travertine honed	3.1	3.2	2.9	3.1
Alabastro Onyx polished	53.9	57.6	53.8	55.1
Red Sandstone honed	3.6	3.8	3.5	3.6
Blue Pearl Granite polished	81.5	80.3	79.9	80.6
Blue Pearl Granite flamed	3.2	2.9	2.9	3.0
Golden Black Granite polished	81.2	79.1	82.1	80.8
Golden Black Granite flamed	2.3	2.1	2.5	2.3
Inada Granite polished	85.5	85.1	85.5	85.4
Inada Granite flamed	1.4	1.4	1.2	1.3
Tan Brown Granite polished	85.1	84.7	83.6	84.5
Tan Brown Granite flamed	3.4	3	3.5	3.3
East Indian Rosewood natural	4.4	4.3	4.0	4.2
Massaranduba Wood natural	2.1	1.9	2.2	2.1
Ipe Wood natural	2.4	2.5	2.6	2.5
Selangan Batu Wood natural	2.4	2.3	2.1	2.3
Bocote Wood natural	1.8	1.9	2.0	1.9
Teak Wood natural	3.4	3.2	3.2	3.3
Zebrano Wood natural	4.5	4.4	4.0	4.3
Cypress Wood natural	3.9	3.8	4.2	4.0
Ash Wood natural	2.8	2.5	2.6	2.6
White Ceramic Tiling	85.7	86.6	85.3	85.9
Grey Ceramic Tiling	2.2	2.3	2.4	2.3
Terracotta Ceramic Tiling	1.7	1.8	1.6	1.7
Offwhite Ceramic Tiling	1.6	1.4	1.5	1.5
Rosso Ceramic Tiling	0.5	0.6	0.6	0.6
Mortar wooden formwork	0.5	0.6	0.5	0.5
Mortar plastic formwork	22.2	22.8	23.8	22.93

Table of collected data for Gloss 60° - values in GU (continuation)

MATERIAL NAME	value 1	value 2	value 3	Δ
Zinc (#3 finish)	307.1	307.1	307.1	307.1
Weathered Steel	2.2	2.4	2.0	2.2
Stainless Steel (#2D finish)	199.9	199.9	199.9	199.9
Stainless Steel (#4 finish)	307.1	307.1	307.1	307.1
Stainless Steel (#4 finish) bronze	109.5	120.0	112.8	114.1
Titanium (#4 finish)	221.5	219.9	222.4	221.3
Brass (#4 finish)	307.1	307.1	307.1	307.1
Copper (#4 finish)	307.1	307.1	307.1	307.1
Clear Laminated Glass	144.4	143.2	143.1	143.6
Acid Etched Float Glass	10.6	10.4	10.4	10.5
Frosted (soft) Float Glass	16.1	16.2	16.2	16.2
Frosted (medium) Float Glass	9.7	9.6	9.7	9.7
Bronze Laminated Glass	94.1	94.5	94.3	94.3
ETFE clear 250mm	93.9	91.9	93.0	92.9
ETFE frosted 250mm	12.5	12.1	12.2	12.3
ETFE white 250mm	61.8	59.8	61.0	60.9
ETFE blue 250mm	79.1	81	78.1	79.4

Table of collected data for *L* a* b** and ΔE00

MATERIAL NAME	value 1	value 2	value 3	value 4	value 5	value 6	value 7	value 8	value 9	value 10	value 11	value 12	value 13	value 14	max	min	Δ	ΔE*00
STONE																		
White Smoke Marble polished																		
L*=	79.3	78.6	70.8	73.1	75.8	79.5	78.3	80.6	80.4	81.4	74.7	77.5	77.3	79.1	81.4	70.8	77.6	7.7
a*=	-0.7	-1.0	-1.5	-1.3	-1.2	-0.8	-1.0	-0.8	-0.8	-0.8	-1.0	-1.3	-1.0	-0.8	-0.7	-1.5	-1.0	
b*=	-0.7	-0.7	-0.9	-1.2	-1.2	-0.7	-1.0	-0.9	-0.7	-0.8	-0.8	-1.2	-1.0	-0.7	-0.7	-1.2	-0.9	
Crema Marfil Marble polished																		
L*=	79.0	79.6	79.7	79.6	80.5	80.4	80.6	80.8	81.0	80.2	79.9	79.9	81.7	80.2	81.7	79.0	80.2	2.2
a*=	1.1	1.6	1.6	1.6	1.4	1.6	1.4	1.3	1.3	1.5	1.6	1.5	1.6	1.4	1.6	1.1	1.5	
b*=	13.1	13.7	13.2	13.2	12.5	12.7	12.8	12.4	12.7	13.1	12.9	13.1	12.0	13.1	13.7	12.0	12.9	
Savona Dark Brown Marble polished																		
L*=	72.3	32.5	30.4	34.6	31.2	32.9	33.0	35.6	31.8	36.3	37.8	27.5	65.8	73.3	73.3	27.5	41.1	46.0
a*=	1.1	1.6	1.0	1.2	1.3	1.1	1.0	0.8	0.7	1.1	1.0	1.1	1.1	-0.0	1.6	-0.0	1.0	
b*=	6.5	6.1	4.9	5.4	7.0	5.7	4.7	5.2	4.5	4.9	5.0	5.0	6.0	6.8	7.0	4.5	5.5	
Djamon Marble polished																		
L*=	34.9	13.9	45.0	42.3	36.4	49.0	24.2	40.2	27.8	38.9	37.4	25.1	35.6	51.0	51.0	13.9	35.8	38.2
a*=	-5.0	-1.4	-5.9	-5.3	-5.7	-5.3	-3.5	-5.9	-2.6	-6.0	-5.8	-4.5	-4.9	-5.6	-1.4	-6.0	-4.8	
b*=	2.6	-4.3	-0.1	-0.1	3.2	3.3	-0.5	1.8	-1.3	2.0	-0.3	-2.1	0.9	1.6	3.3	-4.3	0.5	
Djamon Marble honed																		
L*=	48.7	35.5	51.6	33.6	44.9	32.0	63.5	23.7	30.2	47.6	38.1	46.9	35.3	37.9	63.5	23.7	40.7	40.6
a*=	-5.6	-3.0	-3.7	-3.4	-2.8	-2.9	-4.6	-1.7	-3.3	-4.2	-4.3	-3.8	-4.6	-3.7	-1.7	-5.6	-3.7	
b*=	4.3	1.8	1.7	2.8	2.6	2.0	2.1	-3.1	0.3	2.6	1.0	-1.0	1.3	1.7	4.3	-3.1	1.4	
Noce Travertine polished																		
L*=	66.6	68.2	69.8	75.6	72.8	72.6	70.3	74.6	74.6	69.0	72.9	67.9	69.6	74.6	75.6	66.6	71.4	7.3
a*=	2.6	4.3	3.9	3.0	2.5	3.2	3.8	2.8	2.7	4.2	3.3	4.3	3.9	2.8	4.3	2.5	3.4	
b*=	15.4	20.3	19.1	17.7	15.9	18.3	18.6	17.8	17.4	19.7	18.7	19.7	19.4	17.5	20.3	15.4	18.3	
Romano Classico Travertine honed																		
L*=	79.2	79.9	81.5	80.1	82.2	79.9	81.6	81.7	78.8	80.0	77.8	82.2	81.6	78.1	82.2	77.8	80.3	3.5
a*=	1.9	1.7	1.8	1.8	1.7	2.1	1.8	2.0	2.3	2.1	2.5	1.8	1.9	2.5	2.5	1.7	2.0	
b*=	17.5	16.4	16.2	16.3	16.7	17.6	17.6	17.0	18.5	17.7	17.8	16.9	17.0	18.2	18.5	16.2	17.2	
Alabastro Onyx polished																		
L*=	71.8	68.7	77.1	69.7	71.6	88.5	74.6	74.9	71.9	70.5	69.8	73.7	72.9	85.9	88.5	68.7	74.4	15.4
a*=	5.8	6.5	6.3	4.8	6.3	-0.9	4.2	2.8	5.4	5.0	4.4	5.3	6.5	0.3	6.5	-0.9	4.5	
b*=	22.9	24.5	16.9	20.5	21.8	14.0	15.3	22.0	16.3	23.6	23.0	24.0	19.1	23.5	24.5	14.0	20.5	
Red Sandstone honed																		
L*=	52.2	52.1	51.9	52.1	52.0	52.9	52.2	52.0	53.0	52.3	52.9	52.8	52.4	51.9	53.0	51.9	52.3	1.9
a*=	16.8	16.1	17.3	16.1	16.9	16.9	16.2	16.9	16.5	15.7	16.2	16.5	15.3	16.4	17.3	15.3	16.4	
b*=	14.8	14.6	15.1	14.5	15.1	15.0	14.3	15.1	14.3	14.2	13.7	14.7	14.6	14.8	15.1	13.7	14.6	
Blue Pearl Granite polished																		
L*=	42.9	50.0	34.7	34.0	39.8	40.6	36.7	37.3	36.7	45.1	37.3	48.4	34.4	38.0	50.0	34.0	39.7	14.7
a*=	-1.2	-1.6	-1.0	-1.4	-1.4	-1.3	-1.1	-1.0	-1.0	-1.3	-1.4	-1.4	-1.1	-1.4	-1.0	-1.6	-1.3	
b*=	-1.9	-2.4	-2.5	-3.6	-3.2	-3.4	-3.4	-2.7	-2.3	-2.2	-4.5	-3.2	-4.0	-4.6	-1.9	-4.6	-3.1	
Blue Pearl Granite flamed																		
L*=	58.4	63.8	59.8	56.9	66.3	61.3	55.1	50.8	69.4	58.1	53.2	45.6	59.5	51.1	69.4	45.6	57.8	22.0
a*=	-0.7	-0.5	-0.2	-0.3	-0.6	-0.8	-0.3	0.3	-0.2	-0.5	-0.4	0.2	-0.4	-0.2	0.3	-0.8	-0.3	
b*=	-0.9	-0.5	0.3	0.8	-0.6	-0.5	0.6	2.3	1.2	0.4	-0.2	1.4	0.1	-0.9	2.3	-0.9	0.3	
Golden Black Granite polished																		
L*=	23.3	63.1	25.3	37.7	46.6	49.9	61.0	52.4	57.2	37.9	48.1	51.0	61.4	58.8	63.1	23.3	48.1	39.5
a*=	-0.1	3.5	-0.1	3.0	7.5	5.4	3.5	4.8	4.1	3.4	-0.5	2.3	4.4	2.0	7.5	-0.5	3.1	
b*=	-0.4	9.9	-0.3	6.1	13.5	13.4	9.0	15.4	13.8	9.6	2.3	7.2	10.7	9.2	15.4	-0.4	8.5	
Golden Black Granite flamed																		
L*=	40.6	61.8	61.2	55.7	62.2	64.0	44.6	50.8	48.1	58.3	50.2	71.7	34.9	59.8	71.7	34.9	54.6	37.5
a*=	0.0	2.5	2.5	1.2	2.5	0.3	-0.2	0.5	0.1	3.5	1.3	1.3	-0.6	1.8	3.5	-0.6	1.2	
b*=	0.8	9.8	7.9	6.0	8.3	3.9	1.1	3.1	0.1	8.8	2.8	7.4	-2.0	5.9	9.8	-2.0	4.6	

Table of collected data for *L* a* b** and ΔE00 (continuation)

Inada Granite polished																		
L*=	82.3	89.5	66.8	52.1	65.7	71.7	85.0	66.7	62.8	69.6	84.6	57.1	69.5	55.7	89.5	52.1	69.9	29.0
a*=	-0.3	-0.3	-0.3	0.1	-0.3	-0.6	0.8	0.4	-0.4	-0.3	-0.4	1.3	-0.3	1.0	1.3	-0.6	0.0	
b*=	3.1	2.6	2.9	2.1	1.3	2.5	4.4	5.6	2.0	2.4	3.9	5.2	3.3	4.9	5.6	1.3	3.3	
Inada Granite flamed																		
L*=	77.4	77.0	53.9	74.2	78.7	70.3	76.2	85.9	74.2	72.0	77.4	52.5	81.1	55.7	85.9	52.5	71.9	26.4
a*=	-0.7	0.5	-0.2	-0.7	-0.3	0.9	-0.3	-0.3	0.4	0.2	-0.1	0.1	-0.2	-0.3	0.9	-0.7	-0.1	
b*=	1.5	5.0	3.9	1.3	2.7	4.3	2.0	2.8	3.4	2.8	3.4	1.6	3.0	2.5	5.0	1.3	2.9	
Tan Brown Granite polished																		
L*=	15.4	19.8	18.7	18.1	22.9	22.1	16.4	17.7	17.9	17.9	19.3	17.5	26.4	22.0	26.4	15.4	19.4	11.5
a*=	0.4	5.0	3.4	0.1	6.8	4.5	2.2	1.5	1.6	0.0	3.9	1.4	6.0	3.3	6.8	0.0	2.9	
b*=	1.2	5.8	5.0	1.4	7.2	6.1	2.7	1.7	2.2	1.1	5.0	1.8	7.1	4.4	7.2	1.1	3.8	
Tan Brown Granite flamed																		
L*=	47.3	51.2	47.0	56.5	54.8	48.2	44.4	50.4	47.6	48.2	53.0	50.7	47.9		56.5	44.4	49.8	14.8
a*=	0.5	3.8	2.2	5.3	5.5	0.0	-0.3	2.8	0.2	0.5	3.4	4.0	0.5	2.3	5.5	-0.3	2.2	
b*=	1.9	5.7	4.5	5.8	7.2	2.1	1.5	3.8	2.7	2.2	4.5	5.2	2.0	2.5	7.2	1.5	3.7	
WOOD																		
East Indian Rosewood natural																		
L*=	29.8	29.8	30.8	29.1	30.5	29.8	29.4	30.0	29.2	30.6	30.6	29.7	30.0	29.3	30.8	29.1	29.9	4.9
a*=	7.5	7.6	9.0	5.0	8.9	5.9	5.6	8.0	7.9	8.0	8.9	6.4	8.2	8.0	9.0	5.0	7.5	
b*=	5.3	5.3	7.2	3.4	7.3	4.2	4.7	6.6	6.3	6.9	7.6	5.2	7.1	6.4	7.6	3.4	6.0	
Massaranduba natural																		
L*=	37.0	37.9	41.6	41.4	41.0	41.3	38.2	37.0	38.0	38.5	38.0	43.7	37.7	43.0	43.7	37.0	39.6	7.0
a*=	11.7	11.4	12.5	12.6	12.3	13.4	12.5	11.0	11.5	11.4	12.2	12.7	11.6	13.1	13.4	11.0	12.1	
b*=	12.9	13.0	15.7	16.0	15.1	17.0	14.6	12.3	12.0	13.3	13.6	17.1	13.2	16.0	17.1	12.0	14.4	
Ipe natural																		
L*=	39.1	42.0	38.5	37.9	42.2	38.9	38.1	38.5	40.5	42.4	43.4	39.3	38.7	38.2	43.4	37.9	39.8	5.4
a*=	9.3	10.1	10.5	10.1	9.0	9.8	8.9	9.3	11.3	8.8	9.7	10.6	9.2	9.4	11.3	8.8	9.7	
b*=	14.4	17.9	15.9	16.7	16.7	16.3	14.6	15.4	18.1	16.3	17.4	16.8	15.6	15.1	18.1	14.4	16.2	
Selangan Batu natural																		
L*=	49.0	49.5	49.2	46.7	51.0	48.6	49.1	48.5	49.3	47.7	49.3	48.8	47.1	49.4	51.0	46.7	48.8	4.5
a*=	11.9	11.8	12.0	12.3	12.1	11.9	11.9	12.1	11.8	12.5	12.0	11.3	12.5	11.6	12.5	11.3	12.0	
b*=	24.8	24.1	25.0	23.5	25.1	23.3	23.6	23.9	23.8	24.6	25.1	22.4	24.0	23.5	25.1	22.4	24.1	
Bocote natural																		
L*=	35.7	49.2	45.7	43.3	53.6	43.2	38.2	43.9	41.0	42.3	42.4	42.1	43.1	38.1	53.6	35.7	43.0	18.6
a*=	4.0	8.2	6.4	5.9	7.9	3.0	4.3	7.4	5.3	5.8	6.3	6.0	5.6	4.5	8.2	3.0	5.7	
b*=	10.3	22.2	18.6	17.1	22.7	12.5	12.0	19.5	15.1	16.6	17.0	16.5	16.6	11.9	22.7	10.3	16.3	
Teak natural																		
L*=	55.6	64.7	54.5	49.6	50.9	49.0	51.1	49.6	58.0	55.7	53.0	57.5	49.0	49.6	64.7	49.0	53.4	15.3
a*=	7.8	8.6	8.8	9.7	9.4	9.6	9.7	9.5	9.2	9.2	9.8	9.4	9.6	9.3	9.8	7.8	9.3	
b*=	23.1	24.9	23.4	22.3	22.9	21.1	22.5	21.7	25.8	25.2	23.8	26.1	21.2	22.0	26.1	21.1	23.3	
Zebrano natural																		
L*=	71.0	61.6	62.0	45.7	54.1	43.0	66.5	58.3	63.3	62.8	58.9	60.5	65.2	56.0	71.0	43.0	59.2	26.0
a*=	5.2	5.0	5.2	3.5	4.3	2.0	3.5	5.0	4.4	3.4	5.1	2.9	3.6	4.1	5.2	2.0	4.1	
b*=	23.0	22.0	22.3	18.9	17.4	16.2	25.0	21.2	21.5	22.5	21.2	23.1	22.5	18.4	25.0	16.2	21.1	
Ash natural																		
L*=	65.4	65.5	65.4	66.0	64.8	65.8	66.6	64.0	62.3	65.6	64.9	64.7	65.5	70.1	70.1	62.3	65.5	6.3
a*=	6.3	6.5	6.5	6.3	6.6	6.3	6.4	7.0	6.7	6.5	6.8	6.3	6.5	5.6	7.0	5.6	6.4	
b*=	21.2	21.6	21.8	21.3	21.5	21.4	22.1	21.8	21.2	21.6	21.6	20.6	21.4	22.1	22.1	20.6	21.5	
Cypress natural																		
L*=	84.6	82.3	84.5	85.7	84.9	84.4	84.6	84.9	85.9	85.5	84.7	85.6	84.4	82.8	85.9	82.3	84.6	5.3
a*=	2.6	4.2	2.8	2.4	2.8	3.0	3.1	2.8	2.4	2.3	2.8	2.6	3.0	3.9	4.2	2.3	2.9	
b*=	18.4	24.5	18.5	18.0	18.7	18.6	19.2	18.6	17.2	17.8	19.9	18.1	19.6	24.1	24.5	17.2	19.4	

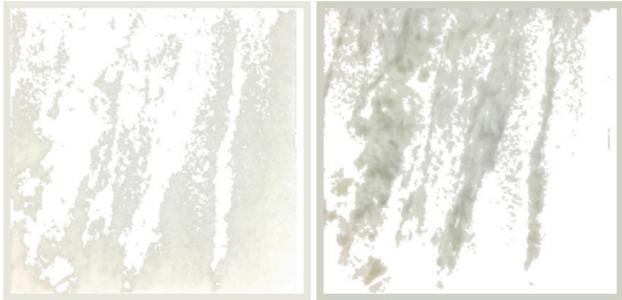
Table of collected data for *L* a* b** and ΔE00 (continuation)

CERAMIC																		
White ceramic tiling																		
L*=	90.2	90.3	90.5	90.3	90.4	90.2	90.4	90.3	90.4	90.4	90.3	90.4	90.4	90.3	90.5	90.2	90.3	0.2
a*=	-0.3	-0.3	-0.4	-0.3	-0.3	-0.3	-0.3	-0.3	-0.4	-0.3	-0.4	-0.3	-0.3	0.4	0.4	-0.4	-0.3	
b*=	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	
Grey ceramic tiling																		
L*=	73.9	77.6	74.3	77.5	74.6	77.7	76.0	75.6	74.3	76.6	77.5	77.0	76.1	77.0	77.7	73.9	76.1	3.5
a*=	1.4	1.9	0.6	1.1	1.9	1.8	1.6	0.8	1.5	1.5	1.4	1.6	0.7	0.2	1.9	0.2	1.3	
b*=	17.5	17.8	17.9	18.0	17.6	18.0	17.9	17.9	17.5	17.7	17.8	17.7	18.0	17.3	18.0	17.3	17.8	
Terracotta ceramic tiling																		
L*=	56.2	56.0	55.8	55.8	55.9	55.8	56.1	56.0	56.0	56.2	56.1	56.2	55.8	56.0	56.2	55.8	56.0	0.6
a*=	21.2	21.3	21.3	21.3	21.3	21.5	21.5	21.3	21.2	21.2	21.3	21.1	21.4	21.4	21.5	21.1	21.3	
b*=	26.9	26.8	27.0	26.9	27.0	27.1	27.1	27.0	27.0	26.8	27.1	26.7	27.1	27.1	27.1	26.7	27.0	
Offwhite ceramic tiling																		
L*=	80.5	79.3	79.7	78.8	79.4	80.2	79.1	79.7	79.7	79.9	79.8	79.0	79.6	79.8	80.5	78.8	79.6	2.1
a*=	2.7	2.8	2.8	2.7	2.6	2.5	2.7	2.7	2.6	2.5	2.7	2.7	2.6	2.7	2.8	2.5	2.7	
b*=	15.6	16.8	17.1	16.5	16.8	16.1	17.4	17.4	16.8	17.0	17.1	16.7	17.1	16.9	17.4	15.6	16.8	
Rosso ceramic tiling																		
L*=	39.6	38.0	36.1	35.2	36.0	36.4	39.4	39.2	39.6	38.9	38.3	36.2	36.0	36.2	39.6	35.2	37.5	3.7
a*=	20.2	20.8	20.4	20.5	20.7	20.6	20.1	20.5	20.3	20.6	20.6	21.2	20.6	20.4	21.2	20.1	20.5	
b*=	18.9	19.0	18.7	18.4	18.3	18.8	18.3	18.7	18.8	18.8	18.4	19.2	18.3	18.3	19.2	18.3	18.6	
CONCRETE																		
Mortar wooden formwork																		
L*=	55.4	50.1	57.7	55.7	58.9	58.1	58.2	58.0	49.1	57.3	57.9	49.8	58.3	58.6	58.9	49.1	55.9	9.8
a*=	-0.5	-0.7	-0.9	-0.9	-0.9	-1.3	-1.1	-1.0	-0.5	-0.9	-1.2	-0.3	-0.9	-1.0	-0.3	-1.3	-0.9	
b*=	8.9	6.7	8.6	8.4	9.0	8.0	8.0	8.2	6.5	8.6	8.2	7.4	9.1	8.9	9.1	6.5	8.2	
Mortar plastic formwork																		
L*=	53.9	54.0	54.8	52.4	54.7	57.7	55.3	56.4	57.4	58.1	59.2	57.2	54.3	53.4	59.2	52.4	55.6	6.5
a*=	-0.4	-0.5	-0.5	-0.5	-0.6	-0.6	-0.6	-0.5	-0.5	-0.5	-0.2	-0.6	-0.5	-0.6	-0.2	-0.6	-0.5	
b*=	6.3	6.4	6.3	6.3	5.8	5.7	5.6	6.0	5.9	6.1	5.6	5.7	6.8	5.8	6.8	5.6	6.0	
METAL																		
Zinc sheeting (#3 finish)																		
L*=	52.2	51.4	52.3	52.1	52.0	51.3	51.5	50.4	50.8	50.8	50.7	51.4	52.1	50.6	52.3	50.4	51.4	2.0
a*=	-1.2	-1.3	-1.3	-1.3	-1.2	-1.2	-1.3	-1.2	-1.2	-1.2	-1.2	-1.3	-1.2	-1.2	-1.2	-1.3	-1.2	
b*=	-1.0	-1.1	-1.0	-1.0	-1.0	-1.2	-1.2	-1.2	-1.3	-1.2	-1.0	-1.1	-0.9	-1.4	-0.9	-1.4	-1.1	
Weathered Steel																		
L*=	38.1	35.2	38.9	30.0	39.8	35.0	36.3	37.2	35.1	39.2	39.0	39.0	35.9	32.2	39.8	30.0	36.5	11.1
a*=	18.3	17.3	24.5	20.9	15.4	15.8	24.6	20.3	22.0	17.7	19.5	16.3	18.2	14.0	24.6	14.0	18.9	
b*=	24.5	27.6	35.4	30.3	29.3	27.6	34.9	23.5	30.7	31.8	24.8	30.3	28.4	21.3	35.4	21.3	28.6	
Stainless Steel sheeting (#2D finish)																		
s	64.9	65.1	65.6	65.5	65.5	65.5	65.3	65.1	65.6	65.2	65.2	65.3	65.7	65.0	65.7	64.9	65.3	0.7
a*=	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.1	
b*=	0.8	0.9	0.7	0.7	0.7	0.7	0.7	0.9	0.7	0.7	0.9	0.7	0.7	1.0	1.0	0.7	0.8	
Stainless Steel sheeting (#4 finish) bronze																		
L*=	37.6	37.3	37.3	37.4	37.2	37.8	37.3	37.4	37.8	37.6	37.6	37.4	37.6	37.8	37.8	37.2	37.5	0.7
a*=	3.1	3.2	3.3	3.2	3.1	3.1	3.2	3.1	3.3	3.2	3.3	3.1	3.2	3.2	3.3	3.1	3.2	
b*=	7.0	7.2	7.4	7.2	7.1	7.1	7.2	7.4	7.3	7.1	7.1	7.3	7.2	7.2	7.4	7.0	7.2	
Stainless Steel sheeting (#4 finish)																		
L*=	74.5	73.8	74.3	74.3	73.8	74.5	74.4	73.9	74.2	74.4	74.0	73.8	74.3	74.2	74.5	73.8	74.2	1.1
a*=	1.2	1.0	1.6	1.2	1.2	1.1	1.5	1.3	1.6	1.6	1.4	1.2	1.0	1.2	1.6	1.0	1.3	
b*=	-2.3	-2.5	-2.3	-2.4	-2.2	-2.4	-2.4	-2.4	-2.2	-2.3	-2.4	-2.3	-2.2	-2.3	-2.2	-2.5	-2.3	
Titanium sheeting (#4 finish)																		
L*=	77.1	76.8	76.5	76.9	76.4	77.0	77.1	76.4	76.7	77.1	76.8	76.9	76.7	76.6	77.1	76.4	76.8	0.6
a*=	-0.8	-0.8	-0.8	-0.8	-0.8	-0.7	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.7	-0.7	-0.8	-0.8	
b*=	4.5	4.6	4.5	4.4	4.5	4.5	4.5	4.4	4.5	4.6	4.6	4.5	4.4	4.7	4.7	4.4	4.5	

Table of collected data for *L* a* b** and ΔE00 (continuation)

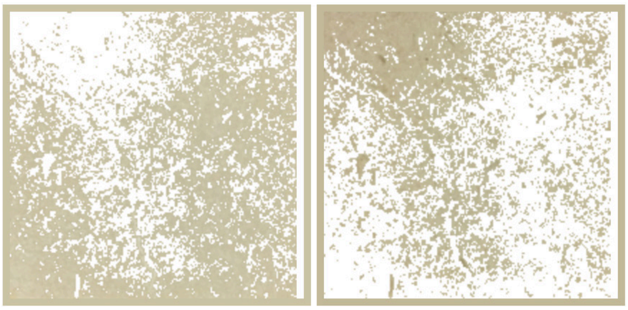
Brass sheeting (#4 finish)																		
L*=	63.9	63.3	63.5	63.7	63.6	63.9	63.4	63.3	63.3	63.5	63.7	63.4	63.4	63.5	63.9	63.3	63.5	0.7
a*=	-0.2	-0.2	0.0	0.2	0.1	0.2	-0.0	-0.2	-0.2	0.1	0.1	0.0	-0.1	-0.1	0.2	-0.2	-0.0	
b*=	17.9	17.8	18.1	18.4	18.5	18.6	18.1	17.6	17.7	18.4	18.7	18.6	18.0	18.3	18.7	17.6	18.2	
Copper sheeting (#4 finish)																		
L*=	56.5	56.4	56.2	55.7	55.5	56.1	56.4	55.7	56.2	56.0	55.4	56.1	55.9	55.7	56.5	55.4	56.0	1.2
a*=	10.5	10.4	10.3	10.2	10.2	10.3	10.5	10.2	10.4	10.5	10.2	10.7	10.6	10.2	10.7	10.2	10.4	
b*=	13.1	13.0	12.8	12.6	12.6	12.8	13.1	12.5	12.8	12.8	12.5	13.5	13.2	12.5	13.5	12.5	12.9	
GLASS																		
clear laminated glass																		
L*=	77.0	77.0	76.8	77.8	76.7	77.9	77.6	77.1	77.5	76.8	77.7	76.9	77.3	77.7	77.9	76.7	77.3	0.9
a*=	-3.6	-3.6	-3.6	-3.6	-3.6	-3.6	-3.6	-3.5	-3.6	-3.6	-3.5	-3.6	-3.6	-3.6	-3.5	-3.6	-3.6	
b*=	2.2	2.1	2.1	2.1	2.2	2.1	2.2	2.2	2.1	2.1	2.1	2.1	2.1	2.1	2.2	2.1	2.1	
acid etched float glass																		
L*=	79.6	79.3	79.6	79.7	79.7	79.6	79.8	79.8	79.7	79.6	79.8	79.5	79.7	79.8	79.8	79.3	79.7	0.4
a*=	-0.8	-0.9	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.9	-0.8	-0.8	-0.8	-0.8	-0.9	-0.8	
b*=	0.6	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.7	0.6	0.6	0.6	0.7	0.7	0.6	0.6	
frosted (soft) float glass																		
L*=	81.5	81.1	81.2	81.3	81.2	81.1	81.3	81.5	81.1	81.4	81.1	81.5	81.1	81.2	81.5	81.1	81.3	0.4
a*=	-2.5	-2.6	-2.6	-2.5	-2.5	-2.6	-2.5	-2.6	-2.5	-2.5	-2.6	-2.6	-2.5	-2.5	-2.5	-2.6	-2.5	
b*=	0.3	0.4	0.3	0.4	0.3	0.4	0.3	0.4	0.3	0.3	0.4	0.3	0.4	0.3	0.4	0.3	0.3	
frosted (medium) float glass																		
L*=	78.3	78.1	77.9	77.9	78.0	78.0	78.0	78.1	77.9	78.2	78.1	78.0	78.0	78.0	78.3	77.9	78.0	0.3
a*=	-2.4	-2.5	-2.4	-2.4	-2.5	-2.5	-2.5	-2.4	-2.4	-2.5	-2.4	-2.4	-2.4	-2.4	-2.4	-2.5	-2.4	
b*=	0.1	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.1	0.2	
bronze laminated glass																		
L*=	27.2	27.0	27.2	27.1	27.0	27.4	27.1	27.2	27.0	27.3	27.2	27.1	27.1	27.1	27.4	27.0	27.1	0.3
a*=	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.6	1.7	1.7	1.6	1.7	1.7	1.7	1.7	1.6	1.7	
b*=	10.6	10.4	10.5	10.5	10.4	10.5	10.5	10.4	10.4	10.6	10.5	10.4	10.5	10.6	10.6	10.4	10.5	
POLYMER																		
ETFE clear 250µm sheeting																		
L*=	87.3	87.2	87.2	87.5	87.2	87.2	87.2	87.3	87.2	87.5	87.5	87.3	87.5	87.2	87.5	87.2	87.3	0.3
a*=	-0.1	-0.1	-0.1	-0.2	-0.1	-0.1	-0.2	-0.1	-0.1	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.1	
b*=	-0.5	-0.5	-0.4	-0.6	-0.5	-0.6	-0.5	-0.4	-0.5	-0.4	-0.5	-0.6	-0.6	-0.4	-0.4	-0.6	-0.5	
ETFE frosted 250µm sheeting																		
L*=	89.0	89.0	88.9	88.9	88.9	88.9	88.9	88.9	88.9	89.0	88.9	88.9	88.9	88.9	89.0	88.9	88.9	0.2
a*=	-0.4	-0.4	-0.4	-0.5	-0.4	-0.5	-0.5	-0.5	-0.4	-0.4	-0.4	-0.5	-0.4	-0.4	-0.4	-0.5	-0.4	
b*=	-0.2	-0.1	-0.1	-0.1	-0.0	-0.2	-0.2	-0.1	-0.1	-0.2	-0.1	-0.2	-0.1	-0.1	-0.0	-0.2	-0.1	
ETFE white 250µm sheeting																		
L*=	91.3	91.2	91.3	91.2	91.2	91.2	91.2	91.2	91.2	91.2	91.2	91.3	91.2	91.2	91.3	91.2	91.2	0.3
a*=	-0.9	-1.0	-1.0	-1.1	-1.0	-1.0	-1.0	-1.0	-1.1	-1.1	-1.1	-1.0	-1.0	-1.0	-0.9	-1.1	-1.0	
b*=	0.3	0.4	0.3	0.4	0.4	0.3	0.5	0.3	0.5	0.4	0.4	0.3	0.3	0.4	0.5	0.3	0.4	
ETFE blue 250µm sheeting																		
L*=	78.7	78.8	79.0	79.0	78.9	79.0	78.8	78.8	78.9	79.0	78.9	78.7	78.8	78.8	79.0	78.7	78.8	0.4
a*=	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	-3.0	
b*=	-12.5	-12.8	-12.4	-12.3	-12.6	-12.8	-12.6	-12.3	-12.5	-12.7	-12.3	-12.6	-12.3	-12.4	-12.3	-12.8	-12.5	

Table of output from Pattern analysis



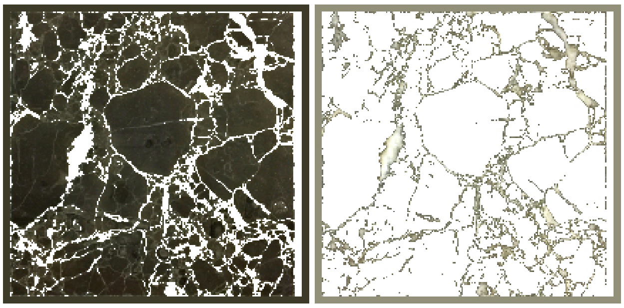
White Smoke marble polished

cluster	pixels
	54.13%
	45.87%



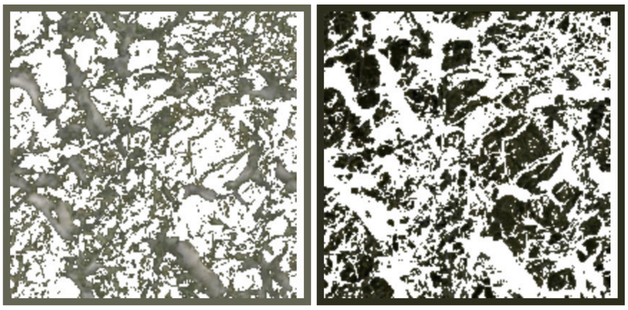
Crema Marfil marble polished

cluster	pixels
	59.47%
	40.53%



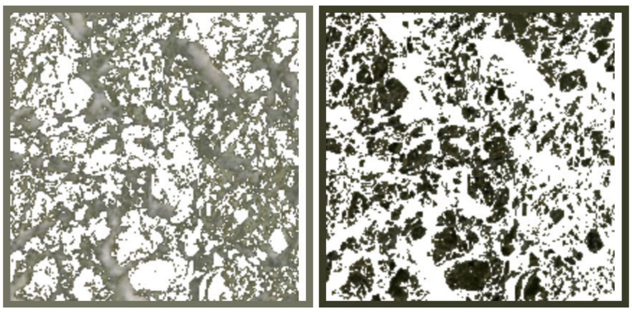
Savona Dark Brown marble polished

cluster	pixels
	81.83%
	18.17%



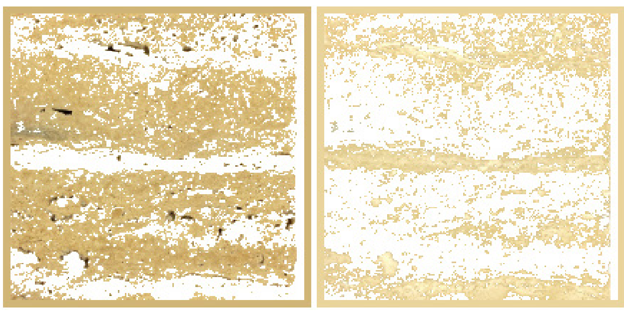
Djamon marble polished

cluster	pixels
	51.68%
	48.33%



Djamon marble honed

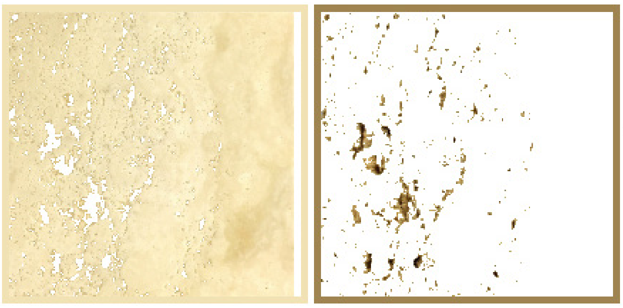
cluster	pixels
	56.77%
	43.23%



Noce travertined honed

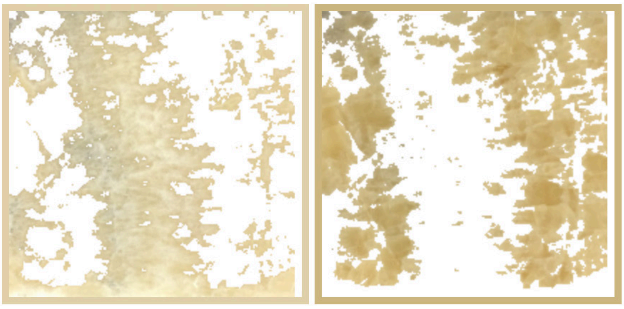
cluster	pixels
	62.50%
	37.50%

Table of output from Pattern analysis (continuation)



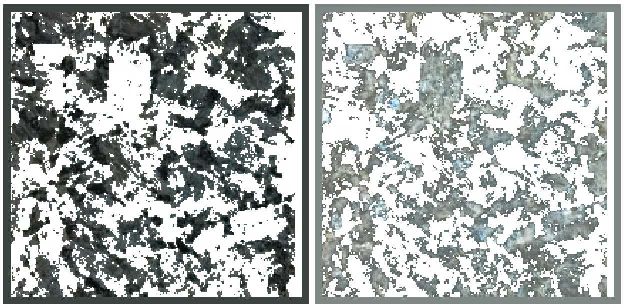
Romano Classico travertine honed

cluster	pixels
	95.15%
	4.85%



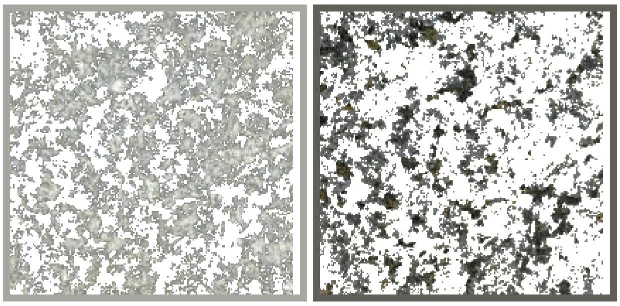
Alabrastro onyx polished

cluster	pixels
	50.53%
	49.47%



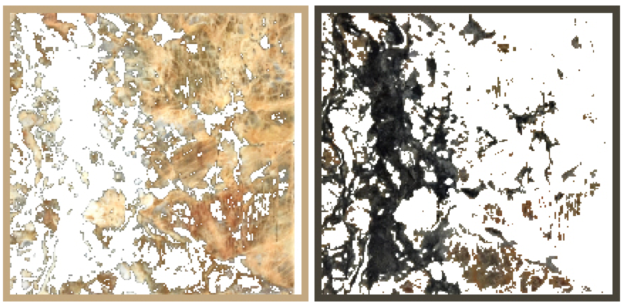
Blue Pearl granite polished

cluster	pixels
	53.03%
	46.97%



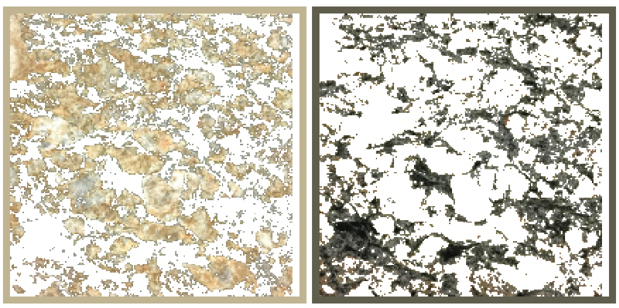
Blue Pearl granite flamed

cluster	pixels
	59.82%
	40.18%



Golden Black granite polished

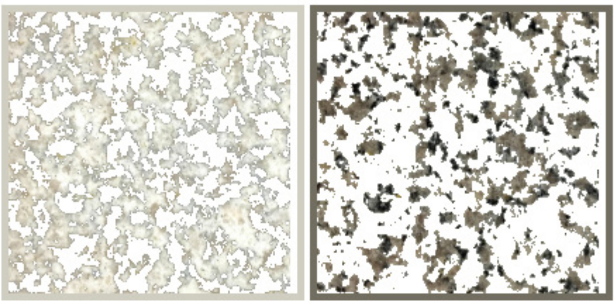
cluster	pixels
	62.16%
	37.84%



Gloden Black granite flamed

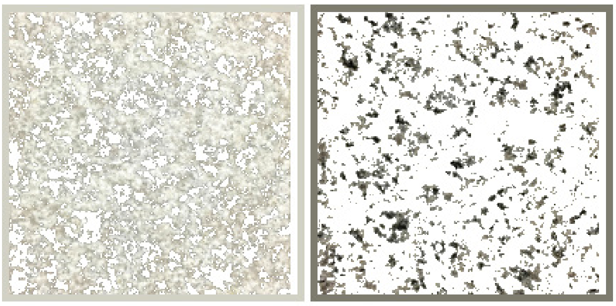
cluster	pixels
	59.42%
	40.58%

Table of output from Pattern analysis (continuation)



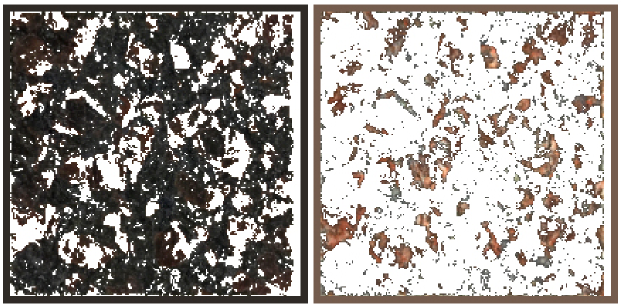
Inada granite polished

cluster	pixels
	61.83%
	38.17%



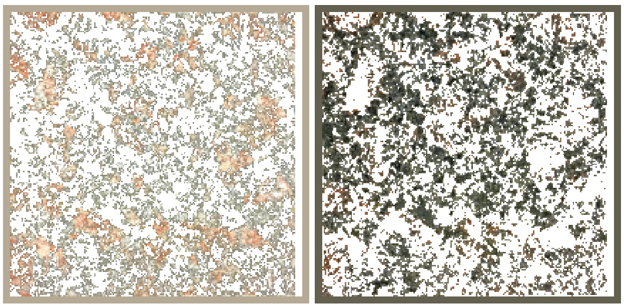
Inada granite flamed

cluster	pixels
	76.94%
	23.06%



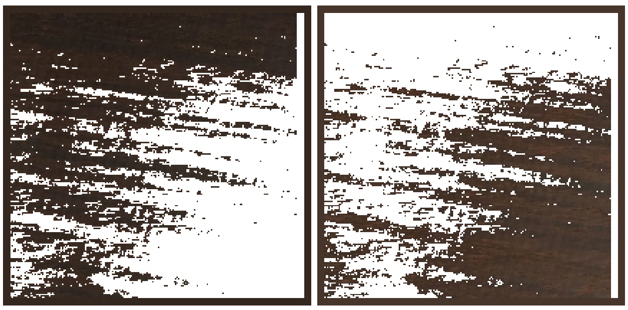
Tan Brown granite polished

cluster	pixels
	74.44%
	25.55%



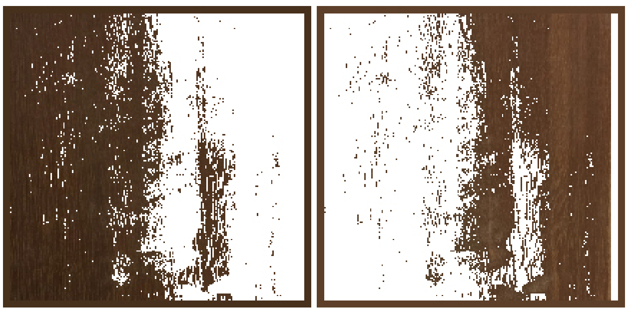
Tan Brown granite flamed

cluster	pixels
	52.10%
	47.90%



East Indian Rosewood natural

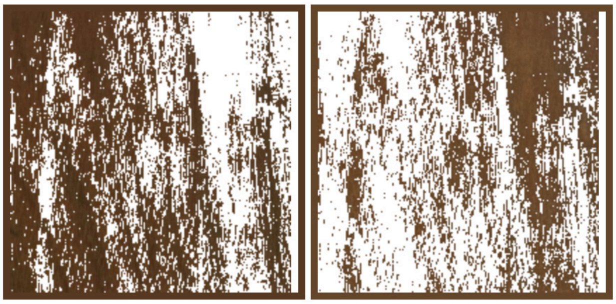
cluster	pixels
	53.53%
	46.47%



Massaranduba wood natural

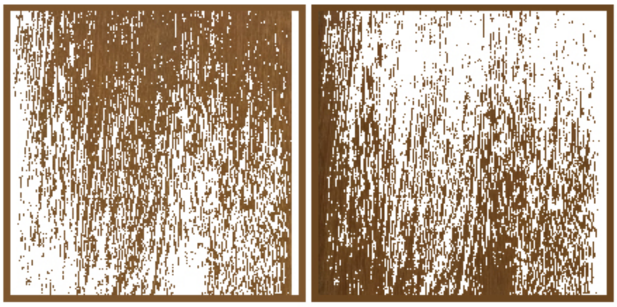
cluster	pixels
	54.16%
	45.84%

Table of output from Pattern analysis (continuation)



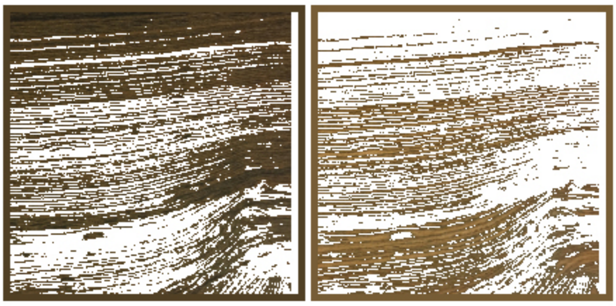
Ipe wood natural

cluster	pixels
	58.41%
	41.59%



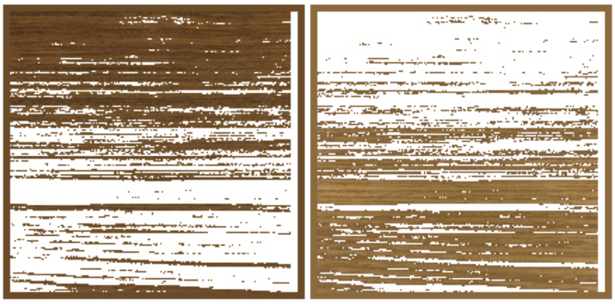
Selangan Batu wood natural

cluster	pixels
	54.82%
	45.18%



Bocote wood natural

cluster	pixels
	59.06%
	40.94%

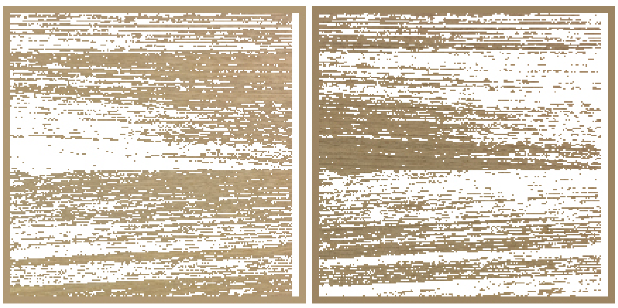


Teak wood natural

cluster	pixels
	52.41%
	47.59%

Zebrano wood natural

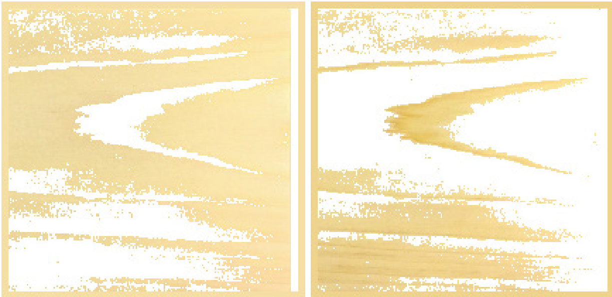
cluster	pixels
	68.87%
	31.13%



Ash wood natural

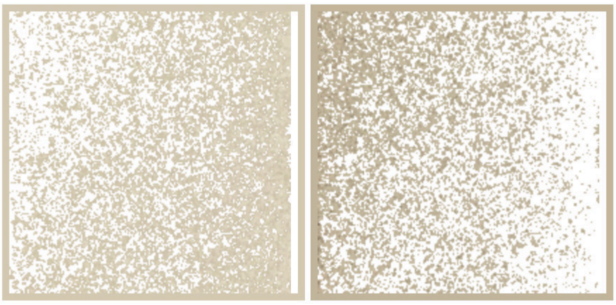
cluster	pixels
	53.74%
	46.26%

Table of output from Pattern analysis (continuation)



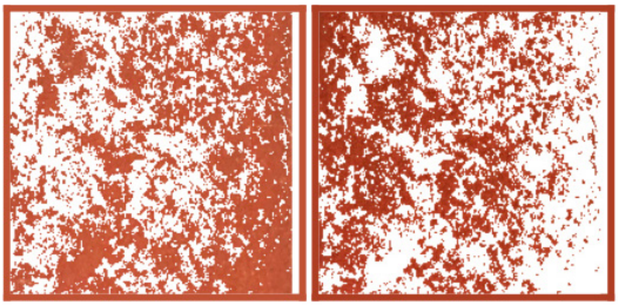
Cypress wood natural

cluster	pixels
	65.88%
	34.12%



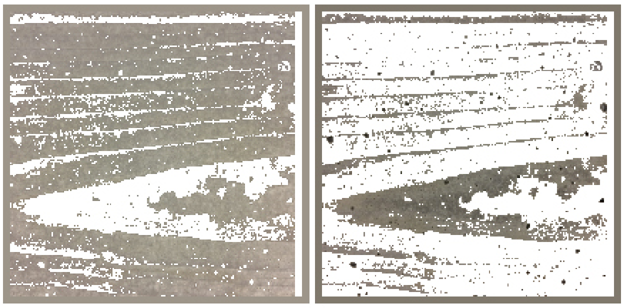
Grey ceramic tiling

cluster	pixels
	56.83%
	43.17%



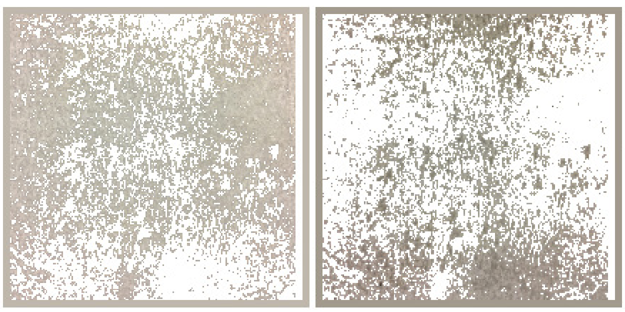
Rosso ceramic tiling

cluster	pixels
	55.71%
	44.30%



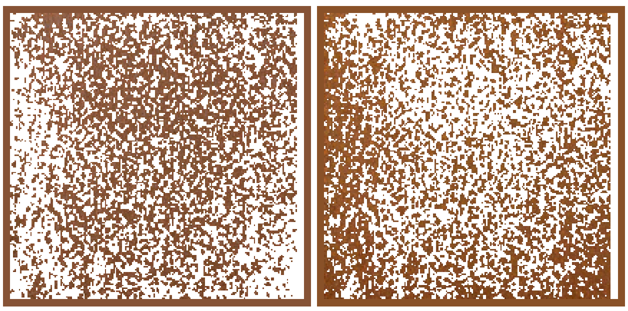
Mortar wooden form-work

cluster	pixels
	74.05%
	25.95%



Mortar plastic frame-work

cluster	pixels
	59.82%
	40.18%



Weathered Steel

cluster	pixels
	50.30%
	49.70%

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