THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Sensation, Perception and Surface Properties

Methodologies to ensure robust production with a remaining product experience.

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Department of Materials and Manufacturing Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

The Swedish manufacturing industry is seeking innovative ways to produce eco-efficient and resource-efficient products while maintaining high quality and competitiveness. To achieve this, the control and optimization of production processes, particularly with novel materials and surface engineering, are essential. As demand for functional and aesthetically appealing surfaces increases, the industry must bridge the gap between technical performance and perceived quality. This thesis examines how surface design and characterization can be integrated with design intention and perception to ensure robust and sustainable production.

The definition and interpretation of surface roughness and appearance varies across different industries and academic fields. Surface topography significantly influences both functional properties, such as wear, friction, and wettability, as well as perceived attributes like gloss and texture. However, conventional average roughness parameters (Ra or Sa) provide limited insight into these multidimensional characteristics. This research, therefore, proposes a methodology that combines standard surface parameters with statistical analysis to identify and optimize the most significant parameters that describe surface function and appearance.

Through case studies and industrial collaborations, surfaces produced by additive, subtractive, and formative manufacturing processes were analyzed using areal parameters (ISO 25178), power spectral density, and scale-sensitive fractal analysis. Regression-based methods were used to identify parameter combinations that best describe surface characteristics and their correlation with process variables. By linking technical and emotional functions, hard and soft metrology, the developed methodology enables an improved understanding of how production conditions affect both functional performance and perceived quality.

The research emphasizes the importance of transdisciplinary collaboration between design, engineering, and production to preserve design intent throughout the manufacturing chain. The proposed framework contributes to the development of robust production systems that coexist with surface functionality and perceived quality, supporting sustainability goals and future integration with AI-driven optimization. Ultimately, this work demonstrates how the interplay between measurable surface characteristics and human perception can guide the industry in designing meaningful, high-quality products that perform well, both technically and emotionally. Contribution: The research bridges the gap between mechanical engineering, product design, and manufacturing by linking surface functionality with perceived quality. It advances surface characterization beyond average roughness, enabling predictive, data-driven optimization.

Keywords: *Characterization, Perceived quality, Manufacturing, Surface roughness, Sensation and Perception, Metrology, Sustainability, Properties, Total Appearance, Kansei Engineering.*

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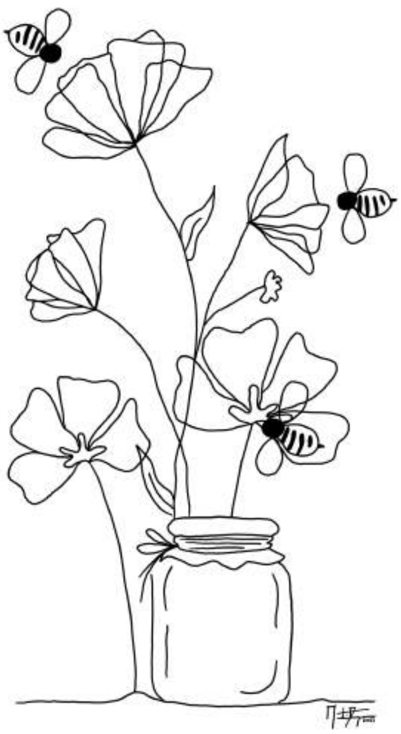

LIST OF PUBLICATIONS

This thesis is based on (but not limited to) the work contained in the following papers.

Paper I

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Paper II

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Paper III

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Bergman, M., Rosén, B.-G., & Eriksson, L. (2012). Surface appearance and impression. In Proceedings of the International Conference on Kansei Engineering and Emotion Research (KEER 2012). CRC Press.

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Rebeggiani, S., Bergman, M., Rosén, B.-G., & Eriksson, L. (2023). On communicating extruded aluminium surface quality along the supply chain: A customer approach to sustainable surfaces. Surface Topography: Metrology and Properties, 11(1), 014002. https://doi.org/10.1088/2051-672X/acb8a5

Co-author statement

All papers are written by Martin Bergman together with Mechanical Engineering Prof. Bengt-Göran Rosén (Halmstad University) and Industrial Design Prof. Lars Eriksson (Jönköping University).

CONTENTS

GLOSSARY: DEFINITIONS AND TERMS USED IN THE THESIS

Aesthetics: The study of the effect of gestalt design on sensation (Monö, 1997).

Engineering design: Design with particular emphasis on the technical aspects of a product, including both analytical and synthetic activities.

Form: Shape (geometry), dimension, surface texture, structure, and configuration.

Gestalt: A discernible whole; an arrangement of parts so that they appear and function as a whole which is more than the sum of the parts (Monö, 1997).

Industrial design: Design with particular emphasis on the relation between product and man, e.g., semiotic, ergonomic and aesthetic aspects of the product. It should also be scalable. (Lippencott, 1947)

Product design: The activities regarding the design of products, including the activities of engineering design and industrial design. (Lippencott, 1947)

Product: A system, object or service made to satisfy the needs of a customer. *Function* see Product function.

Semantic function: Product function related to the meaning we place, or interpret, into its form. Includes the four functions to describe, to express, to exhort, to identify (Monö, 1997).

Syntactic function: Product function related to the structure and configuration of visual form (Monö, 1997).

Ergonomic function: Product function that enables or enhances the use of a product with respect to physical or cognitive ergonomics.

Communicative function: Collective term for syntactic and semantic functions (Monö, 1997).

Form function: Alternative term for Communicative function.

Product semantics: The study of the symbolic qualities of man-made forms in the cognitive and social context of their use and application of knowledge gained to objects of industrial design (Krippendorff, 2006).

Product function: What a product or an element of a product actively or passively does in order to contribute to a purpose, by delivering an effect. A function is intended or incidental.

Functionality: The combination of all effects, properties, and their behavior, that contributes to making the product useful for its purpose.

Property: Any characteristic of an object, that belongs to and characterizes it.

Configuration: A system that is designed by selecting existing elements and arranging them into a product.

Structure: Elements and their relations (functional and spatial).

Artifact: A thing made, or given shape, by man. (Karlsson, 1996)

Design (object): The result of a design process.

Design (process): To conceive the idea for some artifact or system and/or to express the idea in an embodiable form.

Semantics: The study of the sign's message (the meaning of the sign) (Monö, 1997).

Semiotics: The study of signs (Monö, 1997).

Syntax: The study of the signs relations to other signs and the way it interacts in compilations of signs (Monö, 1997).

System: A system is separated from the surroundings by a borderline, and has a structure consisting of elements and their relations.

Technical system: A man-made system that is capable of performing a task for a purpose.

Stakeholder: Any individual who, for a certain purpose, interacts with the product or any realized element (system, part, component, module, feature, etc., manifested in software or as concrete objects) of the product, at any phase of the product life cycle.

Design thinking: A design-specific cognitive activity that designers apply during the process of designing.

Design doing: A design-specific practical activity that designers apply during the process of designing.

Desirability: A term for what is needed on the market, the stakeholders requests.

Viability: A term for what is economically justifiable.

Feasibility: A term for how well the product might be developed and manufactured.

Soft Metrology: Usually implemented with qualitative properties, impressions, etc.

Hard Metrology: Usually implemented with quantitative methodology using sensors and metrology methods. All hard metrology is measured with some kind of measurement system.

Total Apperance: The symbiosis of; Physical, Physiological and Psychological aspects regarding a product.

Functional surfaces: Surfaces that somehow affect a products value regarding function and experience.

Perceived Quality: A customer's perception of the quality of a product, brand or business.

Sustainability: Referring to the three dimensions: economical, environmental and Social.

Design Intention: Referring to the purpose or goal that designers set out to achieve their creations.

1 INTRODUCTION

Define the color ‘red’ to the person next to you. Easy or not, it all depends on your way of describing as well as the listener's way of interpreting the description. What hue, saturation, and lightness of red are you thinking of? If you describe it as a red apple, do you mean the ‘Pink Lady’ or ‘Gala’?

Colors are one parameter of ‘design’ and something that we learned to handle from childhood. Yet, it is a challenging design parameter with several standards linked to it. Try adding perceived gloss to this discussion as well, or describe the surface texture…

The fact that people’s input value will challenge the way ‘design’ is described and interpreted needs to be accepted. Prior experience has a huge impact on sensation and perception. By the way, did the person next to you even know about the different apple species you referred to?

This thesis focuses on material and surface design and evaluation, rather than shape or form factors. So how would you describe the appearance of a product to the person next to you, focusing on the material and surface design? Your eyes are moving over the surface, and you will eventually touch it, and then you say: “It’s smooth, almost like a puppy’s ear!”. Some would instantly be able to relate to the feeling and maybe agree with it. The typical engineer’s first question, on the other hand, might be: “Ok, but what breed of dog?”

The primary outcome of this research is a proposed methodology that builds on the established method ‘Kansei Engineering’, yet adapted for material and surface design. Unlike ‘Kansei Engineering’, which focuses on translating emotion-related values into design parameters, this methodology provides a comprehensive framework for correlating UX and product properties, encompassing functional, contextual, perceptual, and emotional dimensions. A key feature is the direct link between sensation and perception, enabling subjective impressions to be connected to measurable material and surface properties, including ISO 25178-2:2021 surface texture parameters, as well as the manufacturing processes that produce them.

This is a design issue with numerous variables associated with it, and the purpose of design in general is to serve as a value-creating process that integrates holistic perspectives, addressing human needs, societal challenges, and sustainable development through thoughtful, user-centered solutions. The primary focus of this thesis is the development of a methodology that addresses interaction, communication, and functionality in the field of product design, with a specific emphasis on visual stimuli related to materials and surface textures. However, it should be recognized that research regarding perceived quality involves ‘wicked problems’ and depends on time and trends, which means that it is nearly an infinite work, challenging to complete. It is an iterative process, similar to the classical design process, which confirms that the loop of the methodology needs to be tested and verified for each field of implementation. The research has been developed, tested, and implemented through a number of case studies in collaboration with the Swedish industry.

1.1 BACKGROUND

Historically, in the automotive industry, for example, quality has been traditionally measured using quantitative metrics, such as the number of defects per 1,000 cars produced. However, today's consumers also place great importance on qualitative aspects, such as how the car feels to drive, the aesthetics of the design, or the overall brand experience. The perception of what establishes "quality" is therefore changing over time and varies between people.

Customer expectations, demands, and complaints motivate the development of service and product design toward new standards. As a global community, we tend to push development rapidly forward with higher demands and tighter process windows at a very detailed level. Our past can interfere with the interaction of new products or services, jeopardizing the experience if we fail. Desmet and Hekkert (2007) support this perspective in their paper Framework of Product Experience, where they highlight how user expectations, prior experiences, and concerns fundamentally shape the way people perceive and evaluate products. They argue that when a product fails to align with these expectations, the resulting appraisal can lead to negative emotional experiences such as frustration or disappointment.

A product's technical functions (including shape, materials, surface color, etc.) should be carefully developed and thought out to match the customer's expectations and acceptance. If we have 'cognitive flow' in our everyday lives, we tend to relax and lower our psychological guard (Kahneman, 2013). However, the interaction between man and machine must be complete to ensure a pleasant experience; otherwise, the product will be put aside in favor of other products. Therefore, the emotional functions (stimuli of the senses that create feelings) of the product must also be considered (Desmet & Hekkert, 2007).

At the time of writing this thesis, partly as a result of various global crises, including the COVID pandemic, sky-high energy prices and inflation, the world is undergoing a paradigm shift regarding what we refer to as sustainability in all its forms. A lot has changed: the way we design, produce, and trade has been challenged in a short period of time, and businesses are adapting to the ongoing paradigm shift in order to survive. For example, home deliveries of groceries and general merchandise have significantly increased (Sharfuddin, 2020). In the field of material design, on the other hand, this paradigm shift appears to challenge the material selection for future products, raising questions such as: What forms sustainability? Is premium sustainable? Is sustainable premium? How should we produce more sustainably? Is it possible to upscale positive research findings? Is this material durable, and will the user be satisfied with it? How should we measure and categorize total appearance and perceived quality?

In the wake of various global crises in tandem with emerging megatrends, the view and approach of 'sustainability' are somewhat different from before regarding global sustainability goals. Producing companies are compelled to maintain the same rate of production with the same (or better) quality, while also reducing emissions; which could be seen as a wicked problem. Yet, this means that materials, design, and production must be optimized with sustainability in mind (Barbier & Burgess, 2020). The material properties and surface appearance are of high importance, as they have a major impact on both technical and emotional functionality. One recurring question for some industries is: "Is it possible to work with sustainable materials and manufacturing with the maintained total appearance of a product, or should the product's total appearance change towards a more sustainable expression with other, more sustainable specifications?" (Bergman et al., 2016), Paper IV.

Nevertheless, the manufacturing industry is affected and will eventually have to change its processes towards a more sustainable option. The discussion regarding sustainability is becoming increasingly prevalent and has a multidimensional impact on material design and selection (Ashby, 2021). This new era may enable a novel turn in the research of material design and evaluation.

1.2 THE MATTER

Today, the production of materials requires a higher level of process control and verification compared to how we produced in the last few decades. Traditionally, the engineering requirements are superior to other demands, such as experience-based requirements or the ability to recycle components. However, today's production quality is generally better and more evenly distributed on a global level, which has forced the production price to a lower level. This fact, combined with additional regulations and demands, such as those outlined in the Sustainable Development Goals, has led to a focus on additional requirements, including sustainability and the perceived quality of manufactured components, over the last decade (De Simone et al., 2023). The concept of sustainability itself already challenges how we design, produce, and recycle components. One significant issue is how to communicate sustainable intentions to consumers in already complex products. The knowledge of perceived quality will be a competitive advantage for future products. Today's consumers are more educated, or 'woke,' in the field of sustainability, and they tend to choose their investments more carefully (Wang & Su, 2022). However, consumer decisions when choosing a product involve a complexity of aspects, including external stimuli controlled by our five senses and the interpretation of these signals, fulfilling functional requirements, and Gestalt, which describes the sum of the product's properties. This is underscored by the fact that the widely implemented ISO 9001 series is based on seven quality management principles, with the first being customer focus:

"Sustained success is achieved when an organization attracts and retains the confidence of customers and other interested parties on whom it depends. Every aspect of customer interaction provides an opportunity to create more value for the customer. Understanding current and future needs of customers and other interested parties contributes to the sustained success of an organization" (ISO 9001:2015).

Global goals regarding the environment, along with all stages of sustainability, require an understanding of customer satisfaction across various fields. The importance of empathizing with customer needs regarding design parameters should be in the interest of all organizations.

"Because what is the purpose of our work, if not to improve the human conditions in any manner? In every piece we create, there is a responsibility to serve humanity in tandem with the challenges we naively and recurrently generate…"

My own inner voice

For example, Nagano et al. (2013) describe how well-polished metal surfaces and finely woven clothes may be examples of product properties specially designed to appeal to the human sense of visual feedback and touch, targeting an exclusive high-quality market. The view of what could be considered exclusive is challenged in tandem with the interpretation of sustainability. Some findings suggest that luxury buyers have ambivalent attitudes, considering luxury and sustainability to be slightly inconsistent, particularly in terms of the social and economic harmony aspect of sustainable development (Kapferer & Michaut-Denizeau, 2013). It is known that the sub-millimeter scale of the structure in materials affects us as customers and users in a subtle way. The impact of changing the topography on the surface of sandblasted aluminum, for example, could create a completely different stimulus for our senses. Defining the boundary between something that is experienced as sharp or soft in terms of design properties can be a challenging task. Nevertheless, the upcoming challenges of materials (mentioned above), along with the current paradigm-shifting global trends, will constantly alter how customers respond to different materials.

Personal experiences from design work in both teaching and student projects, as well as collaborations with industries on a global level, have contributed to the identification of new needs that have influenced the direction of the thesis work. However, the incentives for this research were the following, where Delft design guide partly highlights similar needs (Van Boeijen et al., 2020):

- The need for increased transdisciplinary collaboration between industrial design and engineering design activities for a holistic approach
- The need to understand perceived quality from a sustainability perspective
- The vision of implementing a methodology regarding challenges in perceived quality and total appearance of materials and surfaces in the industry
- The need for a consensus regarding sustainability vs future trends and the control of perceived quality

1.3 'DESIGN INTENTION', TOTAL APPEARANCE & ROBUST PRODUCTION

What purpose does 'design intention' have, and why is it so important for the production and the total appearance? This section aims to help the reader appreciate the concept of total appearance from a design perspective, while also clarifying how design in an early stage relates to the assessment of components in production.

Design Intention

Design, in general, is a process that involves problem-solving, creativity, and effective communication. Yet, it is also about future possibilities; otherwise, continuous improvements could cease immediately. However, it is not just about highlighting problems and solving them; new products, systems, and services will change the conditions for life and business, not just functional but also emotional (Ullmark, 2004). Briefly, 'design intention' refers to the purpose or goal that the designers define to bring their creations to life. It serves as a guide and is the first and most critical aspect of the design process, as it provides the direction and focus for the design project. 'Design intention' involves a deep understanding of the addressed problem, the needs of the users, and the constraints and opportunities of the design context. It requires creativity, critical thinking, and effective communication to translate ideas into tangible design outcomes (Lawson, 2005). Several factors influence design intention. The designer's tacit knowledge, as well as personal values, beliefs, and experiences, the company's values, the users' needs and expectations, the context's characteristics, and the available resources and technologies are some of these factors. Designers must consider these factors when defining their design intention and ensure that it aligns with the overall objectives of the design project (Cross, 2006). Design intention has a significant impact on the design outcomes. A clear and focused design intention can guide the design process (and the people within it) and ensure that the design meets the needs and requirements of the stakeholders and the objectives of the project (Cross, 2006). On the other hand, a poorly defined or conflicting design intention can lead to confusion, frustration, and ultimately, failure (Norman, 2013). Therefore, designers must invest time and effort in defining and communicating their design intention, both at a high level and in detail, to achieve successful design outcomes. However, this could be challenged by the management structures and cultures of a company (Lippencott, 1947).

Total Appearance

Total appearance, which was introduced by Hutchings in the 1990s (including physical features, colors, textures, and overall presentation), plays an essential role in product design and is highly interconnected with the design intention. The total appearance of a product will likely significantly influence consumer perceptions, emotional responses, and purchase decisions. Research has shown that consumers tend to create their judgments about products within the first few seconds of exposure based on their initial visual appearance (Lidwell, Holden, & Butler, 2003). Additionally, total appearance is used to establish brand identity and differentiate from competitors; however, it also creates emotional connections with consumers, creating what is known as 'meta value' (Pavlou & Dimoka, 2006; Monö, 1997).

However, the impact of total appearance extends beyond creating visual appeal. Total appearance tells "the story" about an artifact and enriches user experience by influencing the functionality, usability, and accessibility of a product. It can be used to communicate information about certain product features, user interface, and important navigation (known as semantics), (Van Boeijen et al., 2020). Furthermore, the total appearance of the product significantly impacts its perception of quality, reliability, and durability (Michailidou, Harper, & Bechhofer, 2008). While total appearance plays a vital role in product design, designers must also consider the broader context in which the product will be used. Total appearance should be controlled to meet the needs of the target audience and align with their values and preferences. It should also cover the environmental impact of the product, such as its sustainability.

Robust production and component assessment

To achieve the expected goals of a design intention and its total appearance, the production must consistently hit the target over time with high accuracy. However, it must also be able to understand possible deviations from the expected goal regarding total appearance and be able to correct these deviations in manufacturing. The production of 'high quality' components is essential for the success of any manufacturing organization today regarding customer needs and expectations of products. To ensure that addressed customer needs are fulfilled, the industry's ability to implement product assessment also plays an essential role (Juran & De Feo, 2010). Product assessment involves evaluating product quality against predetermined standards or criteria. It includes the measurement of various product attributes, such as dimensions, weight, strength, and durability, to ensure that they meet the desired specifications (Montgomery, 2013; Yang & El-Haik, 2010). A robust production system must be able to withstand disturbances to maintain its high-performance level. If the manufacturing organization consistently hits the expected target over time with high accuracy regarding the given specification, you can possibly assume that the production is 'robust.' Robust production refers to the design and implementation of manufacturing processes that can tolerate variations in input materials, equipment performance, and environmental conditions. It is essential to ensure that the products produced are consistent and meet the desired quality standards (Stricker & Lanza, 2014; Taguchi & Wu, 2004).

To ensure high quality, various methods and techniques are used for product assessment, including statistical process control, quality reviews, product testing, and internal inspections of the product. A product assessment can be both quantitative and qualitative, depending on its purpose. A design review or qualitative study among users could be preferable regarding total appearance and perceived quality (Shewhart, 1939).

Statistical process control (SPC) involves monitoring and controlling the manufacturing process using statistical techniques to detect and ultimately eliminate variation (Montgomery, 2013). Quality reviews can be conducted to assess the quality management system and ensure it complies with relevant standards and regulations. This is common in industries such as the automotive industry, where standards like IATF 16949 require rigorous quality management and regular audits. The IATF 16949 standard is based on ISO 9001 and national quality standards for the automotive industry. While ISO 9001 focuses on customer satisfaction, IATF 16949 emphasizes customer-specific requirements related to continuous improvement, defect prevention, and the reduction of variation and waste in the supply chain (Juran & De Feo, 2010). Furthermore, product testing involves evaluating the product's performance against the specified requirements, while inspection involves examining the product for defects or non-conformities.

A 'robust' production has several benefits for both manufacturing organizations and the environment. It ensures that the products produced are consistent and meet the desired quality standards, reducing the risk of customer complaints and product recalls. It also minimizes the impact of variation in the manufacturing process, reducing waste, rework, and scrap (Taguchi & Wu, 2004; Yang & El-Haik, 2010). Product assessment and robust production can be challenging for manufacturing organizations, particularly for those with complex and customized products. A significant investment in technology, equipment, and trained personnel is required to ensure that the manufacturing process consistently produces high-quality products. It also requires a culture of quality and continuous improvement, focusing on data-driven decision-making and problem-solving (Juran & De Feo, 2010; Shewhart, 1939). To understand the impact of quality, it is necessary to explain the term from two different perspectives: the ‘soft’ and the ‘hard’. The quality of a product is a vital factor that affects consumer behavior and purchasing decisions. Consumers assess the quality of a product based on various factors, including performance, reliability, durability, and aesthetics. However, the perception of quality is subjective and varies among individuals. Therefore, assessing the quality of a product is crucial for businesses to meet consumers' expectations and needs. The quality of a product can be divided into two approaches: a user-based approach and a manufacturing-based approach, also referred to as a “soft” and “hard” approach. The soft assessment addresses the user’s highly subjective perspective on perceived quality, while the hard assessment focuses on the component’s measurable qualities, such as engineering and manufacturing features (Garvin, 1984; Lippincott, 1947). Nevertheless, even though there is a distinct line between soft and hard assessment, the symbiosis of the two is crucial for the total appearance. The ability to assess, measure, and control the hard/engineering features makes it possible to influence the soft/perceived quality of components. This implies that quality assessment differs depending on the desired attribute.

1.4 DESIGN AND SUSTAINABILITY

It is widely acknowledged that the design process plays a crucial role in determining the sustainability impact of a product. Key decisions made during the early stages of the design, such as material selection, manufacturing techniques, product lifespan, and end-of-life considerations, have long-lasting effects on a product’s environmental impact. For instance, the choice between renewable and non-renewable materials, or between modular and monolithic product architectures, directly influences resource consumption, energy use, and the potential for recycling or reuse (Bhamra & Lofthouse, 2007; Sherwin, 2000; UNEP, 2011).

Product design is a complex process that involves multiple disciplines, including, e.g., engineering, materials science, marketing, and user experience. The complexity arises from the interdependence of various disciplines and the need to balance multiple factors, including functionality, aesthetics, cost, and sustainability (Charter & Tischner, 2001). Furthermore, product design is often a time- and resource-intensive process that requires significant investment in research and development, testing, and production. Moreover, sustainability is a critical consideration in product design, as it has a significant impact on the environment and society. Sustainability within product design is often approached from various perspectives, such as circular economy, life cycle assessment, eco-design, and norm-critical design (Heijungs et al., 1992; Bhamra & Lofthouse, 2017). Each perspective offers unique insights into sustainability in product design and can be used to make informed decisions that reduce, for example, the environmental or social impact of products. Ultimately, product designers must balance various factors, including functionality, aesthetics, cost, and sustainability, to produce products that meet users' needs while minimizing their impact on the surrounding context.

However, what is considered a ‘high-quality’ product partly depends on time and trends. The perceived quality of materials is a subjective measure that reflects consumers' preferences, expectations, and experiences. Global trends such as sustainability and new technologies are driving changes in consumers' perceptions of material quality (Ashby, 2019). Today’s consumers are asking for sustainable materials that are environmentally friendly, socially responsible, and have a positive impact on the communities where they are produced. Sustainable materials such as bamboo and cork are gaining popularity due to their unique properties and environmental benefits (Ashby, 2019). Hence, by using sustainable materials, companies could enhance their brand reputation, reduce their carbon footprint, and contribute to a more sustainable future (Luchs, et al., 2010).

2 SCOPE OF THE RESEARCH

In this chapter, the reader will be aware of the research's objective and the delimitations that have been established to facilitate the implementation of the cases and projects.

2.1 OBJECTIVES OF THE RESEARCH

New demands for materials and production are a result of a global viewpoint of sustainability, which affects the perceived quality of future products. The main objective of this thesis work is to present the meaning and importance of 'perceived quality' (PQ) and the effect of the possible lack of a comprehensive view of PQ, in symbiosis with the paradigm shift of sustainability, with robust manufacturing as a result. This is achieved through inspiration from a novel and robust Japanese approach called 'Kansei Engineering' (KE), which is then applied to the process of material and surface selection. It is not about generalizing a feeling/experience, or interaction with a product; it is rather about framing what causes the stakeholder's perception of the product's quality and optimizing the total appearance for customer acceptance.

Hence, to be able to implement such an approach, a need arose: a need for a robust model/framework to relate to, which is the core of this thesis, together with the implementation of the model.

The main objective of the thesis is divided into the following sub-goals.

- Study the influence of material/surface properties regarding total appearance, perceived quality, and customer acceptance.
- Study the sensation and perception of materials and surfaces, focusing primarily on visual stimuli.
- Investigate the correlation of perceived quality and sustainability with sensation and perception in mind.
- Create a model for designing and analyzing materials and surfaces in regard to point 1-3.
- Analyze how the product realization process relates to the perceived quality of sustainable materials and surface selections.

2.2 RESEARCH QUESTIONS

At the very beginning of the research, the underlying aim was to understand the stakeholders' feelings or experiences based on material selections; eventually the final research questions became:

1. ***"How should the knowledge of perceived quality be used to control the material and surface appearance in production?"***
2. ***"How can the Kansei Engineering methodology be helpful to link customer acceptance with production specifications?"***
3. ***"How can 'hard metrology' be used as a tool to understand surface appearance?"***

These questions, together with other design-related matters, are frequently discussed in the industry today. Hence, the interest in understanding the impact of materials on perceived quality is high. Figure 1 illustrates the relationship between the surface control loop, introduced by Stout and Davis (1984), the research questions, and the papers presented in this thesis.

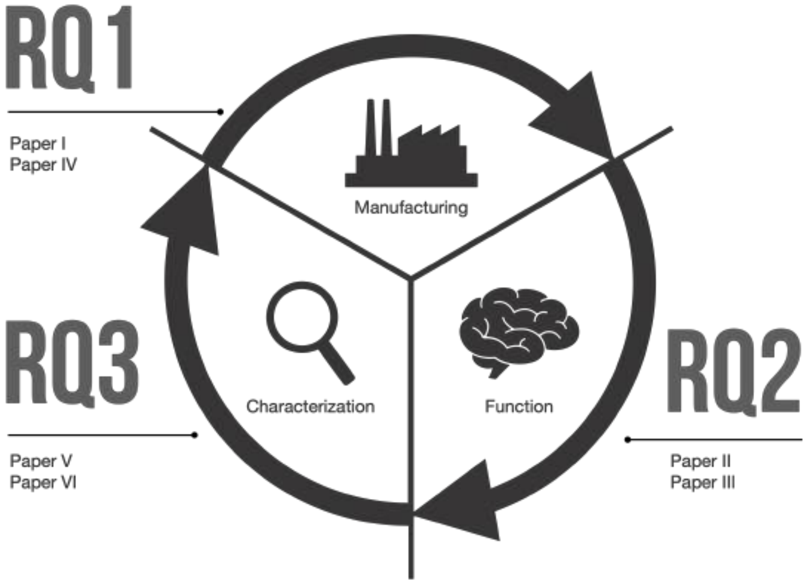

Figure 1. An illustration of the research questions (RQ) in relation to the surface control loop, and the appended papers I-VI.

2.3 APPROACH

The research approach has been developed, tested, and implemented in collaboration with diverse disciplines in the industry. The main common core in all cases, on the other hand, has been the evaluation and improvement of the total appearance and perceived quality of the material and surface of various components. The variety of companies involved in the research has influenced the work. Different cases from the industry imply that the material and surface appearance have varied along with the industry's needs.

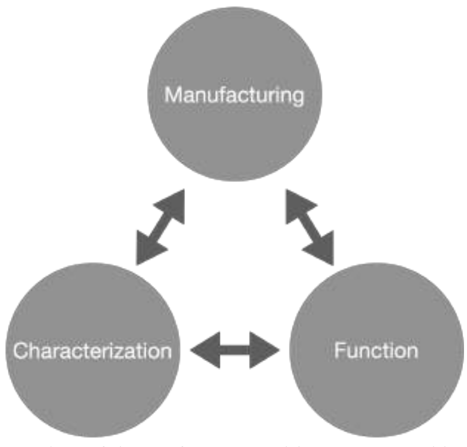

Figure 2. An illustration of the surface control loop presented by Stout and Davis (1984).

The research approach follows two principles in tandem.

Firstly, the surface control loop presented by Stout and Davis (1984), as shown in Figure 2, utilizes surface characterization as the basis for evaluating and optimizing technical functions to ensure robust manufacturing. Secondly, as a complement, theories from 'Kansei Engineering' (KE) presented by Mitsu Nagamachi are used in tandem with the surface control loop to obtain, analyze, and optimize sensorial and perceptual functions.

Table 1. An explanation of how the two principles are connected within the thesis.

Surface control loop	**Kansei Engineering**
Manufacturing	Translates perceived quality into manufacturing specifications.
Characterization	Connects material properties to perceived quality.
Technical function	Identifies technical elements based on various needs
Emotional function	Identifies sensation and perception of customer stimuli.

Table 1 above explains how the two principles are linked together and what the different steps focus on.

2.4 DELIMITATIONS

The focus in this phase of the research work has been to create an understanding of the implementation of the approach presented in this thesis. The design of the approach could be further developed; however, the primary purposes have been to investigate the implementation and usability of the approach, as well as its suitability for the industry in its current state. The focus has been on material and surface design, primarily targeting the sense of sight, although it is sometimes combined with the sense of touch. This means that other design parameters, such as shape, have not been in focus, as well as the other senses of hearing, smell, and taste.

2.5 THESIS STRUCTURE

This thesis is organized into seven main sections.

Section 1
An introduction to the research work, is a section where the reader can get an idea of the background and the incentives for the research.

Section 2
The scope of the research, is a section where the reader will be introduced to the main objective and the research question of the research.

Section 3
The theoretical frame of references, is a section where the reader will get a deeper understanding about the theories and core within the research.

Section 4
The result – the methodology, is a section where the reader could learn about the methodology created for Affective Surface Engineering.

Section 5
Research conclusions, is a section where the reader is getting into the final discussion about the research and future work within the area.

Section 6
References

Section 7
Appended papers.

3 THEORETICAL FRAME OF REFERENCE

The theoretical framework serves to clarify the various areas of knowledge that play a fundamental role in developing an understanding of the chosen field of study.

3.1 THE GESTALT - THE PRODUCT AND THE CONTEXT

"The whole is other than the sum of the parts."
Kurt Koffka

Gestalt psychology emerged in the early 20th century in Germany and focuses on the holistic system of human perception. It highlights integration and how the mind constructs meaningful perceptions from sensory information. These principles have had a significant influence on psychology, particularly in the domains of perception, cognition, and problem-solving. Additionally, Gestalt principles have influenced diverse fields like design, art, and communication, reflecting their broad impact beyond psychology (Köhler, 1929; Koffka, 1935). In product design, we are generally speaking about physical products, and the primary design elements are *form* (as geometry/shape), *color* (as hue, saturation, whiteness, and blackness), *material* (as a chemical substance or raw material, isotropic or anisotropic, structure and strength) and *surface* (as texture, gloss, haze, isotropic or anisotropic).

In the field of design, the physical creation of form, color, material, and surface could be considered as the 'Gestalt'. The 'Gestalt' is a discernible whole, an arrangement of parts that appears and functions as a whole, which is more than the sum of the parts (Monö, 1997). The correlation between a product, its domain, and context is essential to ensure it not only meets its intended purpose but also considers the specific requirements, constraints, and user expectations within the relevant field of study; this is discussed in Paper IV (Bergman et al., 2016). The traditional design methodology is a holistic approach to so-called 'wicked problems' that increases the probability of a product being functional from a technical, cognitive, and emotional perspective (Warell, 2001).

3.2 WICKED PROBLEM

The challenge addressed in this thesis qualifies as a wicked problem, as described by Rittel and Webber (1973). Perceived quality is fundamentally subjective, context-dependent, and continuously evolving, meaning the problem cannot be clearly defined nor solved with a single universal solution. Surface appearance is interpreted differently across users, cultures, industries, and time periods (trends), and a design intention must be balanced against manufacturing constraints, sustainability goals, and emotional user responses. Because each intervention, whether a change in material, process, or specification, alters both the product and user expectations, the problem transforms as it is being solved. These interdependencies between design, engineering, perception, and production create a complex, iterative, and open-ended system characteristic of wicked problems.

‘Wicked problem’ is a term often used in the fields of design and problem-solving to describe multidimensional issues that are difficult to define and understand and sometimes impossible to solve (Margolin & Buchanan, 1995). The concept of ‘wicked problems’ was introduced by design theorists Horst Rittel and Melvin Webber in the 1970s and could be described with the following characteristics:

- No single solution: ‘Wicked problems’ do not have one ultimate solution or answer; however, they are rather open-ended and multi-dimensional.

- Transdisciplinary stakeholders: ‘Wicked problems’ involve a wide range of stakeholders with diverse perspectives, interests, values, and needs. Different stakeholders could define a problem differently and have a polarized view of the actual topic.

- Linked elements: ‘Wicked problems’ are typically interconnected and influenced by a wide range of variables. Changes in one perspective of a problem may have accidental consequences in another.

- Uncertainty and ambiguity: The collected information and data associated with a ‘wicked problem’ is often incomplete, uncertain, or ambiguous. Hence, developing a clear and unbiased view of the problem could be challenging.

- Ongoing and evolving: ‘Wicked problems’ can evolve over time and may never be completely solved due to, e.g., global trends. Hence, solutions may need to adapt and develop in tandem with the surrounding challenges.

- No endpoint: There is rarely any well-defined endpoint or way to say that a ‘wicked problem’ has been totally solved. The given solutions are often a result of a given domain, context, and time.

There are numerous examples of wicked problems that affect us in our everyday lives. Climate change, poverty, healthcare reforms, education reforms, social justice issues, well, any of the 17 global goals are good examples of ‘wicked problems’. These kinds of problems require a holistic, interdisciplinary approach and often involve ongoing efforts to address the various aspects of the problem as it evolves over time (Branth et al. 2023). The design process, on the other hand, and design thinking in particular, offer an approach for addressing ‘wicked problems,’ which typically involve collaborative and participatory methods that engage a wide range of stakeholders with the intention of understanding different viewpoints (Margolin & Buchanan, 1995; Rittel & Webber 1973). Figure 3 illustrates how a wicked problem can be defined, with the design intention at the center of the “diagram,” followed by IDEO’s theory of viability, desirability, and feasibility (Brown, 2009).

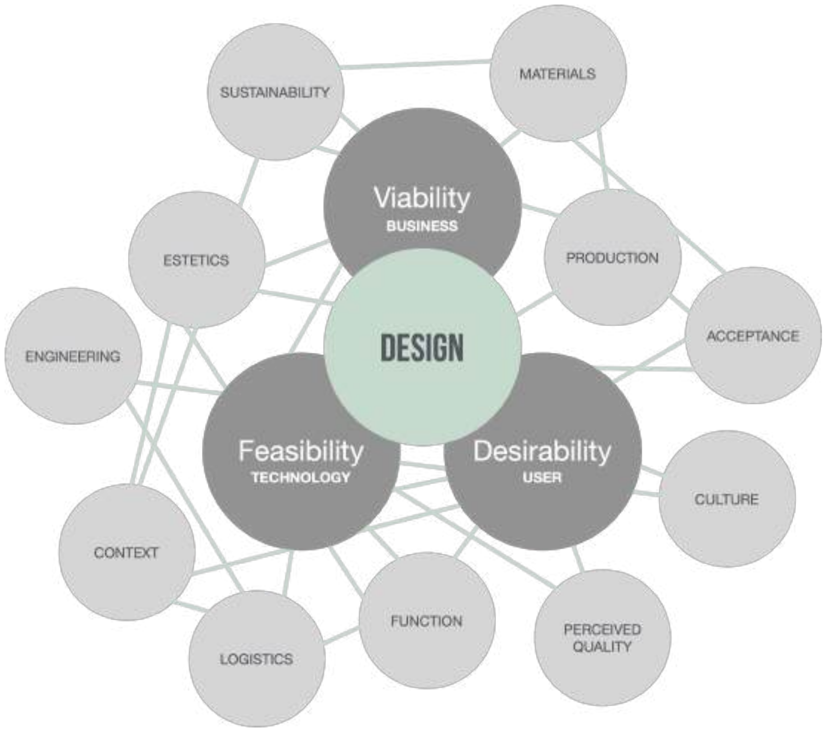

Figure 3. An illustration of how a so-called 'wicked problem' could be defined.

The presence of "wicked problems" in design projects often leads to extended discussions and bottlenecks, which, unfortunately, is a fairly predictable consequence. Hence, the need for various tools to facilitate the cognitive flow in the design process is obvious. For example, the 'Design Compass' is a developed navigation tool for everyone involved in a project, serving as both an external stimulus and a guideline in the design process to facilitate workflow. The tool focuses on the primary questions, WHAT, WHO, WHY, WHERE, WHEN, and HOW, in Figure 4.

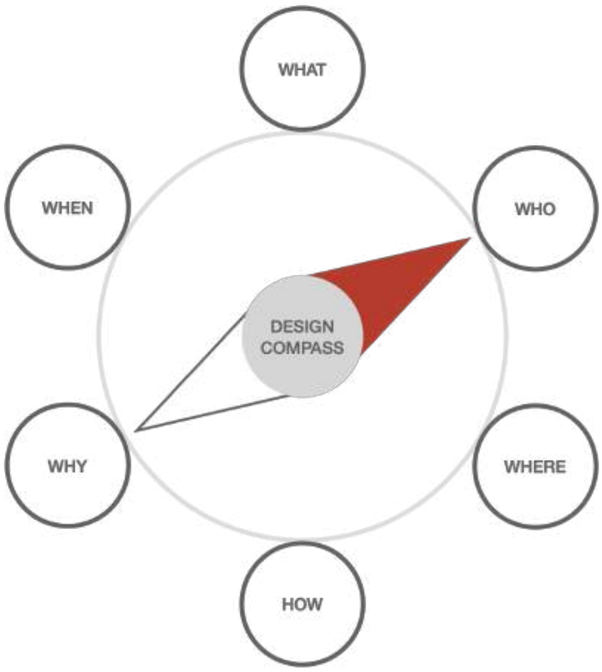

Figure 4. An illustration of the developed 'design compass' tool.

By answering these questions, the design team can transition from concrete observations to a more abstract emotional state of mind in particular situations related to 'wicked problems'. The emphasis shifts from a solution-oriented approach to a deeper understanding of underlying needs. With a broader understanding and knowledge about these questions as a starting point, it is probably easier to navigate through the design process to reach an optimized so-called 'total appearance.' IDEO and d.school at Stanford University also confirm similar methods (Stanford, 2016).

3.3 TOTAL APPEARANCE – A DEEPER EXPLANATION

The world is perceived as a combination of materials (including shapes and colors) interacting to create images and expectations in the viewer's mind. Materials are described in terms of visual structure, surface texture, color, translucency, gloss, and temporal properties, with visual criticism being a key aspect of perception (Wolfe et al. 2012). The primary goal for a designer when creating physical products, from a visual perspective, is to control the overall visual impression of the product. The so-called 'visual appearance'. The term "appearance," as defined by the American Society for Testing and Materials (ASTM) in ASTM E284 (2002), refers to "The aspect of visual perception by which objects are recognized."

A given object's visual appearance is shaped by its interaction with incoming light. The color we perceive as users is a result of the reflection and absorption of light by pigments, while gloss arises from light reflecting off the surface, and translucency occurs when light scatters as it passes through an object (see Figure 5). Due to the intricate nature of an object's appearance, a variety of measurement technologies and instruments are necessary to accurately assess it, as pointed out by Pointer (2003). Texture is another vital aspect of visual appearance that requires consideration. The texture can affect the visual appearance in terms of perceived gloss, lightness, and color.

The idea of "total appearance" has been introduced to expand the concept of an object's appearance. Total appearance encompasses a description of the object's shape, size, texture, gloss, and any other sensory properties that can be detected by our five senses (sight, touch, smell, sound, and taste) and collectively processed by the brain to form a holistic perception of the object, as discussed by Pointer (2003) and McKnight et al. (1997).

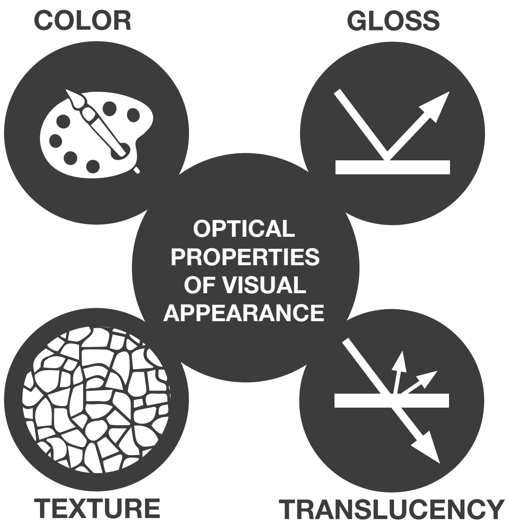

Figure 5. Visual appearance is one aspect of the total appearance. Here, the four basic optical properties (color, gloss, texture and translucency) of visual appearance are grouped together (Bergman et al., 2016).

The total appearance could also be described as a combination of three aspects of appearance:

- Physical (physically by our senses detectable object properties modified by the surroundings, properties of the illumination, individual factors like aging, handicap, etc., affecting our sensibility)
- The physiological aspect (the neural effect when human receptors are subjected to the physical stimuli and convey signals to the cerebral cortex) creates a sensation.
- Psychological aspects are created when sensations are interpreted by the cortex, recognized as an object, and combined with inherited and taught response modifiers (Memory, Culture, Fashion, Preferences). Figure 6 below summarizes the factors affecting the total appearance, resulting in two appearance images.

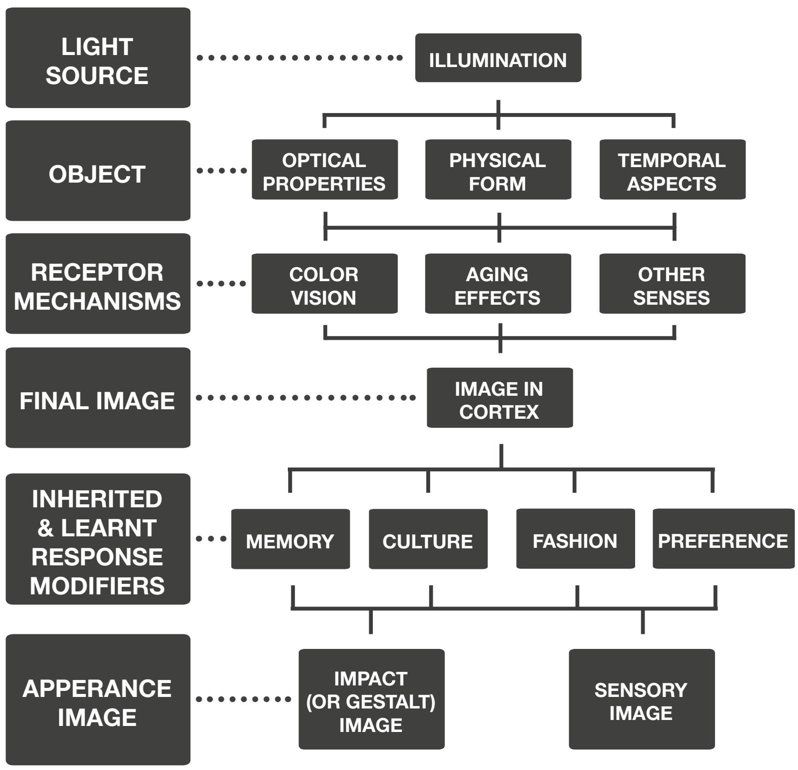

Figure 6. The concept of total appearance (Bergman et al., 2016).

The impact image and the sensory image: the impact image is the initial recognition of the object or scene (the gestalt), plus an initial opinion or judgment. For the sensory appearance image, three viewpoints are used to create the total appearance: sensory, emotional, and intellectual. The sensory viewpoint describes thoughts associated with the colors, gloss, etc. of the object. The emotional viewpoint associates emotions with colors, gloss, and other sensory aspects, while the intellectual viewpoint encompasses other aspects related to the object and situation, rather than sensory or emotional associations (Hutchings, 1977; Hutchings, 1995). Total appearance is closely related to the models of Intended product communication and the Perceptual Product Experience (PPE) framework, and could be used when quantifying customer perception and satisfaction using soft metrology to correlate physical and human factors contributing to product appearance images. Warell (2008) presents the Perceptual Product Experience (PPE) framework to describe how users perceive products through sensorial, cognitive, and affective modalities. The PPE model supports the idea of total appearance by framing product perception as a holistic process in which physical attributes, prior experiences, and contextual factors jointly contribute to the user's overall impression of the product.

3.4 SOFT METROLOGY, A WAY OF MEASURING TOTAL APPEARANCE

Soft Metrology is defined as "the set of techniques and models that allow the objective quantification of certain properties of perception in the domain of all five senses" (Pointer, 2003). Soft metrology addresses a broad range of measurements outside of the traditional field of physical metrology (Pointer, 2003):

- Psychometric measurement or perceived feeling (color, taste, odor, touch),
- Qualitative measurements (perceived quality, satisfaction, comfort, usability),
- Econometrics and market research (image, stock exchange notation), sociometry (audience and opinion),
- Measurements related to the human sciences: biometrics, typology, behavior, and intelligence.

By combining, for example, econometric data (sales, ratings, stock performance) with sociometric analysis (audience opinion and influence), the company gains a holistic understanding of the soft aspects of quality, including how people perceive and socially validate the product.

The ideal would be to perform physical measurements using sensors applied to a subject placed in a test situation and the establishment of useful measurement scales correlating human responses and physical metrology, i.e., combining traditional physical "hard metrology" (geometry, color, gloss, taste, smell, noise and tactile properties) to enable increased understanding of the influence of physical product properties on human responses, see figure 7 below.

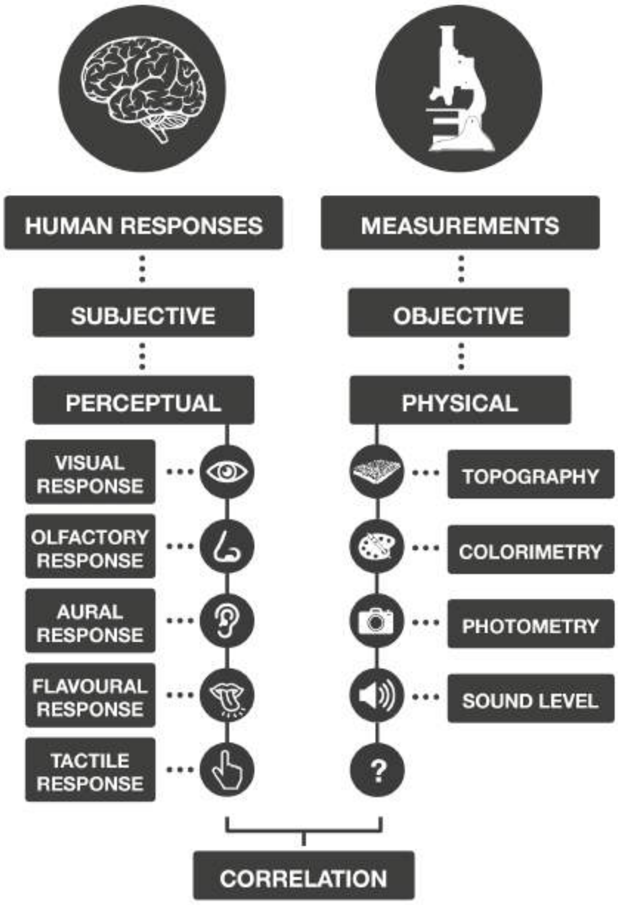

Figure 7. Soft metrology, correlating the objective physical measurements to human subjective perceptions (Bergman et al., 2016).

Here, the human being would be considered as a measurement system defining sensitivity, repeatability, and reproducibility, and comparing the results with those obtained by methods from traditional “hard” physical metrology. The concept of subjectivism can, of course, be discussed further in relation to Figure 7 above. Parts of what are described as subjective human responses in the figure above can be described as general perception, though subjective. For instance, the Bouba-Kiki effect (Figure 10), in which the subjective perceptions are shared by all respondents, and therefore can be seen as a general perception, and not notified as an opinion of what is perceived.

Another way to exemplify the use of soft metrology is the example of the perceived surface quality in automotive interiors, Paper VI (Bergman et al. 2025). In this context, stimuli of the senses can be understood as measurable physical inputs, such as quantifiable surface characteristics, including roughness, gloss level, and textural pattern, as well as material properties like hardness and thermal conductivity. These attributes interact with human sensory systems to produce subjective perceptual outputs, expressed through descriptors such as “premium,” “cheap,” “comfortable,” “cold,” or “plasticky.” Soft metrology provides a systematic framework for connecting these physical inputs to perceptual responses by gathering user evaluations through surveys, semantic differential scales, and pairwise comparisons, and then statistically relating them to the corresponding surface measurements. Prior research by Ignell, Kleist, and Rigdahl (2009), for example, demonstrated that surfaces with lower gloss and fine micro-roughness tend to be perceived as “higher quality” or “more premium.”

Bergman et al. (2025), Paper VI, further illustrate how such correlations can be operationalized in an industrial setting. The study demonstrates that customer acceptance of color and gloss variation can be partially explained through a combination of user studies and detailed surface characterization.

Based on the insights from the study, it could be possible to adjust the tolerance limits directionally depending on the context and product scenario. The results highlight the role of specific areal surface parameters, particularly Sdq, Spd, and Sal, in shaping perceived gloss, suggesting that these parameters should be considered when defining surface specifications for automotive components. This relationship between surface characteristics and production properties is also relevant for discussions with sub-suppliers, helping ensure that manufacturing processes consistently achieve the intended appearance targets.

Ultimately, Bergman et al. (2025), Paper VI, demonstrate that production properties exert measurable influence on total appearance and perceived quality, and that a modified version of Kansei Engineering serves as an effective method for evaluating customer acceptance of materials and surfaces in the automotive industry. The adapted KE approach contributes to the field by explicitly linking surface and material properties with perceived quality and production characteristics, thereby facilitating clearer internal and external communication and supporting well-grounded specification decisions from early design stages through late-stage manufacturing.

The area of soft metrology has received considerable attention, leading to the establishment of dedicated research groups at both NIST in the USA and NPL in England, Pointer (2003), Krynicki (2006) and Eugéne (2008), a European project - Measuring the Impossible (MINET) 2007-2010 with 22 partners from Europe and Israel including industries and academia as well as the national standards institutes in Great Britain, NPL and Sweden SP, European Commission (2007). In 2013, L. Rossi also published her doctoral thesis – "Principle of Soft Metrology and Measurement Procedures in Humans," stating the importance of the field (Rossi, 2013).

3.5 WHAT IS PRODUCT UNDERSTANDING, IDEAESTHESIA AND PRODUCT SEMANTICS?

Besides technical functions, the total appearance works in tandem with what is called 'product understanding' within design thinking. Product understanding can be broadly defined as the way stakeholders interpret and comprehend a product. Product understanding is directly linked to the 'Gestalt' (mentioned earlier), which encompasses the design of the product, including its form, color, material, and surface parameters. The core of product understanding is driven by user needs, expectations, and cognitive ergonomics.

Customer needs and expectations are partly pronounced but also partly unspoken. It is well known that needs come at different levels, and it is, moreover, a challenge to fulfill some of them, as they may be part of a 'wicked problem.' However, to design something meaningful for a user, the needs must be addressed. One theory regarding needs is the so-called KANO model from Japan, Figure 8, where different needs are addressed in relation to customer expectations and satisfaction (Kano et al. 1984).

Firstly, the basic needs (must-be qualities) are the minimum requirements that customers expect from a product or service. If these needs are not fulfilled, customers will be extremely dissatisfied. However, fulfilling them does not significantly increase satisfaction because they are often taken for granted. A good example is the brakes of a car.

Secondly, the pronounced needs (one-dimensional qualities) are features that increase customer satisfaction in a linear fashion. The better you fulfill these needs, the more satisfied the customer will be, and vice versa. A good example is fuel efficiency in a car.

Thirdly, the unspoken needs (delighters) are features that customers do not expect but are delighted when they are present. Their absence does not cause dissatisfaction, but their presence brings a great deal of satisfaction. A good example is heated seats in an economy car.

The Kano Model is often used during the design and product development phase to determine which features to focus on, balancing basic requirements with potential features that could exceed customer expectations and generate greater satisfaction.

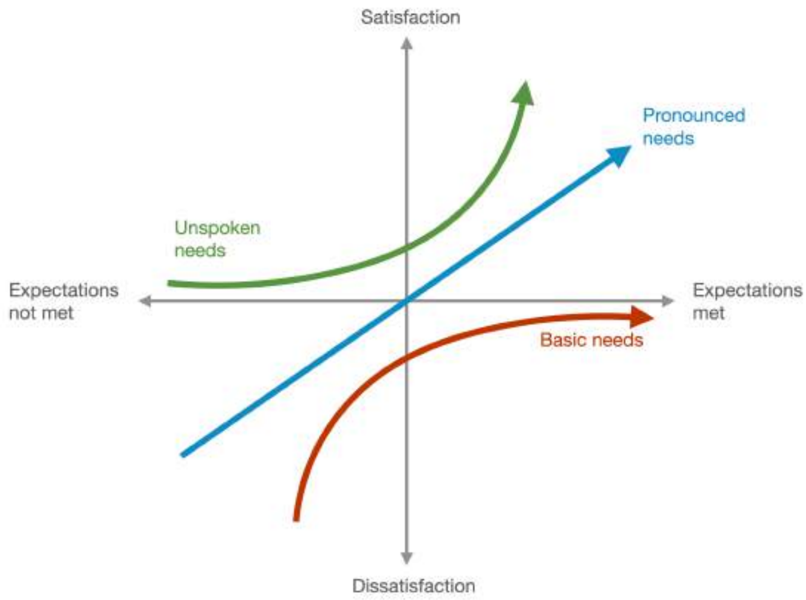

Figure 8. An illustration of the theory of needs, based in the KANO model (Kano et al. 1984).

Product understanding, as mentioned above, is partly based on theories about ‘product semantics’; however, it is also linked to the concept of ‘ideasthesia.’ ‘Ideasthesia’ may not act as a semantic message alone; however, it could clarify and support the product message, such as a luxury experience. These work in tandem, though, and are a vital part of the total appearance (Köhler, 1929). It is well known in the theory of semantics that a product (physical or digital) acts as a messenger of information for the user to interpret. Monö (1997) talks about this in his book “Design for product understanding”. It is important to take the theories of semantics into account when describing the idea of ‘product understanding’ and ‘total appearance’ since they are both highly influenced by the interpretation of sensorial stimuli.

Design is about making sense of things, and to be able to make sense of products, the theories about semantics are essential. Product semantics can be considered as ‘cognitive ergonomics’, which involves the process of understanding and interpreting the meaning of a product (Krippendorf, 2006). Product semantics concerns the relationship between the user and the product, as well as the importance that the artifacts have in use and in the social context. Affordance provides strong clues to the operation of things. The product is the sender of information, and the user requires significant feedback to succeed in using the product (Monö, 1997).

There are sub-functions in product semantics that are important, the semantic functions.

- DESCRIBE – Facts, its function, mode of action, purpose, and handling (practical function and technology).
- EXPRESSION – The nature, characteristics, and qualities, for example. Stable, lightweight, compact, and sporty.
- INVITE – To the reaction, use caution and accuracy, for instance.
- IDENTIFY – Type of product, purpose, origin, nature (affinity with the system, family, range, categories, etc.).

An object can be so much more than just a convenient object for the user. There are numerous parameters that influence the choice, including social values, the desire to belong to a specific group, personal experiences and memories, emotional functions, and so forth. These factors are sometimes more important than the technical functions. However, it is essential that the product is designed to provide clear instructions on how to use it, with intuitive product semantics (Monö, 1997). Briefly, product semantics handles the communication between the product and the user, as expressed through the Expression – Impression – Imprint model, as shown in Figure 9.

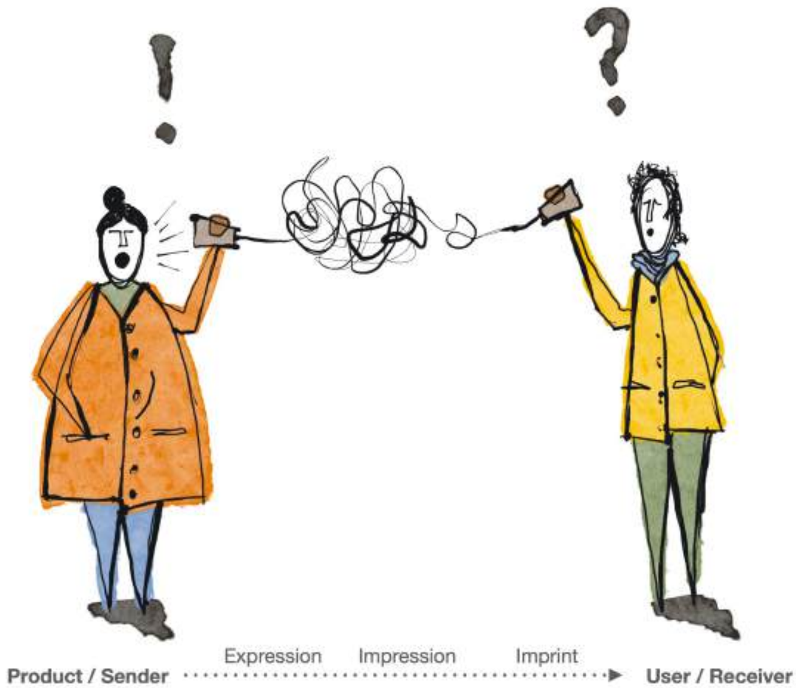

Figure 9. An illustration of the theory of semantics. Semantics emphasizes the idea that products convey meaning and information to users through their form, materials, and overall design. The sender conveys messages that the receiver interprets during the interaction.

'Ideaesthesia', on the other hand, is a perceptual phenomenon where thoughts, concepts, or ideas evoke sensory experiences. It differs from synesthesia, where specific sensory stimuli (such as sounds or colors) trigger other sensory perceptions. In 'ideaesthesia,' the stimulus is not sensory but conceptual; an idea or concept triggers a sensory response. 'Ideaesthesia' could be defined as the phenomenon in which the activation of concepts results in an experience. Creating ideaesthesia is a complex task involving both physical metrology and perceptual evaluations. An example of ideaesthesia is the experiment conducted by the psychologist Wolfgang Köhler in 1929, which showed a correlation between the visual shape of an object and the speech sound (see figure 10), known as the 'bouba/kiki' effect (Köhler 1929). The bouba/kiki effect, which later became known as the lumumba/takete effect, can be explained as a case of ideasthesia (Gómez et al., 2013). In the example in figure 10, the design element of form was possible to correlate to both the sensoric visual and sound experience of the word pair takete (hard) and lumumba (soft).

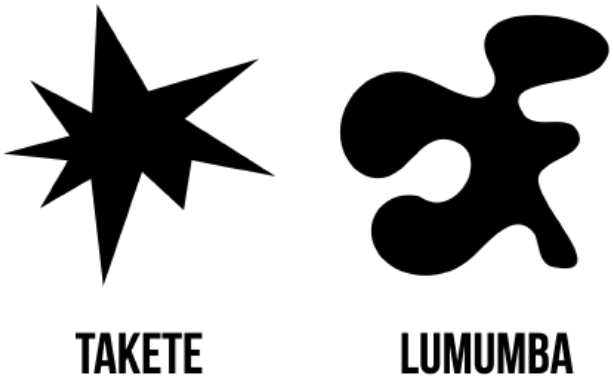

Figure 10. An illustration of the so-called 'Takete' and 'Lumumba'.

The theories of 'Takete' and 'Lumumba' could be easily correlated with measurable parameters, and ideasthesia supports this phenomenon. E.g. 'Lumumba' tends to relate more often to the 'low-frequency curve' than the 'high-frequency curve', figure 11. This admits that Lumumba may be associated more often with base sounds compared to treble. By means of this association, there is a possibility to frame a Hertz (Hz) spectrum where the expression and interpretation of 'Lumumba' is desired. This phenomenon is supported by cross-modal correspondence studies and assists the idea of integrating the theories of ideasthesia within product understanding and total appearance (Spence, 2011).

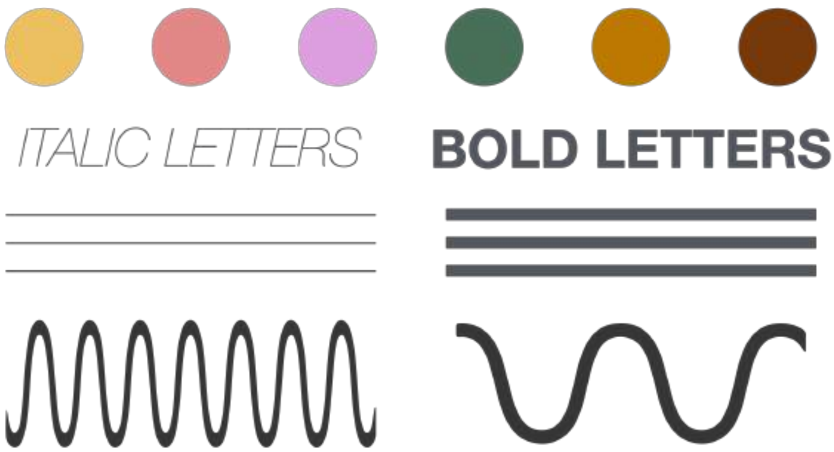

Figure 11. An illustration of design parameters and similar structures that correspond to the theory of 'Takete' and 'Lumumba'.

One cross-modal correspondence study made by Spence (2011) explores the concept of cross-modal correspondences, examining the associations between different sensory modalities, such as sound and shape, taste and color, and their implications for perception and cognition.

3.6 EXPERIENCE AND BEHAVIOR

"It's not what happens to you, but how you react to it that matters."
Epictetus

Most people on earth navigate through life using their impressions, perceptions, and feelings, along with the confidence of their intuitive instincts and preferences, often with acceptable results. People's experiences influence how they perceive and interpret the world around them. For example, two individuals may experience the same occasion differently based on their past experiences, beliefs, and biases, leading to different behavior in response to the occasion (Kahneman, D, 2013). The link between experience and behavior is a central aspect of human psychology, studied in various fields, including psychology, sociology, and neuroscience. Behavioral theories often revolve around the concepts of 'triggers' and 'rewards', which are central to understanding how behaviors are initiated, maintained, and modified. Two historical theories that emphasize these concepts are 'Classical Conditioning' and 'Operant Conditioning'. Both theories have the concept of triggers and rewards, although they differ slightly.

In classical conditioning, initiated by Ivan Petrovitj Pavlov, the trigger is the neutral stimulus that, through repeated pairing with the unconditioned stimulus, becomes associated with it and can provoke the conditioned response. The reward in classical conditioning is the unconditioned stimulus itself, which naturally triggers a response. Over time, the neutral stimulus obtains the ability to evoke a similar response, even in the absence of the original stimulus. One famous example of this is 'Pavlov's dog experiment' (Clark, 2004). In operant conditioning, on the other hand, proposed by Burrhus Frederic Skinner, the trigger is the environmental cue or stimulus that precedes the behavior. The reward is rather the consequence that follows the behavior. The reward can be positive (adding a desirable stimulus) or negative (removing an aversive stimulus), both of which strengthen the likelihood of the behavior occurring again in the future. Skinner's theories were later meant to be central to 'cognitive behavioral therapy' (Staddon, & Cerutti, 2003).

These theories emphasize the significance of understanding the relationship between triggers, rewards, and behaviors in shaping and influencing human behavior. It is possible to manipulate triggers and rewards, and by doing so, individuals can influence their behavior, either to encourage desired behaviors or discourage unwanted ones. This understanding has practical applications in various fields, including education, therapy, parenting, organizational management, and, obviously, design thinking.

The link between the experience and our sensorial system, our five senses, which handle external stimuli from the surrounding context, is fundamental in shaping our perceptions, interpretations, and, ultimately, our behaviors (Wolfe et al., 2012). Perceptions involve any or all of the five senses in symbiosis. By understanding the theories of sensation and perception, product developers can enrich the design process when creating new concepts for a predicted user experience and behavior (Wolfe et al., 2012).

The framework of perceptual product experience (PPE framework) considers perceptual product experience as composed of three core approaches: *the* *sensorial mode,* including perceptions of stimuli experienced with any of the receiver senses; *the cognitive mode*, where we understand, organize, and interpret and make sense of what we perceive; and finally *the affective mode* concerns itself with experiences that are affective: feelings, emotions and mood states, as a result of product perceptions (Warell, 2008; Monö, 1997). The PPE model in Figure 12 illustrates a framework for product communication between the producer and the consumer, e.g., how product developers intended the product message (the semantics) is expressed as core values, adjectives, and converted into measurable design elements with controlled properties (total appearance), creating consumer experience.

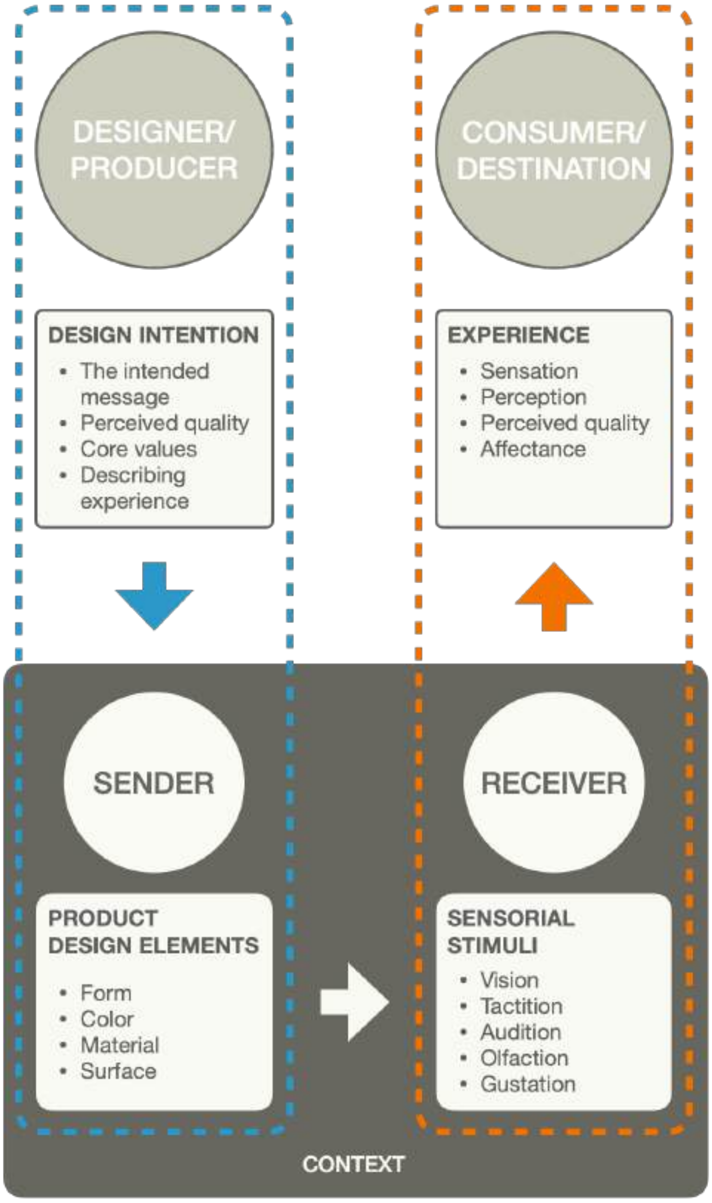

Figure 12. Illustrating the model for intended product communication linked to the PPE framework (Rosén et al. 2016).

One could define "experience" as the process of doing and seeing things, such as an activity on a vacation, or the fact of having been affected by or gained knowledge through direct observation or participation of some sort. Another could define "experience" as the skill or knowledge gained through doing something, e.g., the length of time spent on a particular job. In this thesis, the term “experience” is directly associated with the understanding and cognitive knowledge obtained from external stimuli.

As mentioned at the beginning of this thesis, the fundamental biological system matters for the experience and how one interprets it. However, there are more underlying functions that matter for all the interactions we, as users, are exposed to in daily life. Figure 13 shows the structure of the human interpreting system, where the general and fundamental interpretation system creates the foundation of the pyramid.

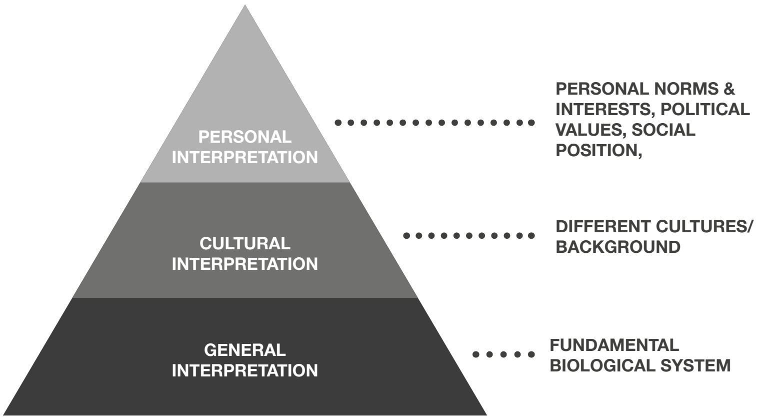

Figure 13. Illustration of the interpretation mapping. (Monö, 1997)

The general interpretation is controlled by the fundamental biological system, which, in turn, is controlled by the brain, nerves, and hormones, responsible for our thoughts, feelings, and actions (Wolfe et al., 2012). However, human beings have fundamental needs that could interfere with how we experience new products for the first time. One recognized example of human needs is Abraham Maslow’s theory, the ‘hierarchy of needs’. Maslow’s hierarchy of needs comprises five levels: biological and psychological needs, safety needs, belonging and love needs, esteem needs, and self-actualization (Maslow, 1943).

Cultural interpretation can be described in various ways, and in this thesis, the term ‘culture’ is used to refer to people with diverse backgrounds in multiple contexts. One way of describing ‘culture’ is that we, as human beings, are born and raised in different places on Earth, in different nations with varying conditions. Another way of describing ‘culture’ is that human beings are active within different occupations, for instance.

Personal norms, political values, social position, interests, and other factors primarily influence personal interpretation. It is often challenging to design products that meet the requirements of each individual's personal interpretation level, as these preferences are highly subjective. Yet, designing products that match the first two levels (the normal distribution) is both easier and more efficient. However, products that allow a final personal choice, e.g., various colors or materials, probably stimulate personal interpretation in a wider range than if they were excluded (Rosén et al., 2015), Paper III.

Sensation and Perception

"The five senses are the ministers of the soul."
Leonardo Da Vinci.

We interact with our environment and with objects in a specific context through our five senses; consequently, the physical measurements most relevant to sensory science are those relating to the parameters sensed through our sensory transducers (Berglund et al., 2012). Sensation and perception are two interrelated processes that play a fundamental role in how we experience and interpret the world around us.

Sensation refers to the process by which our sensory receptors and nervous system detect and respond to external stimuli from the environment. This includes stimuli from our five senses: sight, sound, touch, taste, and smell. Perception, on the other hand, involves the interpretation and organization of sensory information to give it meaning. Perception goes beyond sensorial detection and involves higher-level cognitive processes. Perception also allows us to make sense of the sensory input we receive and to form a coherent representation of the world around us. It includes processes such as recognizing patterns, interpreting depth and distance, identifying objects, and understanding language (Wolfe et al., 2012). There are some critical aspects of sensation and perception:

- **Transduction:** The process by which sensory receptors convert sensory input into neural impulses that can be interpreted by the brain.
- **Thresholds:** The minimum amount of stimulus needed for detection, such as the absolute threshold (the minimum intensity of a stimulus required for it to be detected) and the difference threshold (the minimum difference between two stimuli required for a person to perceive them as different).
- **Sensory adaptation:** The tendency of sensory receptors to become less responsive to constant stimuli over time.
- **Selective attention:** The ability to focus on specific stimuli while ignoring others.
- **Gestalt principles:** Principles of perceptual organization that describe how we group individual elements into more significant, meaningful forms.
- **Depth perception:** The ability to perceive the relative distance of objects in three-dimensional space.
- **Illusions:** Perceptual experiences that do not correspond to the actual physical properties of stimuli, often revealing the brain's strategies for interpreting sensory information.
- **Top-down and bottom-up processing:** Top-down processing refers to perception guided by higher-level cognitive processes (such as expectations, context, and prior knowledge), while bottom-up processing involves the analysis of the raw sensory data without influence from prior knowledge or expectations.

Without sensation, we will not be able to experience external stimuli. Consequently, our perception system will not be stimulated either. On the other hand, if the perceptual system is somehow damaged, the sensory input might not be received either; sensation and perception work in tandem (Wolfe et al., 2012). However, what happens when we, as human beings, experience different scenarios in life, and how do they affect us? Stimuli from the environment are transformed into neural signals, which are then interpreted by the brain through a process called transduction. Transduction is the physical process of converting stimuli into biological signals that may further influence the internal state of the organism, including the possible production of conscious awareness or perception (Wolfe et al., 2012). Let’s start with our physical features and how we, as human beings, pick up information through our five senses.

The visual sense (the system of sight) converts light energy, which occurs naturally in wavelengths, into neural messages through our eyes. This process is known as visuoreception. The very fine qualities of the wavelengths (height, width, and frequency) are detected by different structures inside our eyes. As a consequence of those differences, we experience different intensities of light, colors, shapes, and textures (Wolfe et al., 2012; Berglund et al., 2012).

Our sense of touch is supported by a phenomenon known as mechanoreception. Receptor cells located underneath the skin are designed to detect the slightest amount of force. This helps us human beings to perceive the smoothest breeze, for example. We also have thermal receptor cells underneath the skin, which are constructed to detect temperature and convert that data into information the brain can use. This helps us human beings to perceive the heat in a candle flame within the time of a millisecond, which then triggers a reflex of pulling the hand away, for instance (Wolfe et al., 2012; Berglund et al., 2012).

The sense of hearing (the auditory system) works similarly to the visual system; sound is transferred through the atmosphere in the form of wavelengths, e.g., with different amplitudes corresponding to different loudness levels. Comparable to the wavelength of light, the quality of the auditory wavelength will define the quality of sound that is perceived in the brain. The sound waves enter the ear, and once the wavelengths reach the middle ear, the auditory structures transform them into vibrations. The vibrations, in turn, are transmitted as neural impulses to the brain; this process is also facilitated by mechanoreception (Wolfe et al., 2012; Berglund et al., 2012).

The sense of taste is responsible for transferring information from our mouth to our brain via chemoreception. This procedure is facilitated by chemical receptors in our tongue, known as taste buds. The chemicals in what we eat contain a variety of different characteristics and qualities, which are detected by the receptors (taste buds) and transmitted as information to our brains. Hence, it is the brain that determines what the food tastes like, not the taste buds. The sense of taste can detect the flavors of salty, sweet, bitter, sour, and umami (Wolfe et al., 2012; Berglund et al., 2012).

The sense of smell also operates through chemoreception. We detect smell via receptor cells that are located inside the nasal cavity, which are responsible for transmitting the information to our brain. Unlike the sense of taste, which can only detect five different tastes, the sense of smell can detect any smell to which we are exposed. However, the intensity of the odor will determine whether we can smell it or not (Wolfe et al., 2012; Berglund et al., 2012).

Briefly, the goal of sensation is to detect the signals around us, and the goal of perception is to create useful information from the sensory information (information about the surroundings). In other words, sensations are the initial stages in the functioning of the senses, representing stimuli from the environment, and perception is a higher brain function that interprets events and objects in the world (Wolfe et al., 2012).

The combined sensation of a product's surface gloss, color, and haptic properties, such as friction, elasticity, hardness, and temperature, creates an intended message to the customer, received as stimuli (R) by the human senses, and transformed into a psychological sensation (S). Psychological sensation (S) was expressed in *Fechner's law* as

$$S = k \log R \qquad (1)$$

where k is a constant and the sensation S follows a logarithmic function, where small differences in stimuli create a larger variation of sensation than for changes of stimuli at higher values (Fechner, 1897). Later, S.S. Stevens at Harvard developed a similar model - *Stevens' power law* - sensitive to the fact that different types of stimuli follow different curve shapes to psychological sensation:

$$S = aI^{b}, \qquad (2)$$

where 'a' is a constant, 'b' is a stimulus exponent varying with the type of stimulation (visual, haptic, smell, taste, or audio), and 'I' is the stimulus energy related to stimuli (R), Fechner's law in equation (1) above (Stevens, 1957). To convey a message strong enough to the customer, understanding the limits for the lowest detection level of changes in stimuli and the function relating the stimuli to psychological sensation is crucial (Rosén et al., 2016). E.g., questions that could need to be answered related to surface engineering are *the minimum roughness* of a handle that the customer can sense and *the differences in texture roughness* allowing a handle with two textured parts to be perceived as having the same haptic roughness sensation, i.e., defining thresholds for texture sensation and tolerance in relation to customer expectations and satisfaction.

The experience is partly provoked by the aesthetic functions that appeal to our five senses. It could be explained as the human perception of beauty. Philosophers have long discussed the hidden factors that influence the appreciation of beauty since ancient times. In addition, one important component affecting attitudes toward products is the stakeholders' needs or motivations. If the psychological sensation (S, in equation 1) triggered by the physical stimuli matches the consumer's expectation at the present motivation level, the attitude toward the product would be considered positive regarding the hierarchy of needs mentioned earlier (Maslow 1943).

However, one way to measure the appreciation of design parameters linked to the overall appearance is by using semantic differential scales (Figure 14). A semantic differential scale could be composed of polar opposite adjective pairs separated by a five-to-seven-point rating scale. For example, a customer could rate the attitude to a product by grading adjective pairs (rough to smooth, cold to warm, dark to bright) on a seven-grade scale. Alternatively, it could also be due to dissatisfaction with the current state, as shown in Figure 14. Semantic scales could then be evaluated using, for example, principal component analysis (PCA) to draw general conclusions about attitudes (Osgood, 1943).

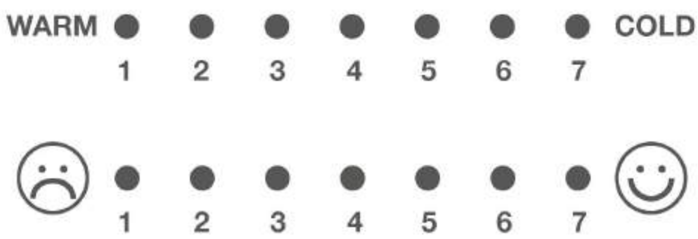

Figure 14. Illustration of different types of semantic differential scales.

Semantic differential scales have been employed in this research work, along with other evaluation tools, such as maximum difference scaling (McLean et al., 2017), where three or more samples are compared with each other to create a range of perceived quality within a population.

However, our motivation for and how we perceive a product are strongly linked to the customer´s buying judgment. In product development, the methodology nearly always aims to create this motivation and pleasurable product experience, including a meaningful message for the stakeholder (Krippendorff, 2006; Monö, 1997; Vihma, 1995). To understand how surface appearance relates to other design features, it was essential to develop a tool that could accurately assess and confirm these relationships. In the research work, Paper III, a tool like this was created to facilitate implementation; that tool is called *the Affective Engineering Equalizer* (EQ), as shown in Figure 15, which is based on the core of semantic differential scales (Bergman et al., 2012; Rosén et al., 2015).

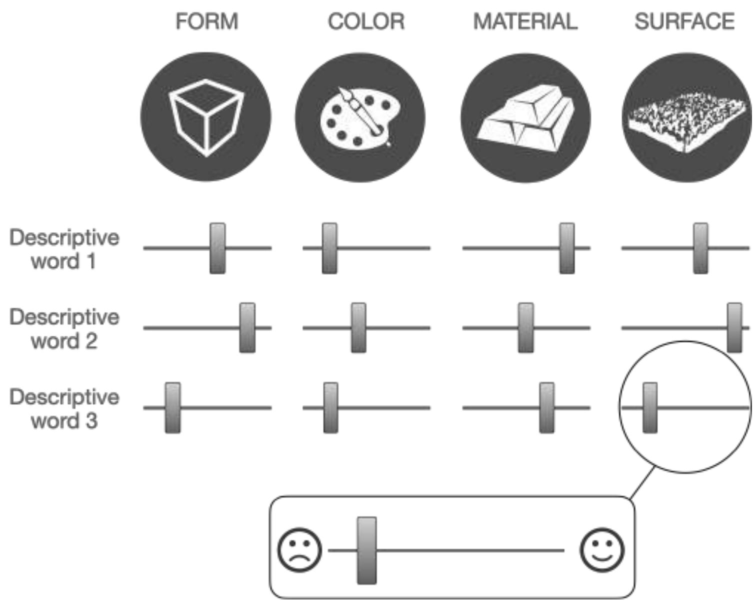

Figure 15. Illustration of the affective engineering equalizer tool, Paper III, (Rosén et al., 2015).

The EQ is essentially an enhanced, customized evaluation tool for designers, and enables the evaluation of design elements, such as form, material, color, and surface, in relation to several core values within the same questionnaire (Rosén et al., 2015). By implementing the evaluation in this way, correlations between the design elements are also obtained. Does the positive influence of an "Aerodynamic" FORM change if the SURFACE appearance changes, for instance? Receiving this specific information about a certain product or service facilitates the development process later on, as well as serving as a reference when discussing the product or service with the company, for example. Osgood (1943) means that Semantic differential scales work as a tool for the evaluation of adjectives, and this is also the basis of *the Affective Engineering Equalizer,* Paper III highlights this as well.

The EQ has evolved over time, rather than remaining static, as it has changed in tandem with the industry-specific needs within a project. To begin with, the EQ changes depending on which sense is in focus; for instance, color might not be interesting for the sense of touch, and so on.

An example

An example of a 'material evaluation' is described below to illustrate how the EQ can change and develop in tandem with project needs.

Natural fibers (NF), for example, have been a focus in material selections as a replacement for various polymers over the last decade, across many fields, in the pursuit of more sustainable solutions. However, since the appearance of NF is highly dependent on the choice of raw material and production process, it is important to specify the expected result (design intention) regarding perceived quality. First, it is important to specify what senses are affected; in this thesis, the visual sense has been in focus (Figure 16). It may also be important to isolate a design parameter or consciously exclude it, for example, the form factor, to enable significant comparisons. This work should preferably be done systematically before any user studies are implemented.

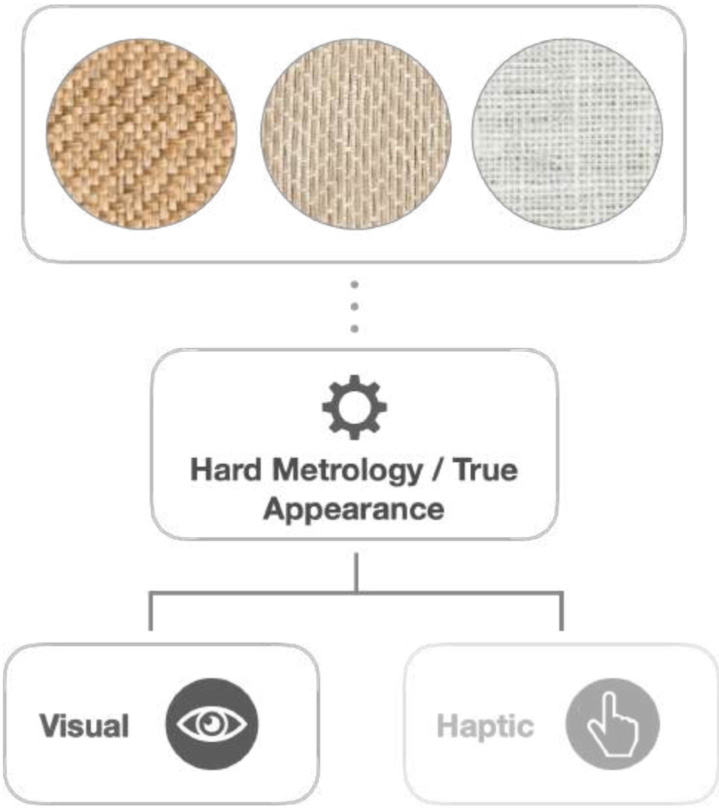

Figure 16. Illustration of the link between different NF materials and the senses of vision and touch.

The next step, given that focusing on visual appearance only, would be to extract what measurable design features impact the total appearance. This could be achieved by first focusing on 'general' design parameters among the chosen population of materials, which could serve as a foundation or first level in a design parameter hierarchy (see Figure 17). Eventually, more 'specific' design parameters of the different materials could be extracted.

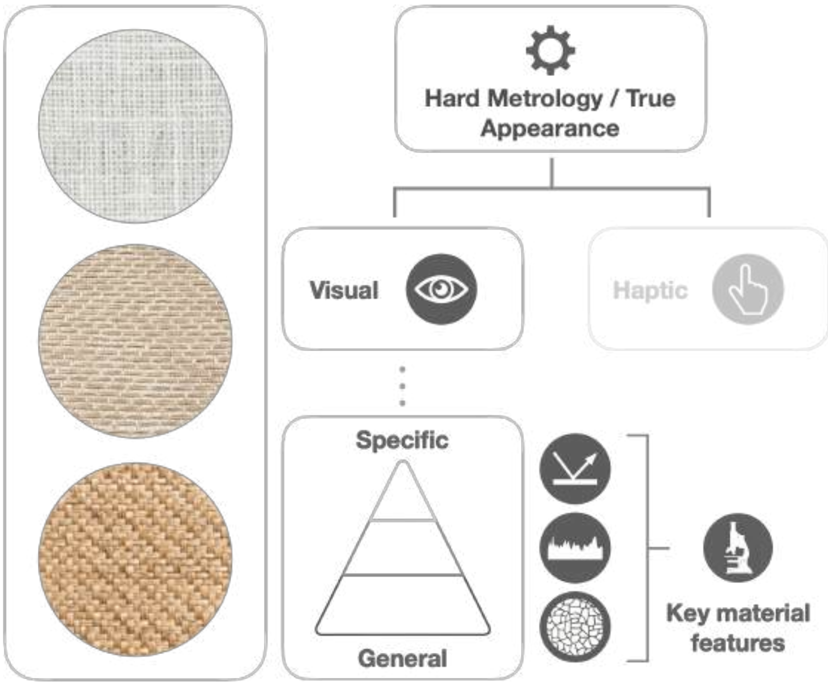

Figure 17. Illustration of the link between different NF materials and the sense of vision and possible design parameters.

Through the years of research, it is known that the design parameters of a 'general level' could be, e.g., color deviation and gloss (Bergman et al., 2025), Paper VI. This is also applicable when discussing NF materials. By specifying the deviation in, e.g., color temperature (yellow-blue) and gloss, the assessment of creating harmony among different materials could be easier. This is where the EQ comes in; Figure 18 illustrates how this could be done.

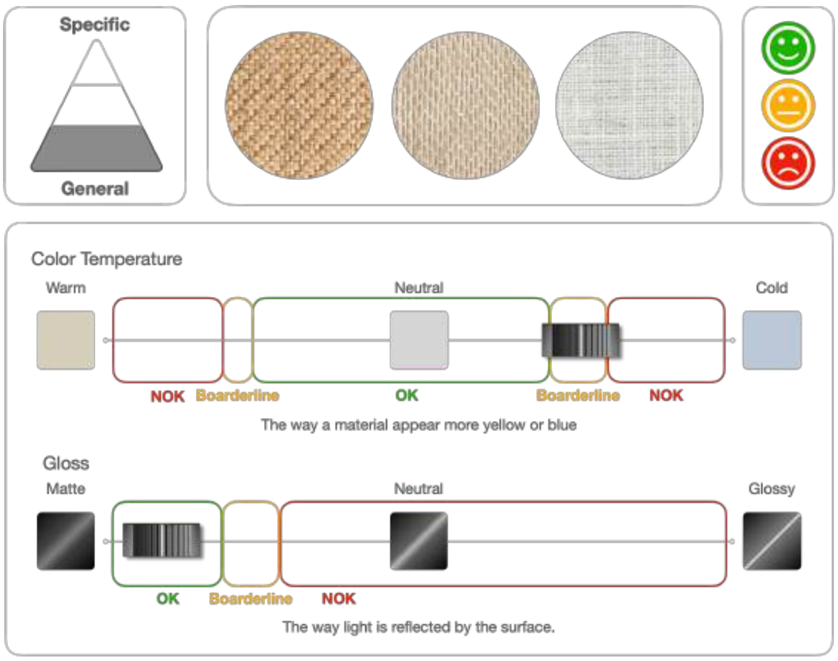

Figure 18. Illustration of how the Affective Engineering Equalizer (EQ) could be used as a tool to frame total appearance.

3.7 PERCEIVED QUALITY

‘Perceived quality’ in product design refers to the subjective evaluation or impression that consumers have about the overall quality, value, and desirability of a product. It goes beyond the objective or measurable attributes of a product and includes the emotional and psychological responses evoked by the user (Karana, 2009). Designing a product or service that fulfills the user's needs or expectations to 100% is rare and nearly impossible; it is indeed a ‘wicked problem,’ as mentioned earlier. However, there are several factors contributing to the perceived quality of a product, and they are all important:

1. Aesthetics: The visual appeal of a product plays a significant role in how consumers perceive its quality. This includes factors such as design, color, texture, and overall aesthetics, collectively referred to as the gestalt.
2. Functionality: The effectiveness and efficiency of a product in performing its intended functions contribute to perceived quality. Products that are user-friendly and meet customer needs are often perceived as higher quality.
3. Materials and Construction: The choice of materials and the way a product is constructed/designed impact its perceived quality. High-quality materials, precision in manufacturing, and attention to detail contribute positively to the overall perception of a product.
4. Durability and Reliability: Consumers often associate quality with a product's ability to survive wear and tear over time. A durable and reliable product is more likely to be perceived as high quality.
5. Brand Reputation: The brand's reputation can significantly influence how consumers perceive the quality of a product. Brands with a history of producing high-quality products are often more trusted by their stakeholders.
6. Packaging: The packaging of a product can influence the perceived quality. A well-designed and sturdy package can enhance the overall impression of the product.
7. Price: This isn’t always a direct indicator of quality; however, the price of a product can influence perceptions. In some cases, consumers may associate higher prices with higher quality.
8. User Experience: The overall experience of using a product, including ease of use, comfort, and satisfaction, contributes to its perceived quality.

Understanding and managing ‘perceived quality’ is crucial for businesses as it directly impacts consumer preferences, brand loyalty, and the overall success of a product in the market. Successful product design considers both the tangible features of a product and the intangible elements that shape consumers' perceptions and experiences (Karana, 2009; Stylidis et al., 2019). To evaluate user perspectives regarding perceived quality, it is necessary to address the effect of interpretation. Individuals interpret their surroundings by means of stimuli from the five senses, as mentioned earlier. The sensory stimuli interact with the brain to convert them into perception. The perception will determine how the user reacts to the sensory stimuli (Wolfe et al., 2012).

In order to design a user test, consideration must be given to what is meant to be measured. Should the subjective sensory experience of the similarity or the difference of surface textures be measured, or should the subjective experience of quality be measured? Lawless and Hildegarde (2010) describe the classification of test methods in the sensory evaluation of food, where three different types of sensory tests are described:

Discrimination is an analytical test that aims to answer the question, ‘Are two or more products perceptibly similar or different?’ (Civille & Oftedal, 2012), and is often used to test the perceived product similarity between the original product and a new version with, for example, a new material. Where the aim is to retain the product similarity.

Descriptive analysis aims at answering the question of how to define the perceived sensory characterization in a product. For example, the qualitative sensory aspects are linked to the perceived attributes of a surface, such as roughness, using a semantic differential scale with anchor words rough-smooth on each side. The intensity of the specific attribute is visually defined by the test person and is collected in a quantitative analysis. In this analysis, a trained test panel who have learned how to identify different surface characteristics is required (Civille & Oftedal, 2012; Lawless & Hildegarde, 2010).

Affective is a hedonic test that aims at answering the question of which product is preferred and how well-liked a product is. To answer this question, people without prior knowledge could be used as panelists.

3.8 HARD METROLOGY AND SURFACE CHARACTERISTICS

Technical and emotional functions are deeply interconnected in product design. Achieving control over emotional responses (soft metrology, as mentioned earlier) requires the measurement and adjustment of physical attributes (hard metrology), such as through specific production control. This aligns with the idea that perceived quality is shaped by measurable product characteristics, such as surface texture, gloss, and other material properties. Briefly, hard metrology provides measurable data (e.g., roughness parameters from ISO 25178-2:2021), soft metrology interprets how these data points translate into human perception (e.g., how a particular surface appearance influences perceived quality).

To help the reader understand the choice of different measurement techniques, a deeper explanation of the primary sensory impression, the visual sense, will be provided.

To perceive anything at all, human beings require a physiological mechanism to sense light. We have our eyes, which can detect more than just light. Additionally, the visual system can create an image of the surrounding world. However, to begin with, visible light waves have wavelengths ranging from 400 to 700 nanometers, as shown in Figure 19.

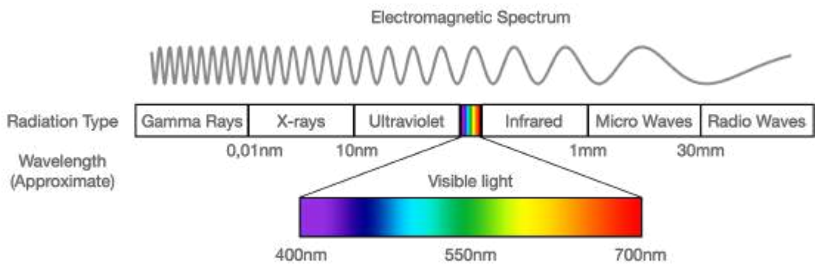

Figure 19. A picture illustrating the principle of the *'electromagnetic spectrum'*.

Even though the hue we observe changes, from violet at about 400nm through the whole spectrum of the rainbow up to red at about 700nm, the light waves themselves are not colored. It is only after our visual system interprets an incoming wavelength that we perceive the light as a specific color. In addition, when a ray of light strikes an object with a light-colored surface, most of the light is reflected, causing the surface to appear "light." In contrast, a dark-colored surface absorbs most of the light that strikes it, resulting in less light being reflected from the surface. Therefore, light that is neither reflected nor absorbed by the surface is transmitted through it.

When light enters the eye, it passes through several anatomical structures, including the cornea and crystalline lens (which allows for focus adjustments), and eventually travels through the vitreous chamber before reaching the retina.' The 'retina' is a light-sensitive membrane located at the back of the eye, containing approximately 100 million photoreceptors known as rods and cones. These photoreceptors capture images from the lens and transmit them to the brain via the optic nerve (Wolfe et al., 2012). Figure 20 illustrates the eye structure.

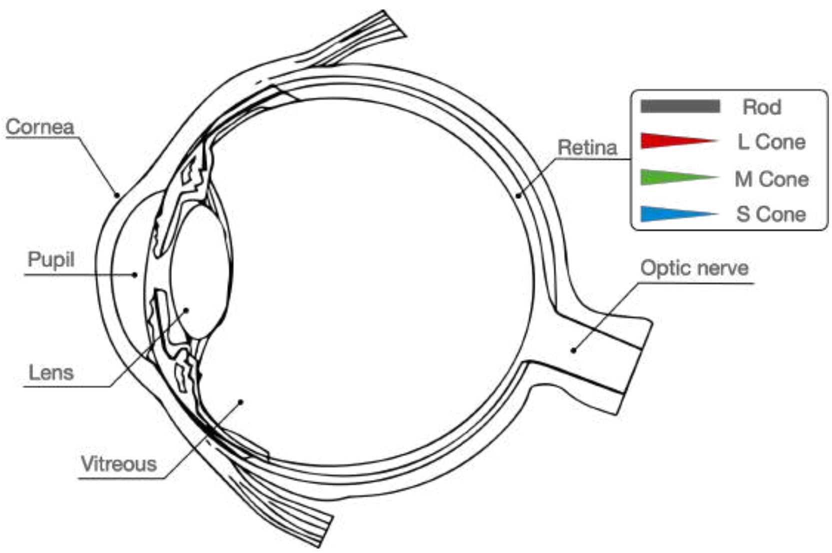

Figure 20. A simplified illustration of the human right eye in cross-section (viewed from above).

Together, the rods and cones enable us to see under various lighting conditions and perceive color, shape, and motion (Figure 21). However, they serve different functions. The rods are specialized for low-light (scotopic) vision and are sensitive to light; they do not detect color (unlike cones) and play a crucial role in detecting motion and contrast in dim conditions. The cones, on the other hand, are specialized for daylight (photopic) vision and are responsible for color perception. Cones require more light to function effectively compared to rods, and there are three distinct types of cones (Janet, 2017):

- S cones (short-wavelength), blue
- M cones (medium-wavelength), green
- L cones (long-wavelength), red

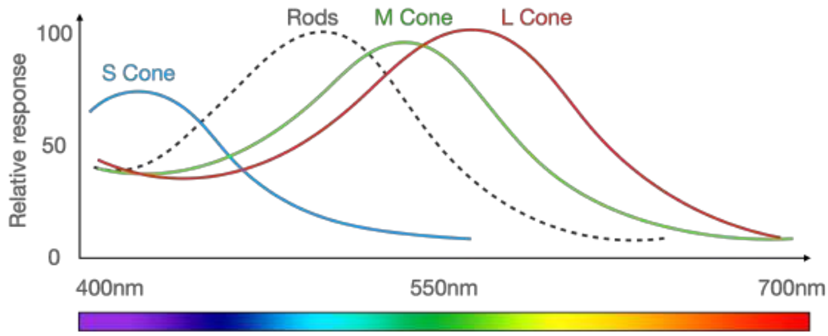

Figure 21. A picture illustrating the principle of the rods and cones.

Once light is converted into neural signals, it is transmitted through the optic nerve to various processing centers in the brain, such as the primary visual cortex (V1), (Wolfe et al., 2012). Knowledge of the eye's structure, features, and functions serves as a guideline for assessing surface appearance. The goal is to capture features in the same or a very similar way as the human sensory system does. This approach aims to identify which features of a material or surface create a particular appearance and influence the user's perceived quality (Wolfe et al., 2012).

Technical functions and hard metrology

In this thesis, technical functions are used as a term for the design elements' different properties that are measurable, adjustable, and possible to control in a process. Narrowing this down, the technical functions primarily focus on color, gloss, and texture (surface topography), which are measured using recognized methods and instruments in 'hard metrology.' Typical measurement instruments for surface topography are categorized and described in the ISO 25178-6 ('Classification of methods for measuring surface texture'). The *'Contact Measurements* 'group includes measurement techniques as *'The Stylus Profiler'* (figure 22)*, 'Scanning Probe Microscope',* and *'Atomic Force Microscope'* (Flys, 2016).

Figure 22. A picture illustrating *'The Stylus Profiler'* in action.

'The Stylus Profiler'('stylus' ISO 25178-601) is the most common technique that determines the surface characteristics by means of a stylus measurement system. The stylus is moved horizontally across the surface, recording different variations in amplitude using a transducer, and the signals are converted into height data (Figure 23). The stylus tip is usually made of a hard material (e.g. diamond) and has a radius of 0.5-50μm, and because of its hardness, it could scratch the surface sample during the measurement (Al-Jumaily et al., 1987; Bennett & Dancy, 1981; Bennett & Mattson, 1989; Bennett et al., 1991).

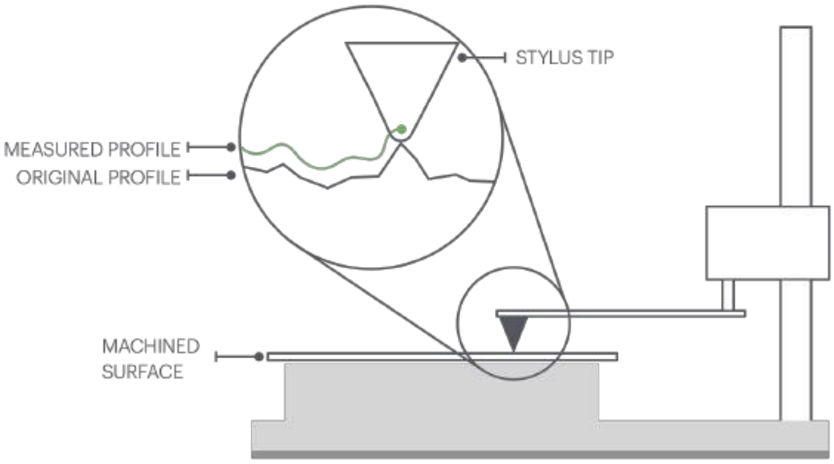

Figure 23. A picture illustrating the principle of *'The Stylus Profiler'*.

In the area of contact measurements, *'The Stylus Profiler'* is the one regularly used in this thesis and in the case studies. For further reading and understanding about contact measurements, Mironov (2004) shows *'Scanning Probe Microscope'* (SPM), and Flys (2016) describes *'Atomic Force Microscope'* (AFM) in more detail in her thesis *'Calibration Procedure and Industrial Applications of Coherence Scanning Interferometer'*. Further, the *'Noncontact Measurements* ' group includes measurement techniques as *'Scanning Electron Microscope', 'Confocal Microscopy', 'Phase shift interferometry', 'Coherence Scanning Interferometry',* and *'White light interferometry'* (figure 24), (Flys, 2016).

Figure 24. A picture illustrating a *'White light interferometer'* in action.

In the area of noncontact measurements, *'White light interferometry'* (WLI) is the one mainly used in this thesis and in the case studies. WLI ('coherence scanning interferometry' ISO 25178-604) is a coherence-based optical method widely used for high-precision measurement of areal surface topography, utilizing the broadband illumination of a white light source to overcome some limitations typical of single and multiple-wavelength methods (Huang et al., 2024). The technique operates by analyzing the interference pattern produced when broadband light is split into a reference and measurement beam. As the objective is scanned vertically, constructive and destructive interference occur only when the optical path lengths match within the coherence length of the illumination (Leach, 2011). By locating the axial position of the coherence peak for each pixel, the system determines the surface height with extremely high accuracy. Because the detection of interference fringes is highly sensitive to minute changes in optical path length, WLI achieves sub-nanometer vertical resolution, making it particularly suitable for smooth, reflective, and low-roughness surfaces (Huang et al., 2024).

The method is widely used for measuring, e.g., engineering and machined surfaces. It is usually limited in the vertical scan axis and constrained by the distance the reference mirror can move; however, theoretically, the vertical scan axis is theoretically unlimited. Figure 25 illustrates the principle of the *'White light interferometry'* (Flys, 2016).

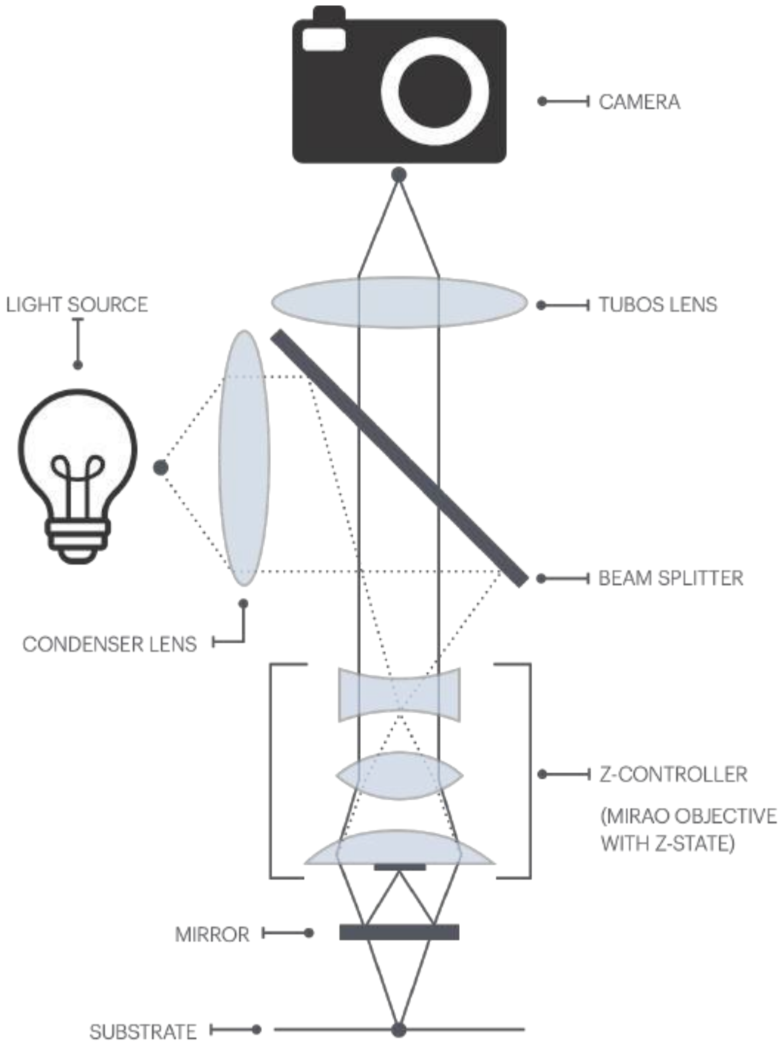

Figure 25. A picture illustrating the principle of the *'White light interferometer'*.

Despite the precision of WLI, it has some limitations. The method struggles on steep or highly scattering surfaces, where fringe contrast is lost, thereby restricting its slope capability (Leach, 2011). Furthermore, WLI measurements require a relatively stable environment and are sensitive to vibrations. On rough or matte surfaces, multiple scattering and diffuse reflection can further reduce the quality of the interferometric signal, resulting in incomplete or noisy data. Thus, although WLI is the preferred technique for high-precision metrology on smooth surfaces, its applicability becomes constrained when measuring complex geometries or highly textured materials (Huang et al., 2024). Focus Variation Microscopy (FVM), ('focus variation' ISO 25178-606), serves as a complementary measurement technique that overcomes many of these limitations. Instead of relying on interference, FVM uses the shallow depth of field of high-numerical-aperture optics to determine surface height based on local focus (Leach, 2011). Since FVM relies on optical texture (focus) rather than fringe contrast, it performs particularly well on rough, matte, or complex surfaces, where natural micro-roughness provides rich focus information (Nikolaev, Petzing, & Coupland, 2016). A significant advantage of FVM is its ability to measure steep slopes, which exceeds the capabilities of interferometric techniques. FVM is also less sensitive to environmental vibrations and can handle surfaces with non-uniform reflectivity. The trade-off is that FVM typically offers lower vertical resolution, compared to WLI, and can struggle on very smooth or highly polished surfaces where insufficient texture prevents reliable focus detection (Danzl, Helmli, & Scherer, 2011).

For further reading and understanding about noncontact measurements, Flys, (2016) describes *'Scanning Electron Microscope', 'Confocal Microscopy', 'Phase shift interferometry', 'Coherence Scanning Interferometry',* and *'White light interferometry'* in more detail in her thesis *'Calibration Procedure and Industrial Applications of Coherence Scanning Interferometer'*.

Moving on, gloss is a significant design parameter that affects the total appearance and perceived quality for users. One phenomenon associated with gloss is Total Integrated Scatter (TIS). Both TIS and gloss pertain to how a surface interacts with light, although they emphasize different aspects of visual and physical surface quality. TIS is primarily used in optics and surface metrology to measure the amount of light scattered by a surface in relation to the amount of light reflected or transmitted from it. It could be explained as: Total Integrated Scatter = (diffuse reflectance radiant flux + diffuse transmittance radiant flux) / [(specular reflectance power + specular transmittance power) + (diffuse reflectance power + diffuse transmittance power)]. Though in radiometry, the term 'radiant flux' is identical to 'radiant power,' represented by the Greek phi (Φ). Therefore, this can be expressed as 'radiant flux' = 'radiant power' = 'Φ', and the unit is watts (W). The equation could therefore be written:

- Φ_{rd} - Diffuse reflectance radiant flux
- Φ_{td} - Diffuse transmittance radiant flux
- Φ_{rs} - Specular reflectance radiant flux
- Φ_{ts} - Specular transmittance radiant flux

$$TIS = \frac{\Phi_{rd} + \Phi_{td}}{(\Phi_{rs} + \Phi_{ts}) + (\Phi_{rd} + \Phi_{td})} = \frac{\Phi_{scattered}}{\Phi_{incident}}$$

This formulation assumes that all incident light is accounted for through reflection and transmission, with insignificant absorption. (James, 2020). However, this implies that TIS is a unitless number with a value between 0 and 1, or a percentage ranging from 0% to 100%. Moreover, gloss and TIS are inversely related; a higher TIS indicates lower gloss and vice versa (Manallah & Bouafia, 2011). This is because the amount of measured gloss depends on the intensity of specular reflection, while TIS measures how much light is lost to scattering. Figure 26 illustrates this phenomenon. TIS measurements are particularly challenging to execute, mainly because the specular reflected and transmitted incident light must be distinguished from the scattered light. These radiation patterns typically overlap and cannot be easily separated by the geometry of the measurement equipment (James, 2020).

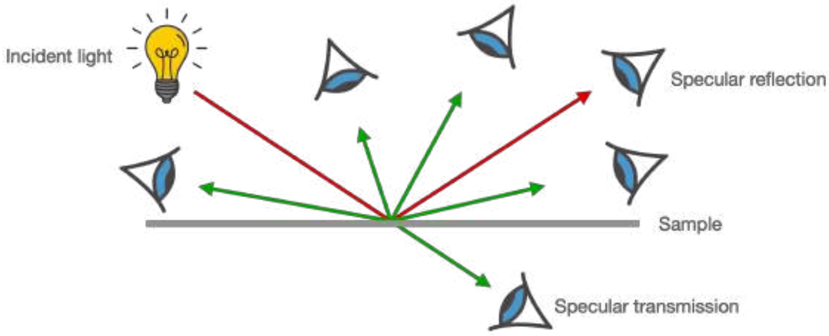

Figure 26. Illustration of the theory of 'Total Integrated Scatter'. The idea is to collect all scattered light in all directions without the specular beam.

Gloss measurement, on the other hand, is performed using a glossmeter, an instrument specifically designed to project a beam of light onto a surface at a certain angle and then measure the intensity of the reflected light at that same angle. Figure 27 demonstrates this principle. The level of reflectance indicates the surface's glossiness, with higher reflectance values suggesting a glossier surface, while lower values indicate a matte or diffuse appearance. Choosing the measurement angle is crucial for achieving accurate gloss readings, as different surfaces and materials exhibit varying reflectance properties (Hunter, 1937; Wetlaufer & Scott, 1940). Commonly used measurement angles include:

- *20° (high gloss):* This angle is primarily used for highly reflective surfaces, such as polished metals or exterior automotive finishes, where high specular reflection is present.

- *60° (universal standard):* This angle serves as a *'general-purpose'* gloss measurement, applicable to a wide range of surface finishes and industries.

- *85° (low gloss):* Designed for matte and low-gloss surfaces, this angle enhances sensitivity to subtle variations in low-reflective materials.

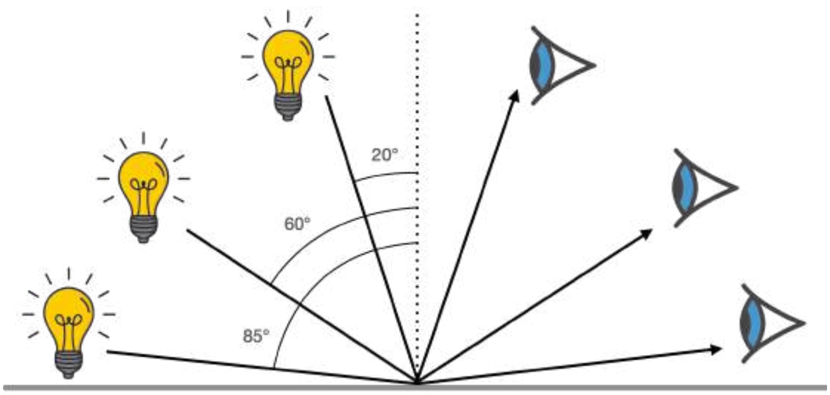

Figure 27. A picture illustrating the principle of *'gloss measurement'*.

The gloss value is presented in *'Gloss Units'* (GU), a standardized measurement based on the calibration of a gloss meter against a black glass reference standard, which is defined as 100 GU at a 60° angle (the universal standard above). Various international standards regulate gloss measurement to ensure consistency and comparability across different industries. Notable standards relevant to this thesis include:

- ISO 2813:2014: Central gloss measurement in paints and coatings.

- ASTM D523-14 (2018): Providing standardized procedures for gloss measurement in coatings.

- ISO 7668:2021: Specifies methods for the measurement of specular reflectance and specular gloss for metallic surfaces such as anodized aluminum.

Several factors influence the perception of gloss. Surface roughness is an example; the microscale surface texture, often characterized using ISO 25178-2:2021 parameters mentioned earlier, significantly impacts the perceived gloss level. A smoother surface typically reveals higher gloss due to reduced scattered light. However, the material properties also have a great impact on the perception of gloss. Different materials, such as plastics, metals, and wood, interact with light in distinct ways, resulting in variations in perceived gloss. The fundamental optical properties of a material influence its ability to reflect or absorb light (Leloup et al., 2013). The contextual impact of measurement is also necessary to reconsider. External conditions, including ambient lighting, the presence of dust or contaminants, and the precise alignment of the gloss meter, can affect measurement accuracy and repeatability. Accurate calibration and controlled measurement conditions are essential to obtaining reliable and significant results.

Colors have been a mystery to humans; however, they have been of great interest to humanity for a very long time. Yet, Isaac Newton’s contribution to the field was his 1672 paper, "A New Theory of Light and Colours", in which he conducted experiments using a prism to demonstrate that white light is composed of a spectrum of colors. This was revolutionary because it challenged the idea that colors were modifications of white light. Instead, Newton proved that colors were fundamental properties of light itself. He also developed the color circle (or color wheel), which was published in the first edition of the ‘Opticks’ (1704). Newton´s color circle, Figure 28, serves as a foundation for modern color systems and how we measure and define color today (Newton, 1704).

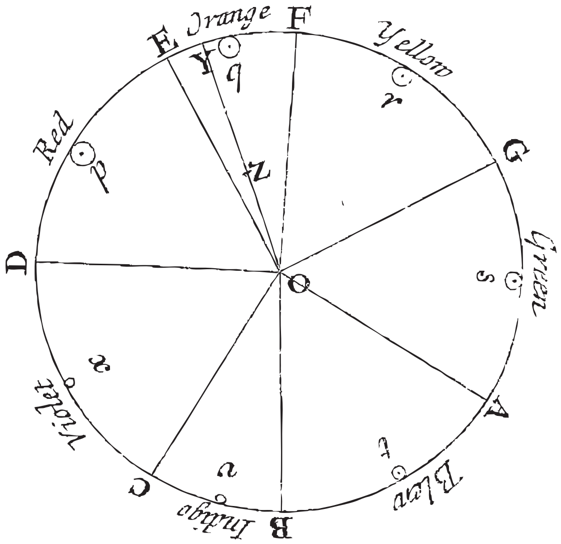

Figure 28. A picture illustrating Newton´s color circle (Newton, 1704).

Thanks to the initiated work of early researchers, the first spectrophotometers and modern color measurement emerged in the early 20th century. Today, color measurement is essential across many industries, acting as a quality control tool to ensure consistent and standardized color reproduction (Ohno, 2000; MacAdam, 1942). Unlike human visual perception, which can be subjective, color measurement relies on objective numerical values obtained through instrumental analysis of light interactions with surfaces. An object's color is determined by the wavelengths of the light it reflects, absorbs, or transmits. Standardized measurement techniques can quantify color. However, the primary technique used in this thesis is the 'spectrophotometer.' A spectrophotometer measures color by analyzing light across the visible spectrum (400–700 nm). These instruments provide high-precision spectral data, making them ideal for scientific and industrial applications (Best, 2017). Materials to be measured can be solid, liquid, opaque, translucent, or transparent. However, various methods are employed to measure these materials, depending on their form and transparency. Opaque materials are measured with reflectance spectrophotometers, which assess the amount of light reflected from a sample. In contrast, transparent materials utilize transmission spectrophotometers, which quantify the amount of light that passes through the material (Schanda, 2007; Clarke, 2006). Regardless of the used method, all spectrophotometers share the same fundamental technology and design, Figure 29:

- A controlled light source to illuminate the material, e.g. tungsten.
- A lens to collimate the light to the monochromator.
- A monochromator that separates the light into its constituent color wavelengths.
- A wavelength selector.
- A detector that quantifies the light emitted from the sample.
- A display that provides results.

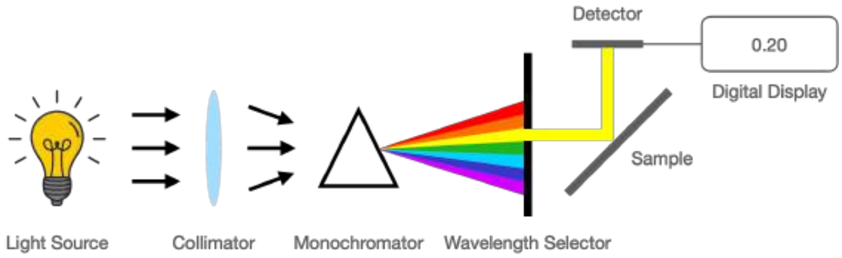

Figure 29. A picture illustrating the principle of *'reflectance spectrophotometry'*.

Some use colorimeters instead of spectrophotometers, and they differ in function. Colorimeters are tristimulus (three-filtered) devices that utilize red, green, and blue filters to mimic the human eye's response to light and color. In certain quality control applications, these tools provide the most cost-effective solution. Blended instruments, known as spectrocolorimeters, combine the features of a colorimeter with some functions of a spectrophotometer. The primary difference between them lies in their capabilities and usage. Spectrophotometers are highly powerful tools that provide more detailed color measurements than colorimeters, including spectral data. This is why they are mainly used for accurate measurements in research, development, or laboratory settings (Schanda, 2007; Clarke, 2006). Another variant for measuring color is imaging-based color measurement systems, which offer a powerful alternative to point-based instruments by capturing spatially distributed color information across an entire surface (Hunt & Pointer, 2011; Hardeberg, 2001). These systems operate by using high-resolution cameras to record images that are processed by specialized software to extract and analyze color values over defined areas (Sharma, 2002). The repeatability of such systems depends strongly on calibration quality, illumination control, and system stability (Hunt & Pointer, 2011). Moreover, when measuring color, the result is typically linked to a standard and presented in a color space or model (Best, 2017). Standardized color spaces ensure consistent color communication across different devices and industries. This thesis primarily addresses color spaces as measured by a spectrophotometer; however, additional color spaces will be described to provide a comprehensive overview of color spaces and models (MacAdam, 1981).

Mathematically defined

- CIE XYZ (1931): A foundational color model that defines the relationship between the visible spectrum and human color vision.
- CIE LAB (L, a, b): A perceptually uniform color space where L represents lightness, a represents red-green, and b represents yellow-blue. It is widely used in industrial color management.
- CIE LCH (Lightness, Chroma, Hue): A derivation of LAB that represents color in terms of perceptual attributes.

Device dependent

- RGB (Red, Green, Blue): Used in digital displays and imaging technologies, such as a smartphone screen.
- CMYK (Cyan, Magenta, Yellow, Black): A subtractive color model used in printing.

Physical color standard systems (Color matching systems)

- NCS: Based on how human beings perceive color (perceptual). Often used in architecture, design, industrial coatings, and paints
- RAL: A fixed reference system with specific paint formulations. Often used in industrial coatings, paints, plastics, and design
- Pantone: Used in graphic design, textiles, and branding with spot colors for printing. Often used in printing, branding, textiles, and packaging

Regardless of the standard or color system used, several factors impact the accuracy and reliability of color measurement. First, calibrating known reference standards is crucial for ensuring measurement accuracy and consistency. Additionally, controlling the illumination conditions is vital for both the context and the measurement equipment. Standardized lighting conditions (such as D65 'daylight' in a light booth) are important for achieving consistent measurements and making significant comparisons (Best, 2017). The surface properties, such as gloss, texture, and translucency, can alter light interactions and impact color appearance. Therefore, it is essential to consistently compare surfaces in terms of surface topography when analyzing color appearance.

The viewing angle is also an important factor to consider. The surface appearance changes with different viewing angles in relation to the light source, suggesting that a consistent viewing angle is crucial for making meaningful comparisons. Preferably, measurements should be implemented with the standards of viewing angles mentioned above.

Surface characteristics

Regardless of the measurement technique, the primary intention of measuring a surface is to obtain information about its structure and characteristics. To help the reader with the definition of *Surface characteristics* used in this thesis, an explanation may be required. Surface characteristics refer to micro- and nanoscale features of a material's surface that influence its functionality, both technically and emotionally. These characteristics include roughness, waviness, texture, and gloss (Reddy, 2023). However, in this thesis, color is also considered a surface characteristic that influences the appearance and perceived quality. The following section provides a brief explanation of the fundamental theories underlying key surface/material properties discussed in the thesis.

Physical and optical surface properties

Areal surface parameters (ISO 25178-2:2021) correlate with perceived gloss, lightness, and color.

- Surface roughness and texture - Microstructures scatter light differently, affecting perceived color and gloss.
- Material composition - The presence of pigments, coatings, or oxidation, affecting perceived color and gloss.
- Surface coatings and films - Thin films (e.g., anodized aluminum, interference coatings), affecting perceived color and gloss.

Metrological considerations

While ISO 25178-2:2021 focuses on geometric surface texture (height, waviness, roughness etc.), other standards like ISO 7724-1:1984 (colorimetry) and ISO 11664-4:2022 (CIE color measurement) define how color is measured in a standardized way.

- Spectrophotometers or colorimeters measure surface reflectance and quantify color in CIE Lab (or/and LCH), RGB, or CMYK.
- Gloss & Reflectance (e.g., ISO 2813:2014 and ISO 7668:2021) affects color perception by changing how light interacts with the surface.

Perceived quality & emotional response

From a soft metrology perspective, especially visual interaction, perceived gloss and color are crucial for user perception.

- Matte vs. glossy finishes can make the same color appear different, which is linked to surface roughness and texture (ISO 25178-2:2021).
- 'Rough' surfaces can cause diffuse reflection, reducing color intensity.
- Consumer preference does not always correlate with objective data, for example, perceived versus measured gloss.

Having these theories in mind while searching for key surface properties that impact perceived quality is important, as different surface characteristics affect different sensorial stimuli. Figure 30 illustrates an example of how an injection-molded plastic surface differs in appearance in different scales and, therefore, could, e.g., scatter light differently depending on the level of magnification applied.

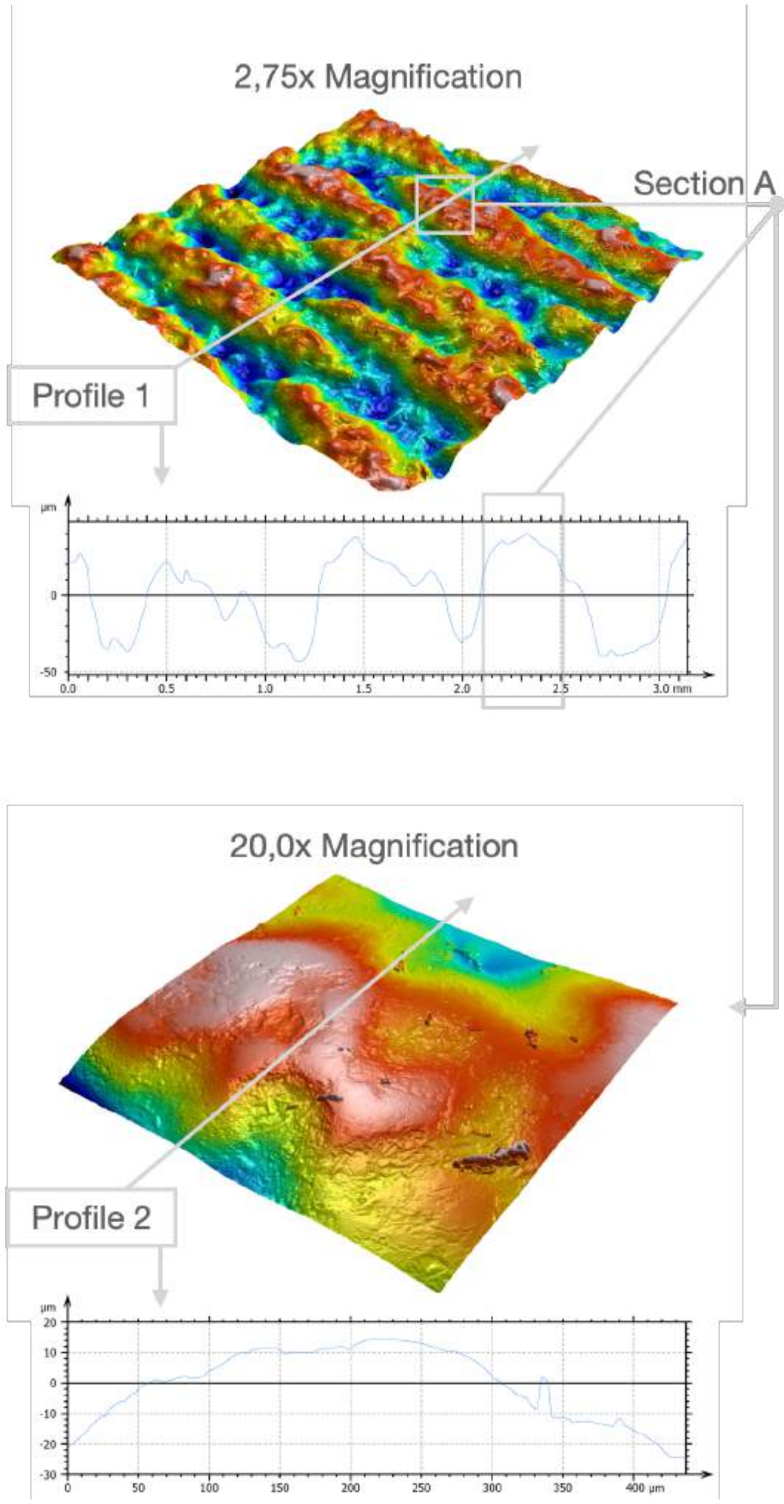

Figure 30. A picture illustrating the microstructure captured by white light interferometry (WLI), where different magnification displays different surface characteristics.

Figure 31 illustrates a simplification of the theory regarding different surface characteristics and their impact when light hits the surface. Peaks, or plateaus, could scatter light differently compared to the valleys, where light could "bounce" differently and scatter light in more diverse directions or be absorbed.

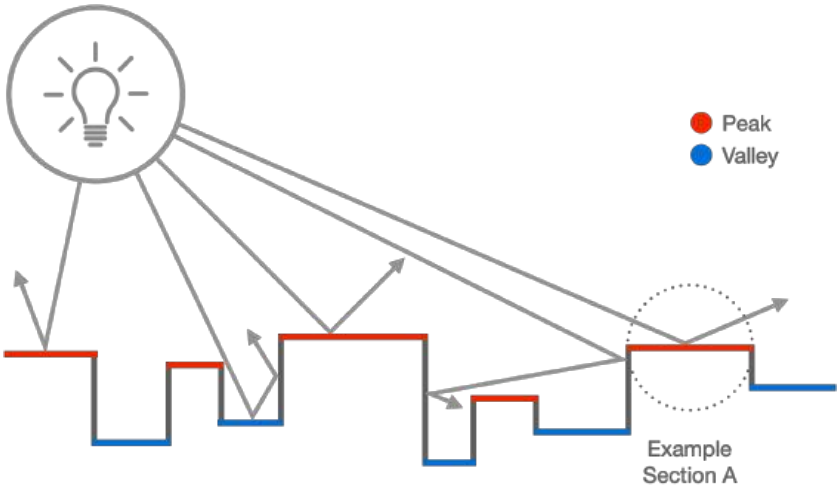

Figure 31. A picture illustrating a simplification of peaks and valleys of a surface microstructure.

Analyzing a surface appearance from a perceived quality point of view requires knowledge of how surface characteristics, such as texture or gloss, behave in different scales of a surface. This is because the surface characteristics (such as areal surface parameters from ISO 25178-2:2021) change in tandem with production variations, such as injection temperature or hold pressure of injection-molded polymers (Bergman et al., 2025). The example above is an injection-molded polymer from Paper VI; however, these theories are applicable to any material/surface.

As a project-specific example, from Paper VI, focusing on injection molded polymer surface parameters, the hybrid surface parameter 'Sdq' (from ISO 25178-2:2021), which is the root mean square gradient value, traditionally has an impact on surface appearance characteristics and may be an interesting parameter for investigating gloss, both in an early stage as well as in a late stage of a development process. However, the feature parameter 'Spd' also has an impact on surface appearance characteristics, which is the density of peaks parameter. They both impact gloss and are likely to change when production changes (Bergman et al., 2025). Gloss is one of several key factors that designers consider when creating a balanced appearance. The gloss and color of injection-molded components result from complex psychophysical phenomena of visual perception, where light reflected from the surface of an opaque part is either primarily specular (in a single direction) or diffuse (scattered in all directions), (Pisciotti et.al., 2005). Gloss is usually measured using two approaches: soft metrology, which involves psychophysical evaluation, and hard metrology, which focuses on physiological measurements (Wang et.al., 2017). Studies made in research explore the relationship between gloss and surface texture, indicating surface texture as a significant factor impacting appearance and presenting strong correlations with measured gloss. (Alexander-Katz & Barrera, 1998; Ariño et al., 2005; Wang et al., 2017)

In a study made by Gim et al. (2020), it was found that mold temperature and flow front speed were the production parameters that had the most significant influence on surface gloss. However, there are several factors that could impact gloss. The holding pressure strongly influences hybrid parameters, Sdq (Root mean square gradient), tool temperature is found to have a higher influence on the surface topography represented by the spatial parameters, Sal, which implies tool temperature affects the larger wavelength features, while the injection speed has a more significant effect on the density of peaks, Spd (Density of peaks), (Reddy et.al, 2023a; Reddy et.al, 2023b). These phenomena could vary depending on the scale of the measured texture and whether the texture is fine or coarse. However, Vijeth Venkataram Reddy et al. (2023a, 2023b) and Reddy (2023) mean that for fine-grain surfaces, parameters such as Sdq have negative correlations with measured gloss, while Sal has a positive correlation. That conclusion is interesting for this study as well since there are strong indications of this phenomenon supporting that result. The diagrams in Figure 32 from Paper VI, illustrate this relationship between the Gloss Unit and the parameters Sdq, and Sal. The measured surfaces, A-J (C is master), are all injection-molded samples made of ABS, where samples A and B are considered to be "too glossy" and therefore not ok from a perceived quality point of view (Bergman et al., 2025).

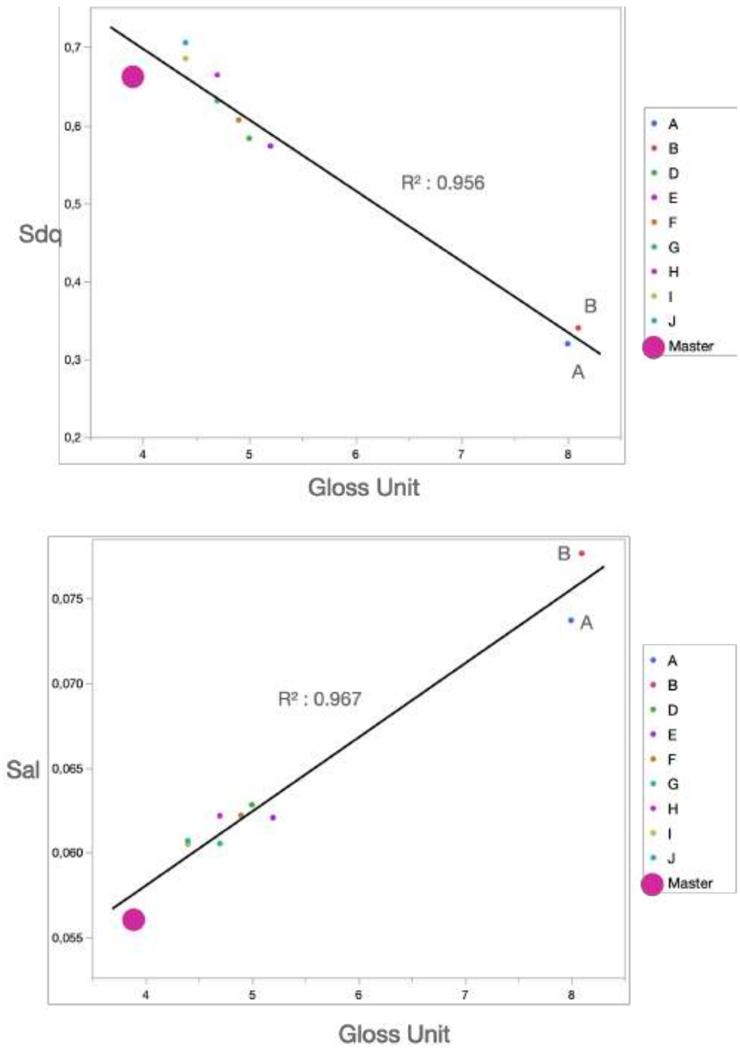

Figure 32. Two diagrams from Paper VI illustrating the relationship and R2 value between the Sdq value versus gloss (top) and the Sal value versus gloss (bottom), for all the samples.

As described at the beginning of this thesis, the linkage between total appearance and production is important to be able to implement any significant changes regarding perceived quality. The example described above is a case-specific issue that partly confirms that deviations in production regarding temperature, speed, and pressure of injection molded polymer components affect the surface structure on the sub-millimeter scale. These small changes in the surface can be captured within 'hard metrology', and by means of traditional gloss measurements, together with human responses, the linkage between customer acceptance and manufacturing process parameters can be established (Figure 33).

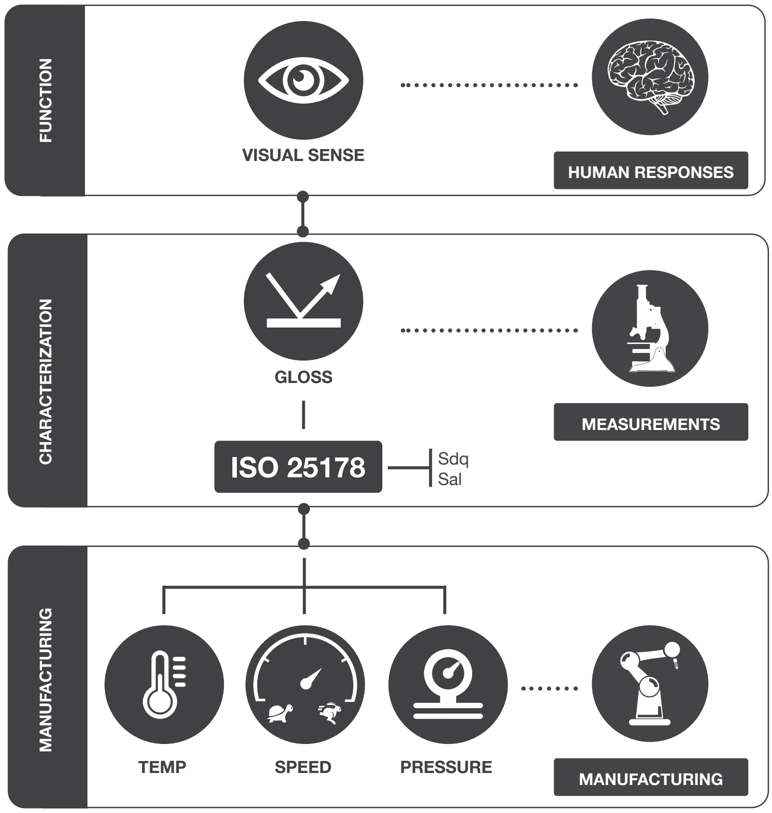

Figure 33. A picture illustrating the correlation of the 'surface control loop' and manufacturing process parameters affecting areal surface parameters, gloss and human response.

3.9 CONTINUOUS IMPROVEMENTS AND META VALUE

The implementation of new methodologies, organizational structures, and process-oriented frameworks has been recognized to be a complex organizational activity for a long time. Approaches such as Lean Production, Total Quality Management (TQM), Six Sigma, and design-led innovation models are frequently introduced to enhance efficiency, improve product quality, and strengthen strategic capabilities within the industry (Antony, 2006; Oakland, 2014). However, research consistently shows that the success of such initiatives depends not only on the methodologies themselves but also on the organizational conditions that support the implementation (Rogers, 2003).

Implementation theories emphasize that new practices typically diffuse gradually throughout an organization. The implementation, or adoption, often begins with focused pilot projects or isolated departmental efforts before evolving into fully integrated organizational routines. Critical factors such as top management commitment, employee involvement, alignment with business strategy, and the establishment of a supportive organizational infrastructure are frequently cited as essential to this process (Antony, 2006; Oakland, 2014). Lean Production frameworks, for instance, highlight the importance of fostering a culture of continuous improvement (kaizen), while TQM emphasizes organization-wide participation and long-term commitment to quality. Design integration models, such as the Danish Design Center's "design ladder" (Figure 58), further illustrate how organizations progress from limited or ad hoc uses of design principles to more advanced and strategic applications (Danish Design Centre, 2015). Collectively, these theories indicate that the introduction of new structures or methodologies rarely yields instant value for the organization. Rather, value emerges progressively as organizations adopt new ways of working, adjust existing processes, and develop shared skills and capabilities. This gradual evolution provides the conceptual foundation for understanding meta-value.

In this thesis, the meta value refers to the long-term, emergent benefits that arise not exclusively from the direct outcomes of a methodology or project but from the maturation of its implementation over time. In research-driven or innovation-oriented organizations, meta value often appears when early-stage results, often situated within an R&D setting, begin to inform broader organizational practices. Over time, this diffusion can foster new routines, strengthen cross-functional collaboration, and increase the organizational awareness of quality, design, or innovation principles.

In this sense, continuous improvement frameworks describe the mechanisms through which organizational learning and adaptation occur, while the concept of meta value highlights the accumulated and sometimes unexpected advantages that arise during this process. Understanding both perspectives is essential when evaluating how new methodologies, such as KE or other quality tools, contribute to long-term organizational development and capability building.

Within this research, the meta-value of the implemented methodology was identified and refined through a series of extended research projects, with timelines prolonged partly as a consequence of the COVID-19 pandemic.

4 RESULT

Previous work has shown that the industry desires a more comprehensive and robust approach to controlling perceived quality. The result of the research work so far is an enhanced model that combines the established development method of Kansei Engineering with traditional design and mechanical engineering methodologies. However, this version is now more closely aligned with industry needs compared to previous work.

The primary outcome of the research work is the methodology presented in this section. It should be recognized that the methodology has a strong foundation in Kansei Engineering, however, it is adapted to what is briefly described as 'Material/Surface design'. The proposed methodology differs from Kansei Engineering (KE) in its scope, focus, and integration of material science. While KE is centered on translating emotional semantics into design parameters, the presented methodology functions as a comprehensive UX and product-property correlation process that encompasses sensorial experiential dimensions, including functional, contextual, perceptual, and emotional aspects. A key difference lies in the direct connection between sensation and perception, allowing subjective impressions to be linked to measurable material and surface properties, including surface texture parameters defined in ISO 25178-2:2021, as well as to specific manufacturing processes that generate these properties.

Although both methods share a similar structural logic, KE relies on a rigid, quantitatively driven process supported by established statistical tools and emotional adjectives. In contrast, the proposed methodology enables broader qualitative interpretation in the early stages regarding perceived quality; however, it also evaluates holistic "meta value" impacts and integrates business, stakeholder, and systems-level reasoning. This makes it more general and adaptable to diverse design and production contexts, with the perceived quality of materials/surfaces in mind.

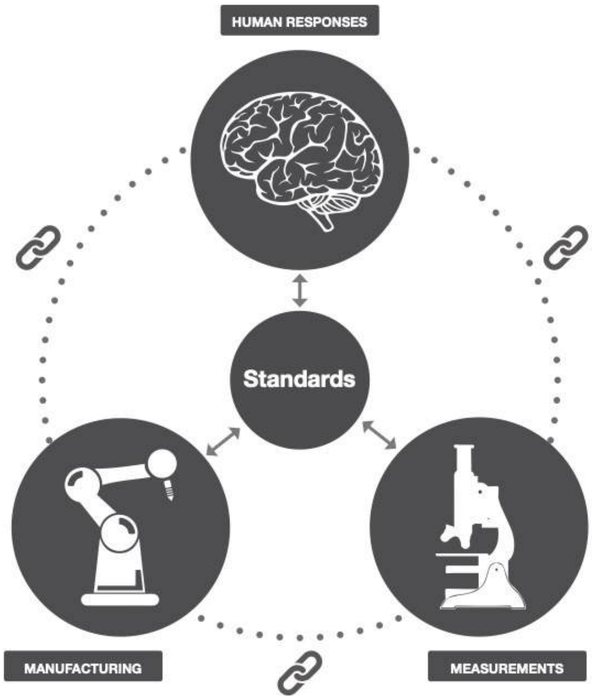

Figure 34. A picture illustrating the correlation between manufacturing process, objective measurements, human response and their link to standards.

Nevertheless, linking human response to production could be done in different ways. Yet, the application of Kansei Engineering has proven to be a comprehensive tool and framework that influences the research presented in this thesis. The link between manufacturing, objective measurements, human response, and current international standards must be considered when controlling the perceived quality of components, as shown in Figure 34.

Professor Mitsou Nagamachi (Hiroshima International University) had a vision of improving products on a more detailed level than before. Hence, he developed the method of Kansei Engineering (KE) in the 1970, which has its roots in the Japanese concept of Kansei ("intuitive mental action of the person who feels some sort of impression from an external stimulus") (Nagamachi & Lokman 2011) and (Lokman 2010). KE can also be defined as a customer-oriented approach to product development (Frisk & Järlskog, 2002; Hedberg, 2004; Nagamachi, 1997, 2002). *State of the art:* For over four decades, Kansei research has served as a critical framework for product development, particularly in Japan, China, and Korea. Since the early 2000s, the dissemination of Kansei principles has expanded to Europe and other regions worldwide, reflecting their growing academic and industrial significance. Several organizations have been established to advance Kansei studies, including the Japanese Society of Kansei Engineering (JSKE, 2007), the European Kansei Group (EKG, 2014), the Taiwan Institute of Kansei (TIK, 2007), and the Malaysia Association of Kansei Engineering (MAKE, 2017). The bi-annual Kansei Engineering and Emotion Research (KEER) conference has evolved from a conventional academic meeting to a central hub for scholarly inquiry and interdisciplinary collaboration in the field. The diversity of cultural, technical, and disciplinary perspectives within the Kansei research community has enriched its theoretical foundations and driven the development of novel methodologies and applications. By fostering dialogue and knowledge exchange, this academic network continues to shape the global understanding and application of Kansei in product design and development (Shütte, 2024).

Today, on the other hand, some industries have 'perceived quality' (PQ) departments dealing with customer stimuli and experience as a part of the development and manufacturing process. These departments are normally involved in the development process in both early and late stages. This is where the research and this thesis could probably make the most impact. The model is a simplified version of reality, and it is rarely linear but rather iterative, similar to the traditional design process. Hence, it is essential to recognize that the six steps in the model serve as framing gateways or important milestones on the journey to establishing a robust link between perceived quality and robust production. One finding of recent research work has shown that the modified KE approach can serve as a tool rather than a method, or ultimately, as a combination of strategic work and the use of comprehensive tools within the methodology. One example could be finding adequate equipment to implement objective measurement of surfaces as a result of understanding key properties (step 3) of the relevant domain. The methodology, with its tools, is described below.

Figure 35. Illustration of the implemented methodology, based on Kansei Engineering, partly described in Paper IV.

The 6 phases range from the first step, "ask questions", where the product or service is defined, including specification of the product and market, down to "synthesis and modeling" of the result of the given study, Figure 35.

1. Ask Questions – Define what, who, why, where, when, and how.
2. Clarify the Experience – Collect adequate adjectives or expressions interpreted by different stakeholders.
3. Define Key Properties (Span the space of properties) – In this phase, it is essential to identify physical product properties that impact stakeholders, including both effects and defects.
4. Connect the Experience and Product properties.
5. Validity Checkpoint by establishing correlations.
6. Synthesis and Modeling – Design and validation of a "prediction model".
7. Meta Value – The underlying impact of the implementation of each step.

The challenge with a model is to adapt it to reality, and in the past years, the aim has been to adjust the model piece by piece to match the industry's needs. Within an industry project, step 1 is not necessarily the initial phase. The company may have been working internally, unconsciously, with some of the steps already. The developed model takes this fact into account by working iteratively.

4.1 ASK QUESTIONS

This step could be seen as an insight into the 'early-stage phase' of a development project, where the 'design intention' is discussed. Initially, there may be many questions that need to be answered. It is necessary to navigate efficiently in the right direction from the beginning of a project. You might be dealing with a 'Wicked Problem' even if you think it is a fairly straight-up issue. Product designers, in general, have a good internal navigation and understanding of the design process; however, sometimes the lack of communication in a project can result in endless discussions about what the aim is for whom, and so forth. D.School at Stanford University also talks about this in their book 'Bootcamp Bootleg' (Stanford, 2016). However, to pursue continuous improvements in the early stages of product development and design in a structured manner, 'The Design Compass' was developed as a tool within the research, as mentioned earlier. The 'Design Compass' works as a stimulus tool and guideline in the process of 'Affective Engineering' to facilitate the workflow. By focusing on the primary questions (what, who, why, where, when, and how; the compass tool), Figure 36, majorly in the first step, but also during the design phases (define, explore, and refine), deeper levels of observation and a higher level of understanding are obtained by the designers and project participants.

This task also enables the topical implementation team to transition from concrete observations to a more abstract emotional state of mind in specific situations related to user needs. With a wider understanding and knowledge about these questions as a starting point, it is probably easier to navigate through the design process. IDEO and d. school Bootcamp Bootleg also confirms similar methods (Stanford, 2016).

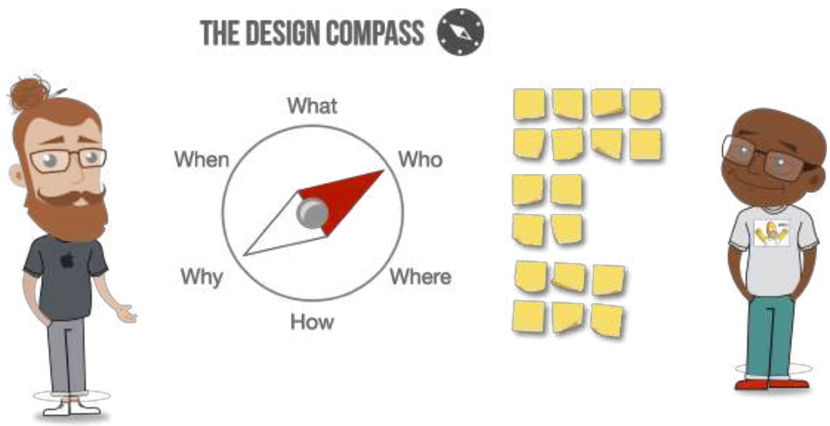

Figure 36. Illustration of the workflow with the compass tool.

Since the design process, in general, is considered iterative, the tools used within it can also be useful in the later phases. So is the design compass. However, it should be recognized that the emergence of new needs in a late project phase, for example, close to production, can make modifications both complex and expensive, as changes often require rework of designs, tooling, or planning.

4.2 CLARIFY THE EXPERIENCE

This step is also linked to what is considered an early stage of the development process. The idea of clarifying the intended experience or perceived quality of a product primarily involves framing and understanding 'emotional functions' within the design intention, as well as the needs of a future solution. Customer satisfaction and acceptance are directly linked to perceived quality, which needs to be defined in this stage.

Shütte (2013) added to the discussion of needs of the customer the pleasures of motivation by Jordan's four pleasures: *physio* – to do with the body and the senses; *psycho* – to do with the mind and the emotions; *socio* – to do with relationships and status; and *Ideo* – to do with tastes and values. Jordan's four groups complete Maslow's five steps in the hierarchy of needs mentioned earlier (Jordan 2002). However, to be able to frame 'emotional functions', there is a need to scan the semantic space and collect expressed interpretations of a product linked to the design intention. Nevertheless, this could be made in different ways. In previous research, this matter involved collecting adequate descriptive words that users express when interacting with the product. By using descriptive words, it is possible to find appropriate expressions for a product or service, which facilitates the project later in the design process by evaluating the experience. When the project is implemented, the selected describing words can be evaluated in relation to the company´s vision to verify the outcome. One way to use descriptive words effectively is to prepare a list of adjectives in advance, rather than generating them on the spot. 'The word game' was developed in this research work, Paper I, as a design tool for this matter, see Figure 37 (Bergman et al., 2012; Bergman et al., 2014a). Recent research indicates that some industries already rely on well-defined semantic spaces or core values that directly inform early design intentions. This can make it easier to articulate and achieve the intended product experience, such as a sense of softness.

However, to map the experience, the result of the previous work (the design compass) must be taken into consideration; hence, that result can be seen as the foundation of how the user will experience the new product. Finding words or core values that work in tandem with the sensation and perception of a new product's interaction could be a challenge and may be seen as an issue of 'ideasthesia,' as mentioned earlier. Different words have different meanings when speaking of experience; Takete/Lumumba, mentioned earlier, is a good example of this statement. Therefore, the choice of describing words is important; adequate words should be chosen (Hedberg, 2004).

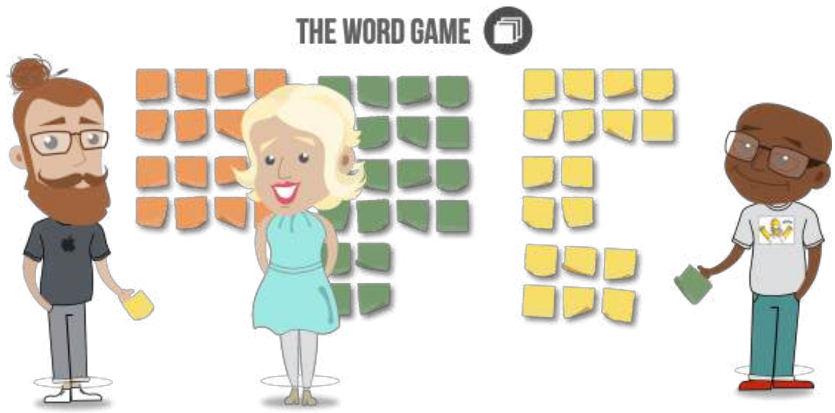

Figure 37. Illustration of the workflow with the word game tool, where the participants cluster different descriptive words.

Traditionally, core values or descriptive words associated with a specific experience or expression can be translated into pictures, creating a so-called 'mood board'. A 'mood board' could be used within a project group as a guide for the intended expression of a product. Figure 38 illustrates an example of a 'mood board' with a 'soft', 'calm', and 'smooth' expression that could be translated out of a cluster of words. What do you think, is the mood board more of a 'Lumumba' or 'Takete' vibe?

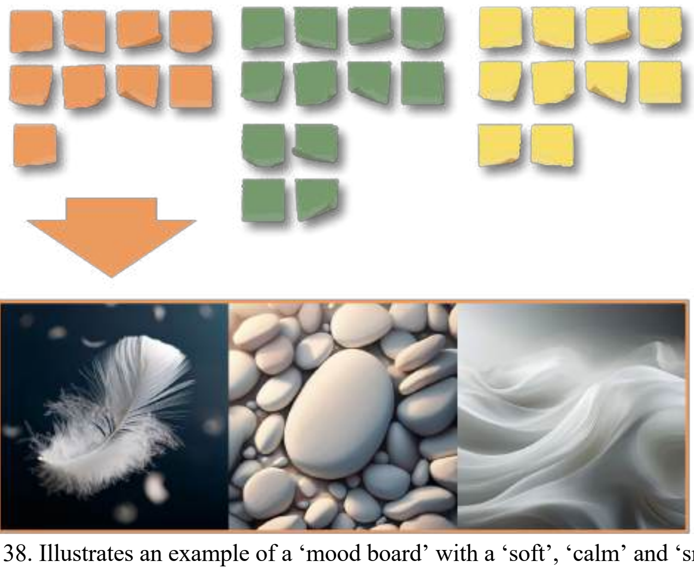

Figure 38. Illustrates an example of a 'mood board' with a 'soft', 'calm' and 'smooth' expression.

Hence, descriptive words are important to create an agreement on the intended perceived quality. The collection of words was initially implemented with regular Post-it notes, where new words were ideated from scratch. Today, the collection phase is optimized to offer a more efficient and cost-effective process. The *'Word Game'* was developed to serve as a physical tool for designers to set high-quality core values for a product or service in a structured manner. The 'Word Game' is also faster in comparison to work with regular Post-it notes. Instead of implementing questionnaires, a structured focus group participates in a physical word game where the intensity and the level of ambition usually end up being very high. Figure 39 illustrates a schematic view of the word game implementation. By having different "filters", such as domain, context, and culture, the number of collected adjectives is reduced and validated in a structural manner (Bergman et al. 2012).

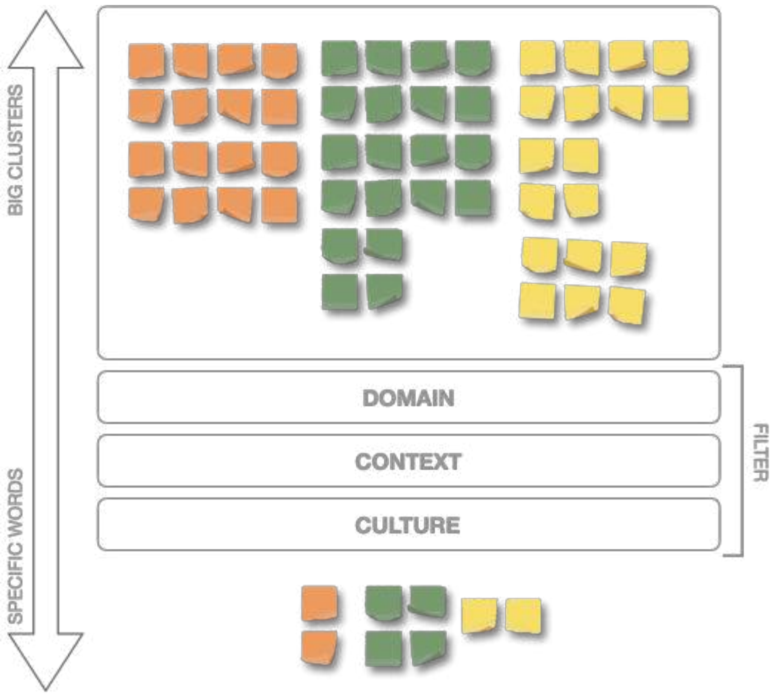

Figure 39, illustration of the different filters that are used to implement the *"Word Game* (Bergman et al. 2012).

The implementation: The *'Word Game'* is implemented, and initially, the focus group sorts out ambiguous words that do not fit in the domain, context, and culture. Preferably, it could be three different groups when this step is implemented: one "yes", "maybe", and "negative" group. The words that are sorted out obviously do not advance to the next level. The cluster division takes place, and the focus group starts with the "yes" group (followed by the "maybe"-group if necessary). The primary purpose of this step is to identify synonyms among the descriptive words or words that can be directly related to each other. For example, the words "Modern" and "Stylish" can be directly connected, even though they are not synonyms.

The number of words is reduced during this part of the project. If two or more words are very similar, the most appropriate word shall be used. The focus should be on finding words that are commonly used in everyday language and are easy to understand, to avoid any confusion about a specific word. The selected words should be related to the domain, context, and culture as well.

When this part of the game is implemented, there should be approximately 150 descriptive words distributed evenly across 10 clusters (the number of words and clusters may vary, as shown in Figure 40). The last part of this game is to reduce the number of words one more time. Instead of erasing ambiguous words, the top five descriptive words from each group shall be selected to form a new group, as shown in Figure 40. This reduction results in 50 descriptive words, distributed equally among ten clusters (the number of clusters may vary) (Bergman et al. 2012).

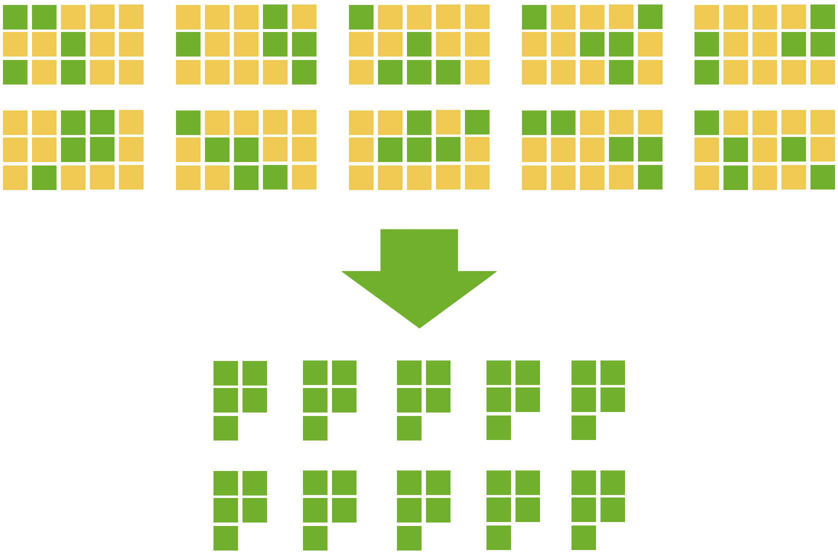

Figure 40, illustration of the word game reduction procedure.

The implementation of the *"Word Game"* results in 50 potential descriptive words related to the domain, context, and culture (Bergman et al. 2012). As the next step, the company should be invited to choose one word from each cluster, which would be considered the core values for the next generation of products in this context (Figure 41). Wikström (2002) says that it is of great importance to involve the company in an early stage to be able to respond to the focus group results.

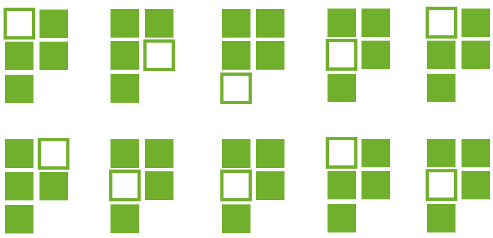

Figure 41. Illustration of the word game reduction procedure.

The group of negative words is usually not used in the project, although it could be used, e.g., to state what a product should not express. To ensure the selected core values align with the company's vision for the product, they are compared to the initial core values discussed with the company. It is possible that some of the core values are the same or grouped together, which is considered beneficial (Bergman et al., 2012).

Case Specific

For example, Figure 42 illustrates a focus group in the midst of implementing the *"Word Game"* for a research project in collaboration with the industry, Paper I, (Bergman et al., 2014a). The focus was on the perceived experience of interacting with medical and food contact surfaces, as well as surfaces with various coatings. The resulting adjectives that were used in the development process were robust, resistant, clean, warm, sleek and elegant. The selected adjectives were then analyzed and verified in collaboration with the topical company. These adjectives were used in the subsequent material evaluation process to identify materials and surfaces that align with the total appearance of medical and food contact surfaces (Bergman et al., 2014a).

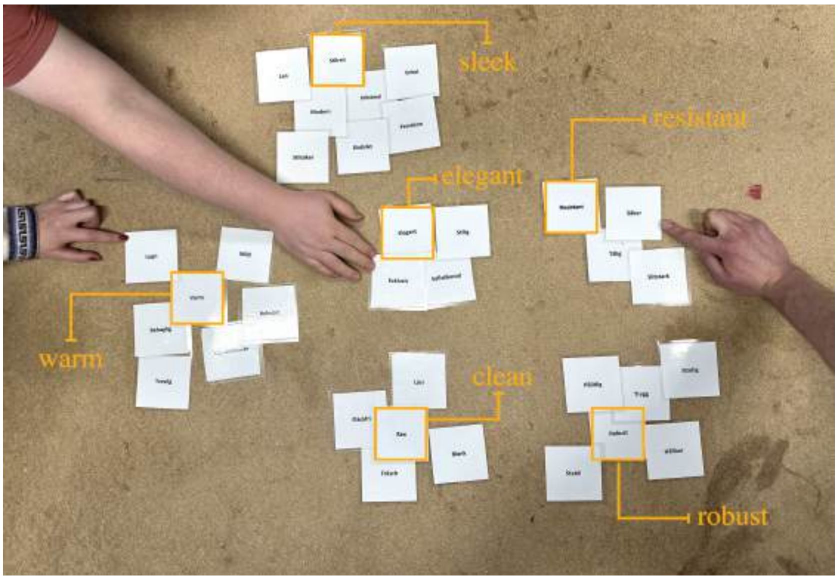

Figure 42. A picture illustrates a focus group implementation of the *"Word Game"* in a research development project together with the industry. The words in the upper part of the picture are the selected adjectives for further implementation.

4.3 DEFINE KEY PROPERTIES

Once the product characteristics are identified, the primary objective is to determine the properties of the existing product that can be controlled and influence the product's total appearance. These properties can also be referred to as design elements. In product design, the primary design elements are 'form' (as geometry/shape), 'color' (as hue, saturation, whiteness and blackness), 'material' (as chemical substance or raw material, isotropic or anisotropic, structure and strength) and 'surface' (as texture, gloss, haze, isotropic or anisotropic). The design elements are compared later on in the process with the selected describing words (also known as core values). This is designed to systematically identify specific words that appear to influence the experience of a product. The design elements should be appropriately measurable using standardized methods and parameters, such as the surface texture field and stratified and feature parameters, in accordance with the recognized ISO 25178-2:2021 series of standards. The surface appearance can be further described in detail, including polish and structure, which facilitates the analysis of the surface appearance later on.

Papers I and II highlight the correlations between the experience and feeling (psychological requirements) and the functional requirements (physical requirements), which must also be established. For instance, the adjectives clean and hygienic express stakeholders' psychological demands for a surface in the environment of medical healthcare, which also is connected to demands on: cleanability, thus related to chemical resistance against stains and cleaning agents; and scratch-proofness to resist harmful wear and cleaning effects (Figure 43) on the surface (Bergman et al., 2014a; Bergman et al., 2014b).

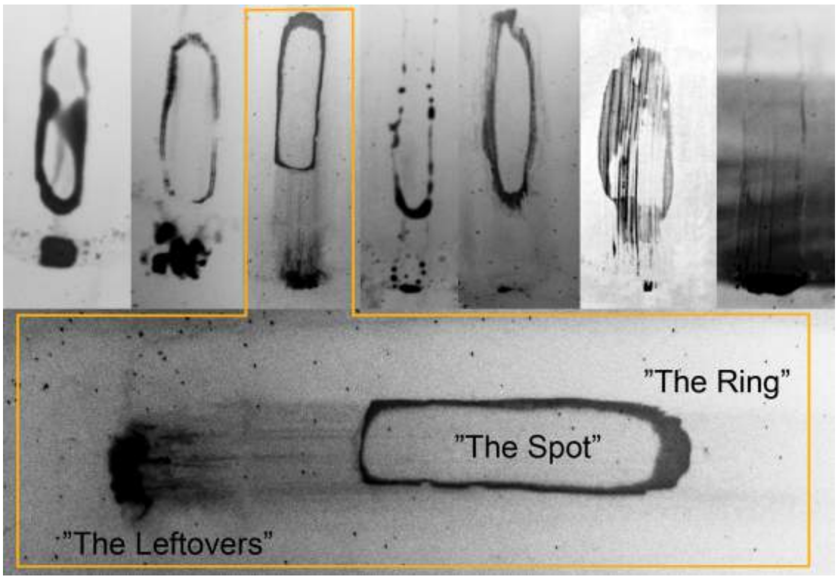

Figure 43. An illustration from Paper II of a selection of seven different results from a wipe off test were the factors; the ring, the spot and the leftovers, have got a variance depending on surface micro texture, (Bergman et al., 2014b).

An ASME standard (ASME 2009) connects today's requirements of hygienic surfaces to texture average arithmetic amplitude (Ra) according to ISO 4287:1997, and it is considered sufficiently smooth when the Ra value for a given surface is <0.8 μm (Bergman et al., 2014a; Bergman et al., 2014b). Here, the ASME standard defines the surface's texture mean amplitude as the design element controlling the tactile and psychological requirements of cleanliness and hygiene.

However, in this thesis, the design elements are illustrated as pictograms, as shown in Figure 44.

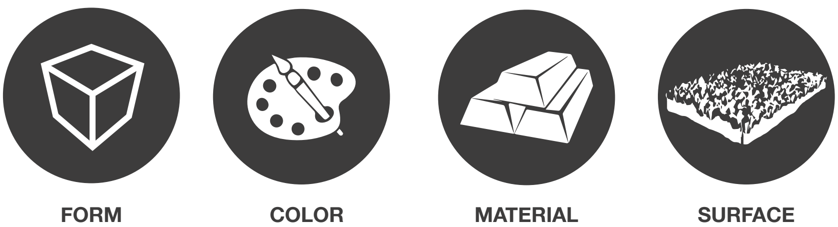

Figure 44. Illustration of the design element pictograms.

In the specific field of material design, the surface appearance is of high importance, as it has a major impact on both technical and emotional functionality. The reader already knows what a surface really is, hence the description earlier in this thesis. However, surface appearance is experienced mainly through the senses of sight and touch. In this thesis, the visual sense has been the primary focus, and the haptic sense has been a secondary focus when analyzing the surface's total appearance.

Focusing on the micro-scale geometrics of the 'surface appearance', this depends on several sub-design elements, which are primarily described as gloss, haze, roughness, and texture (Figure 45). Those sub-design elements are linked to the surface standard ISO 25178-2:2021, which contains several parameters describing the surface design on the micro- and nano-scales.

Figure 45. Illustration of surface sub-design elements pictogram, from Paper IV (Bergman et al., 2016).

However, to connect the sub-design elements' parameters to the industry and their process control, it is also important to establish a correlation between the sub-design elements and the process parameters. Process parameters could be material temperature, cycle time, processing speed, and pressure, as a few examples (Figure 46).

Figure 46. Example illustration of production process pictograms, from Paper IV (Bergman et al., 2016).

Once all technical functions for the design elements and process elements are set and defined, the connection between product properties and the experience can be implemented.

Case specific

As an example, Figure 47 illustrates a picture from a project (Paper IV) involving the automotive industry, where a material for interior design was evaluated. The material consisted of chrome-plated plastic components, and the topical company sought to evaluate the possibility of developing robust measurement and verification methods for the technical functions of the surface sub-design elements, including gloss, haze, and color temperature of the surfaces. Another aim of this research case study was to identify any unknown correlations between the parameters that unconsciously affected one another when modifying, for example, the haze on a surface (Bergman et al., 2016).

Figure 47. A picture illustrating the chrome-plated plastic component in the interior design for the topical research project from Paper IV. Gloss, haze, and color temperature were the sub-design elements that were in focus for the surface evaluation (Bergman et al., 2016).

4.4 CONNECT THE EXPERIENCE TO PRODUCT PROPERTIES

This phase is essentially where users begin to interact with the topical product and its associated domain. If the product properties could somehow connect to the experience, the possibility of controlling the semantic message and the total appearance increases. The ideal would be to perform physical measurements using sensors applied to a subject placed in a test situation and the establishment of useful measurement scales correlating human responses and physical metrology, i.e. combining traditional physical “hard metrology” (geometry, color, gloss, taste, smell, noise and tactile properties) to enable increased understanding of the influence of physical product properties on human responses, see figure 48. Here, the human response would be considered a measurement system that defines sensitivity, repeatability, and reproducibility, and compares the results with those obtained by methods from traditional “hard” metrology.

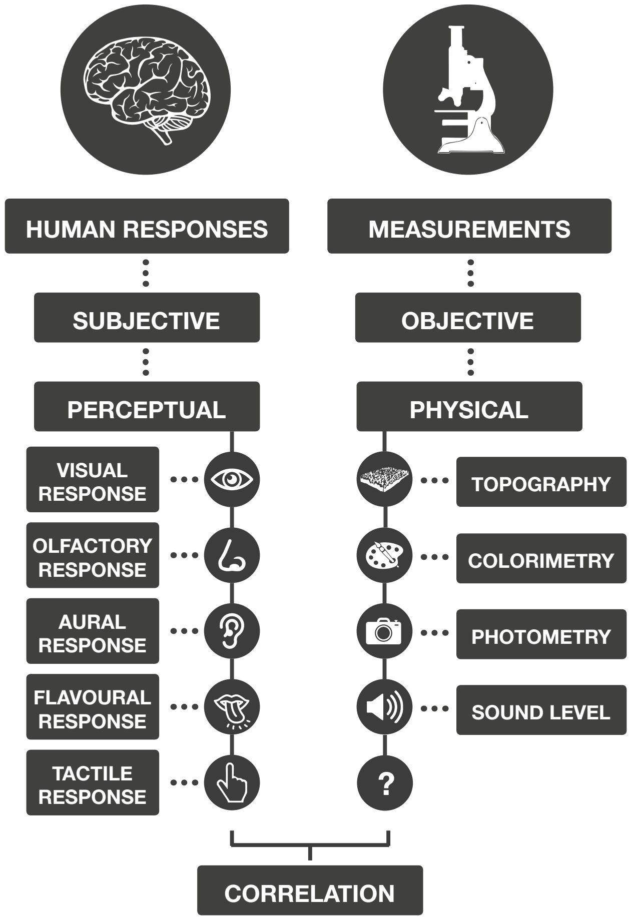

Figure 48. Illustration of the soft- and hard metrology theory Paper IV (Bergman et al., 2016).

Measurements involving people require human perception and interpretation to assess complex, holistic quantities and qualities that are perceived or generated by the human brain and mind. This is important to consider when using focus groups (Berglund et al., 2012). However, by using qualitative studies on focus groups or statistical methods such as multivariate analysis, a connection between human responses and physical measurements becomes possible. The first step is to create a focus group within the actual context or create a real-world environment. If the context is inaccessible for some reason and it is difficult to replicate it accurately, then the tests should be implemented in an environment with as few external stimuli as possible. There are other theories about the implementation of a focus group as well, such as the physical environment design (e.g., the size of the room) and also the distance between the participants (Wibeck, 2010).

To evaluate and control the relationship between surface appearance and other design elements, the Affective Engineering Equalizer (EQ) from Paper III, Figure 49, was developed, as mentioned earlier (Bergman et al., 2012; Rosén et al., 2015). The EQ is a dynamic evaluation tool for designers that assesses form, material, color, and surface in relation to core product values, allowing correlations between design elements to be identified (Rosén et al., 2015). For example, it can show how the perceived effect of a "smooth" form changes with different surface appearances. The EQ is based on semantic differential scales, which evaluate product attributes using descriptive adjectives (Osgood, 1943). Importantly, the EQ evolves over time, adapting to project-specific and industry-specific needs, and can focus on different senses depending on the context, such as prioritizing touch over color when relevant.

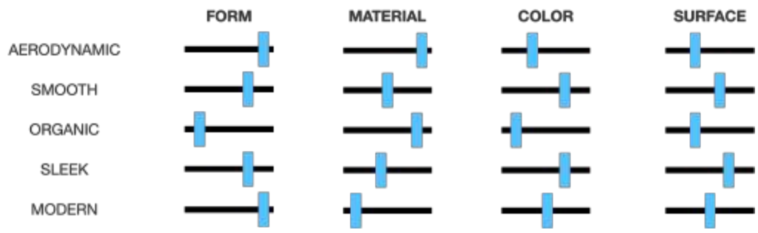

Figure 49. Illustration of the affective engineering equalizer tool, Paper III (Rosén et al., 2015).

Moving into *soft metrology*, it may be important within a project to understand whether the user perceives any differences among a population of surfaces, as well as whether the user can establish a level of acceptance for variation in each design parameter. This could be done using a variation of pairwise comparison called maximum differential scaling, also known as the 'maxdiff variation'. By conducting this type of evaluation, data can be collected more efficiently, and the results are more significant over a given population compared to traditional pairwise comparisons, Paper V (Bergman et al., 2020). The collected data regarding the users' perceived quality could later be compared to an expert panel's assessment of quality and, preferably, also measured data of the same design parameters to establish interesting correlations.

The collected adjectives or descriptive words can also be obtained through focus groups that evaluate existing products. Depending on how a user study protocol is designed, it is possible to obtain the user's initial impression of an interaction with, for example, a specific material. This qualitative data could be useful in comparison with quantitative data at a later stage when analyzing the data. Several questions need to be answered during a user study that involves affective engineering and perceived quality. Questions like, "Do you like it?", "Which one do you like the most?" or "Could you describe the difference?". These questions are all linked to Lawless and Hildegarde (2010) classifications of test methods in the sensory evaluation mentioned earlier.

Figure 50. A 'word cloud' illustration of the response of user comments in combination with Quality Marginal Utility (perceived quality). The word's font size in the figure corresponds to how often the word was mentioned in the study, together with the perceived quality, Paper V (Bergman et al., 2020).

Figure 50 above illustrates a so-called 'word cloud,' where the size and color of the text relate to how participants answered in a user study. The word's font size in the figure corresponds to how often the word was mentioned in the study, together with the perceived quality (Bergman et al., 2020).

Case Specific

In one of the research cases, Paper I, where stainless steel was challenged, the main topical materials for evaluation were glass, spray-painted aluminum, and acrylic plastics (Bergman et al., 2014a), as shown in Paper I. The focus group was introduced to the challenging materials and material evaluation for the first time in a typical environment at the sterilization department of Halmstad hospital. The main topical adjectives for analyzing and evaluating the materials were: *robust, warm, sleek, elegant, resistant,* and *clean*. Figure 51 illustrates how an implementation might look in a typical healthcare environment (Bergman et al., 2014a).

Figure 51. A picture illustrating a focus group in the middle of the implementation of a material evaluation of material and surfaces for the health care environment Paper I (Bergman et al. 2014a).

Further research expanded this case by examining how alternative materials might challenge the long-standing dominance of stainless steel in healthcare environments. This can be further explored in Paper II (Bergman et al., 2014b). Although stainless steel is valued for its technical performance, it also carries strong cultural associations with cleanliness, hygiene, and trust. The follow-up study, therefore, focused on whether new materials, while meeting the necessary cleanability and antibacterial requirements, could also convey similar qualities from a customer acceptance perspective, regarding perceived quality.

The results indicated that materials with equal or better cleanability properties could replace traditional brushed stainless steel, and that an optimized combination of surface design, wiping materials, and cleaning agents can be achieved (Bergman et al., 2014b). The work from Paper I and II demonstrates that experiential and technical qualities can be addressed simultaneously, thereby opening the possibility of reconsidering deeply rooted material choices in medical contexts.

4.5 VALIDITY CHECKPOINT

Paper IV and VI highlights that, when the connection phase is implemented and the data collection of the interaction is established, the correlation between the technical and the emotional functions is of great interest regarding the surface appearance (Bergman et al., 2016; Bergman et al., 2025). The validity checkpoint is essential, as it can reveal information about the properties of the domain that are worth keeping or changing. The primary objective of the validity checkpoint is to identify the underlying data and relationships between the properties and the experience that affect the product's perceived quality. If those properties are located, it will be a lot easier to control the total appearance of the product in the development process (Bergman et al., 2016). With knowledge of how the senses, such as touch and sight, respond to surface properties (i.e., which parameters from the ISO standard affect the surface properties), the surface appearance can be controlled. However, when we refer to control, we mean industry process control, as it is typically the industry that manufactures the pieces. Therefore, the surface properties should also be correlated to relevant process parameters (Bergman et al., 2016; Bergman et al., 2025).

Figure 52 illustrates a project example from Paper V of a parallel plot, explaining the connection between subjective perceived similarity, manufacturing properties, and surface roughness as an example of traceability and correlation. Four injection molded pieces/surfaces (marked as 1 in figure x): L, I, H, and C, which are considered similar from a user perspective, where surface L is the highest ranked surface regarding perceived quality. The Sa (arithmetical mean height) value is one surface roughness parameter among others in ISO 25178-2:2021 that could be linked to the process and perceived quality (Bergman et al., 2020).

The parallel plot reveals several interesting aspects that could be explored further through additional hypotheses and investigation. One way of interpreting the data is that even though the similar surfaces have a comparable *Sa* value and the same texture, they are ranked differently. Given that the manufacturers of these components are equally focused on production quality (i.e., hitting the target), the material selection could have the greatest impact on the perceived quality in this case. Another way to interpret the data is to note that surface “J” has the same material as surface “L” (marked as 2 in Figure 52), but with a different texture and *Sa* value. This implies that a combination of texture and material may affect the perceived quality more than the material alone (Bergman et al., 2020).

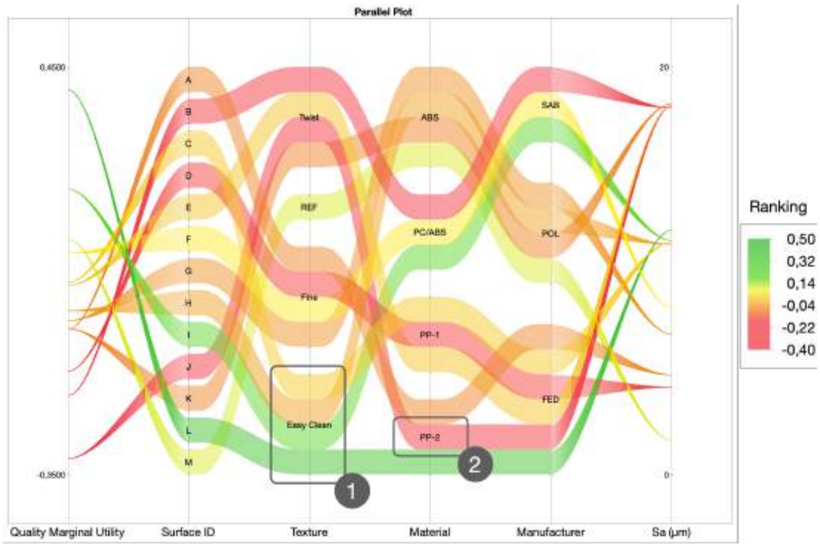

Figure 52. A project example of a parallel plot illustrating the connection of the subjective perceived similarity, manufacturing properties and surface roughness as an example of traceability and correlation Paper V (Bergman et al., 2020).

This is one way to validate key product properties related to customer acceptance. There may be some significant conclusions that will directly impact production properties (Bergman et al., 2020). However, there may also be other hypotheses worth exploring to achieve a higher level of customer satisfaction in relation to the theories of wicked problems.

Furthermore, in the affective surface engineering methodology, a connection is established between Kansei words and surface texture parameters that describe the micro- and nano-topography. Briefly, with knowledge of how the tactile and visual senses respond to surface properties, and further, which parameters from the ISO standard affect these properties, surface design can be controlled within a manufacturing process, as shown in Figure 53 and Paper IV and VI (Bergman et al., 2016; Bergman et al., 2025).

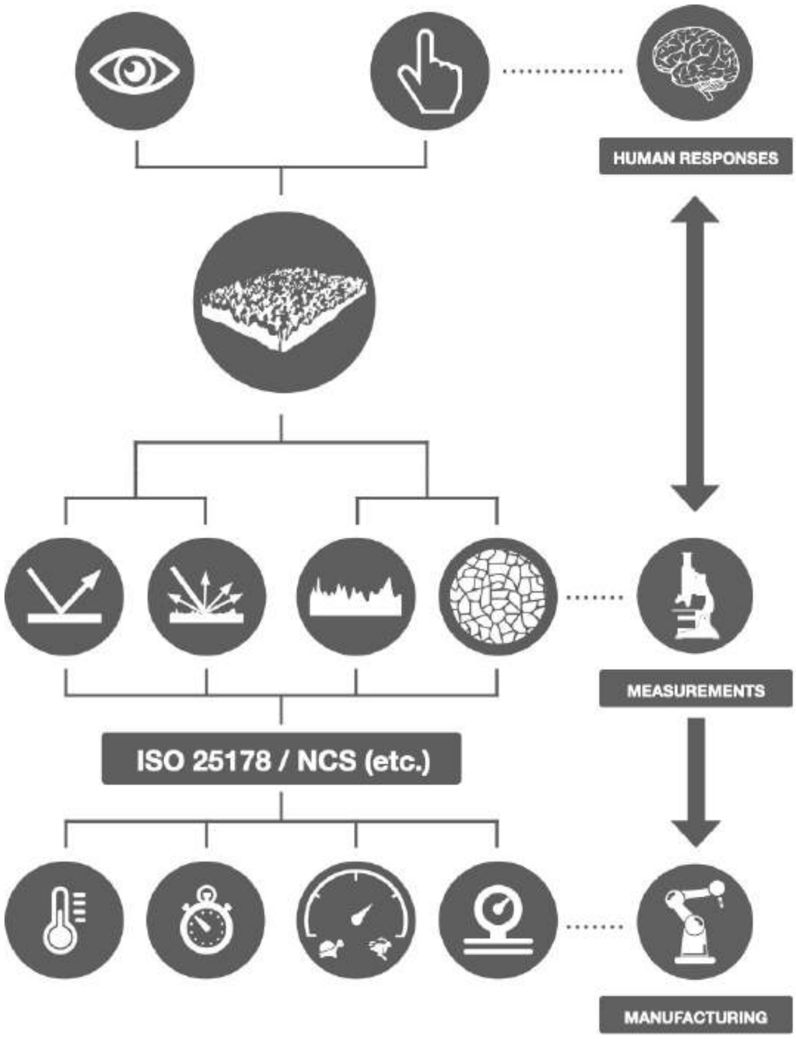

Figure 53. Illustration of the correlation of the soft-, hard metrology and the process parameters Paper VI and VI (Bergman et al., 2016; Bergman et al., 2025). © IOP Publishing. Reproduced with permission. All rights reserved.

Case Specific

In Paper IV, Affective Surface Engineering for Total Appearance - *Soft Metrology for Chrome Surfaces in Car Interior Design* 2016 by (Bergman et al., 2016), the links and correlations between the total appearance and the process window were the main task. It is a good example of when the industry can utilize the developed methodology to achieve robust repeatability in a process, resulting in higher perceived quality regarding the total appearance of a product. The primary finding of this study was the established link between the process parameters and the perceived quality of the topical product, as illustrated in Figure 54. It is essential that the material and surface choices made by, e.g., a color and trim department, are taken seriously. The intended message will change if the manufacturing process is not optimized. The topical company´s sub-supplier needs to know what parameters affect the surface and material negatively, and by that, also know how to implement a robust manufacturing process. Hence, this step is not to question the designer's choice of materials, but to ensure that his intended message is possible to verify and control for repeatability. By examining the correlations between gloss, haze, and color temperature of chrome-plated plastic components, it is possible to establish links between the total appearance, key product properties and eventually, production (Bergman et al., 2016).

Figure 54. A picture illustrating the aim and ideal relationship between process control, material, and surface design in relation to total appearance.

4.6 SYNTHESIS AND MODELING OF THE DOMAIN

The final step in the process is to create a model that combines and describes the results of the previous steps. Hence, to assemble the entire project in this model, a link between the technical functions and the emotional functions must be established. This means that this step does not look the same each time; it all depends on the project's structure and objectives. Creating an approach that links technical functions and emotional functions in general is difficult without reliable connections that provide significant traceability. Consequently, the Affective Engineering approach can be applied in many contexts and projects. Therefore, tailor-made relationships are developed for the topical project.

A study presented in Paper II examines the correlation between the cleanability of materials and user experience in healthcare product design of a sterilizer

(Figure 55); it also illustrates an example of a future product based on the results (Bergman et al., 2014b). Ultimately, the study concludes that glass, spray-painted aluminium, and acrylic plastic are viable or superior alternatives to traditional stainless steel in some healthcare environments. They provide not only clean surfaces but also improved emotional and experiential qualities. Surface roughness analysis confirms that all materials meet the technical requirement of Sa < 0.8 μm, and smoother surfaces (lower Sa-values) generally correlate with better cleanability. Sa is proposed as a suitable design parameter because of its industrial familiarity and relevance to cleanability research (Bergman et al., 2014b).

Figure 55. Illustration of the existing sterilizer (left), and a visionary product (right), (Bergman et al., 2014b).

In another project, Paper VI, a car manufacturer evaluated gloss and its impact on users. The goal was to identify key surface characteristics that influence gloss and to correlate these characteristics with production properties, investigating how these surface characteristics challenge the current specification. It was found that different manufacturing properties can influence the final appearance, particularly in terms of gloss. For example, mold temperature and flow front speed significantly impact surface gloss. However, several factors could also impact gloss:

- The holding pressure strongly influences the ISO 25178-2:2021 hybrid parameters, *Sdq* (Root mean square gradient).
- The tool temperature is found to have a stronger influence on the surface topography represented by the ISO 25178-2:2021 spatial parameters, *Sal.*
- The injection speed has a significant effect on the ISO 25178-2:2021 density of peaks, *Spd* (Density of peaks).

Yet, parameters such as *Sdq* have negative correlations with measured gloss, while *Sal* has a positive correlation. The diagrams in Figure 56 illustrate this relationship between the Gloss Unit and the parameters *Sdq* and *Sal* (Bergman et al., 2025).

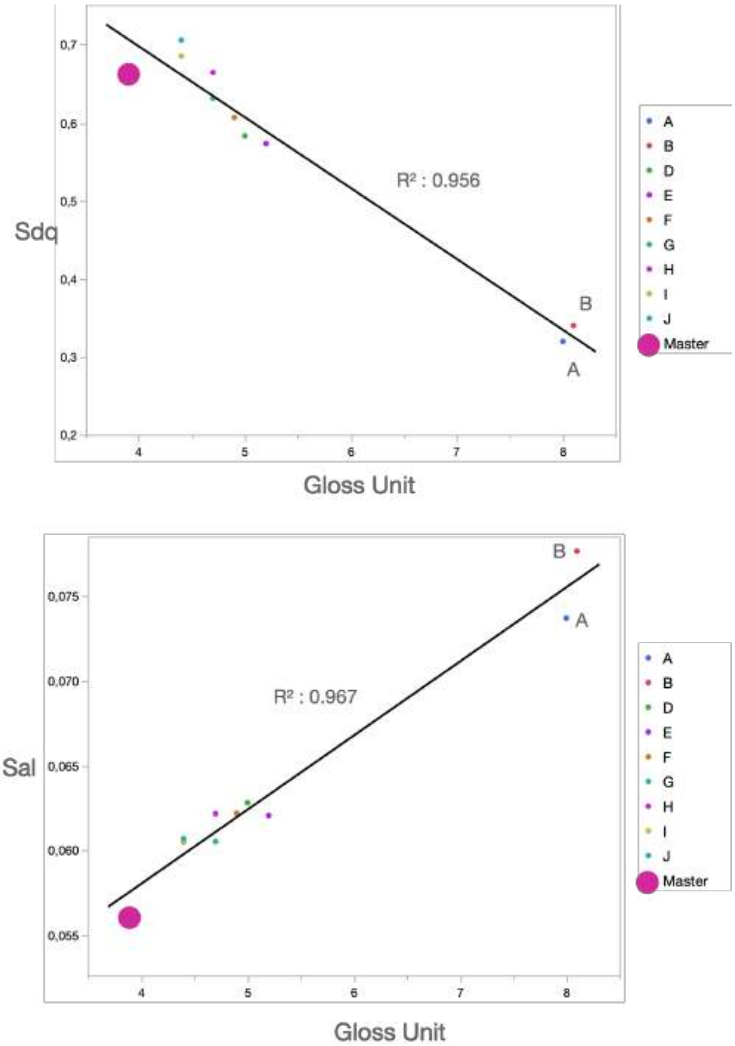

Figure 56. Two diagrams illustrating the relationship and R2 value between the Sdq value vs. gloss (top) and the Sal value vs. gloss (bottom), for all the samples Paper VI (Bergman, 2025).

The study from Paper VI indicates a potential gap between experts and consumers in detecting surface variations (Figure 57). Green areas show delta values considered “acceptable” by both groups, yellow “borderline,” and red “unacceptable.” The “safety window” highlights the gap, which could serve as a margin for perceived quality, but can it be adjusted? Experts detect variations within narrow delta ranges, while less experienced users perceive a wider range. This suggests that future specifications might leverage the safety window to allow surface properties that do not affect consumer-perceived quality (Bergman et al., 2025).

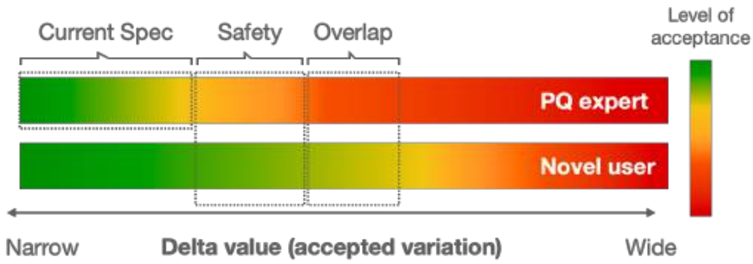

Figure 57. An illustration of how a specification could link to the variation of surface delta value and the level of expertise in assessing the surface appearance. Paper VI (Bergman, 2025).

In other cases, there is a need to quantitatively formulate models that describe the relationship between design elements and the desired soft metrology, serving as a complement to the design manuals with qualitative designer rules. In a previous study, Paper III, by Rosén et al. (2015) about the haptic appearance of tissue paper, a complex model was created using eight constants (A–H), three material properties (layer type (DL), stiffness, elasticity (stretch)) and four areal ISO 25178 surface texture properties (peak material volume (Vmp), core height (Sk), maximum height (amplitude, Sz), autocorrelation length (repeating wave length, (Sal)) (Rosén et al., 2015).

$$
\begin{aligned}
&\text{'perceived haptic roughness'} = A - B*DL \\
&+ C*Vmp + D*Sal + E*Sk \\
&+ F*stiffness - G*stretch - H*Sz
\end{aligned}
$$

In the equation above, the product design properties DL, Sz, and stretch have a negative regression coefficient sign (-), showing that an increase in the parameter value results in a decrease in perceived haptic roughness. The coefficients for Vmp, Sk and Sal were positive (+), hence positively correlated with increased (improved) perceived haptic roughness, i.e. increased texture peak material volume, core height, autocorrelation length and reduced maximum texture height improve the stakeholder's haptic perception of tissue products within the context of the performed study (Rosén et al., 2015).The designer rules and the equation above are examples where affective engineering and soft metrology results are synthesized into tools able to predict customer perception and aspects of total experience supporting organizations' possibilities to maintain customer focus and competitive improvements (Rosén et al., 2015).

4.7 META VALUE – A COMBINED RESULT

One parameter that was not initially expected, however, became more apparent in tandem with the increasing number of research projects implemented: the 'meta value' of the work. The 'meta value' is a long-term result that slowly emerges in the actual implementation industry. The 'meta value' could include several factors; however, in topical research projects, it typically relates to the maturation phase of implementation.

This phenomenon could be equated to implementing a design or innovation process within an organization. One example is the so-called 'design ladder'

(Figure 58, used by The Danish Design Center – DDC[1]), which is a model that illustrates how companies or organizations utilize design at different stages of development. It's often structured like a staircase with several steps, where each step represents a higher level of awareness and strategic use of design.

1. No design – Design is not used at all or only unconsciously.
2. Design as styling – Design is primarily used to give products a visually appealing appearance.
3. Design as a process – Design is integrated into the development work and used to improve function, usability, and user experience.
4. Design as a strategy – Design is an integral part of business strategy, used to drive innovation, differentiation, and business value.

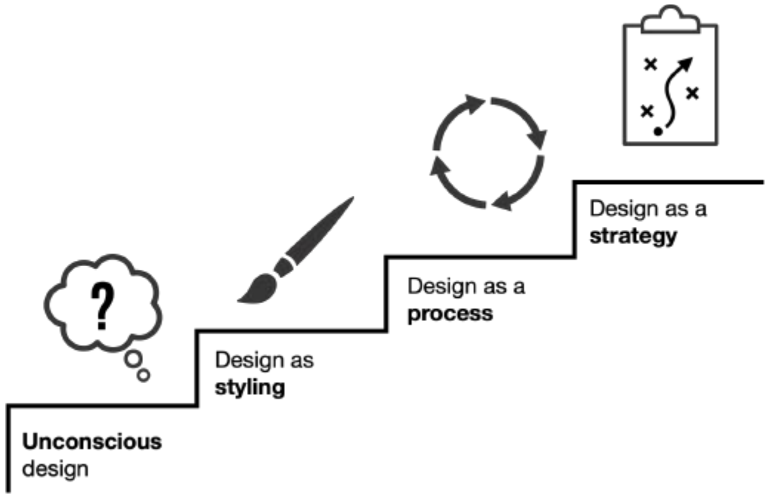

Figure 58. A picture illustrating the design ladder.

The model can be used to analyze where a company is currently positioned and what is needed to take the next step in its use of design.

The hypothesis regarding the implementation of quality tools (such as KE) follows a similar structure. However, research projects can typically serve as a catalyst for a company, where the results are initially owned by, e.g., an R&D department, which in turn can influence how quality work is implemented more broadly. Preferably, the project evolves from being just an R&D project to a strategic quality tool for the company, leading to the creation of production, such as increased employee engagement regarding the quality of components.

Similar to implementing other quality tools, such as Six Sigma, TQM and ISO 9001, workers in the production historically feel their knowledge matters if they're included in quality initiatives. Employees tend to gain a sense of ownership and pride in the quality outcomes. This culture has proven to be a key factor in achieving sustainable and robust production. Stankalla, et al. (2018) found in their research that top management commitment is the most essential critical success factor for implementing initiatives such as Six Sigma in manufacturing SMEs. This is followed by other key factors, including linking Six Sigma to the customer, aligning it with business strategy,

[1] DDC – 'The Danish Design Center', est. 1978

establishing a clear communication plan, and ensuring a supportive organizational infrastructure. The findings in this thesis do not confirm that this might be the case for KE. However, it strongly implies that implementing a strategy for controlling total appearance and perceived quality within an industry requires some supportive culture beyond the concerned team to make an impact over time.

5 CONCLUSION, DISCUSSION AND META CONCLUSION

The concluding chapter is divided into a number of sub-sections: firstly, a conclusion about the research result and the synthesis; secondly, the novelty and value of the research result; and lastly, the outlook for future work.

5.1 RESEARCH CONCLUSION

I would like to begin this section by focusing on the three research questions and the needs presented at the beginning of the thesis, as well as the objectives.

First of all, the research questions;

1.
"How should the knowledge of perceived quality be used to control the material and surface appearance in production?"

This is discussed in papers I and IV. The surface appearance stimulates customers' sensation and perception, ultimately influencing the perceived quality, which determines whether we, as receivers, will like what we experience or not. Knowledge about the perceived quality of a certain something would be more or less worthless if it were not converted into process parameters that control production. On the other hand, it would be difficult to adjust process parameters to achieve a quality product if you don't know what you are looking for within perceived quality, as shown in Figure 59. It might appear to be an infinite loop of optimization, regardless of where you start. However, the knowledge of perceived quality should be taken into account when specifying process parameters within production.

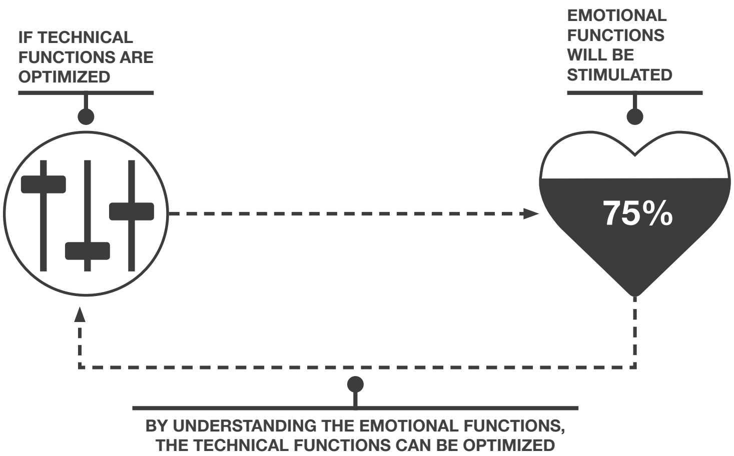

Figure 59. Illustration of the synthesis loop in regard to the technical and the emotional functions.

2.
"How can the Kansei Engineering methodology be helpful to link customer acceptance with production specifications?"

This is discussed in papers II and III. Through the KE framework, combined with traditional design methodologies, a link can be established between customer acceptance and robust production. Tools like the 'Equalizer' facilitate the understanding of customer acceptance, while also allowing critical design parameters to be specified. This knowledge combination could be the foundation of a product specification, easy to quantify, control and adjust.

3.
"How can 'hard metrology' be used as a tool to understand surface appearance?"

This is discussed in papers V and VI. To understand why different surface appearances affect customers' perceived quality differently, we need a comprehensive view of appearance in general. Appearance changes in tandem with changes in design parameters, such as form, color, material, surface texture, gloss, etc. We do know that we may find different surface appearances in an injection-molded plastic component, for example, if the holding pressure changes or if a different polymer is used for the same component. This acknowledges that we can measure these kinds of variations and assign a value to the parameter. The fact that we can quantify variations in the surface's appearance, caused by production variation, suggests that we could also change the surface appearance in a controlled way, if we understand why a certain parameter changes in production, e.g., adjusting the holding pressure to achieve the expected surface appearance. Figure 60 is taken from a project where plastic components for car interior design were evaluated (Paper V).

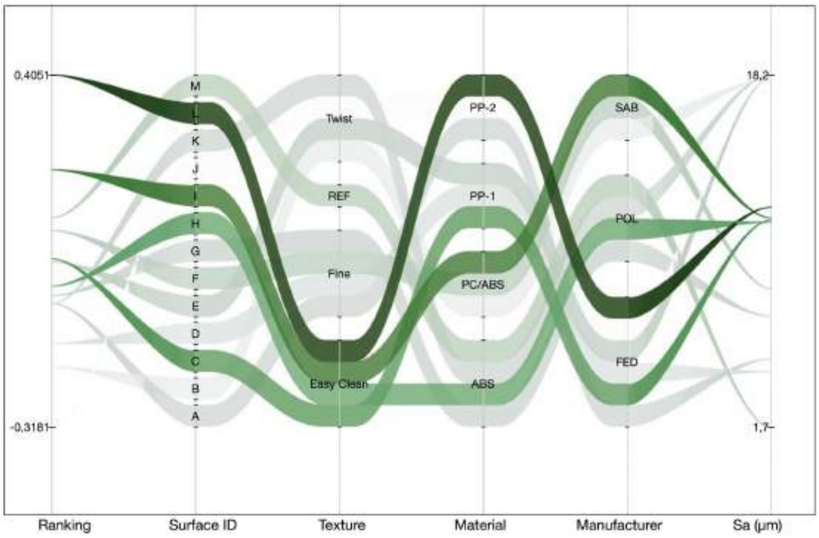

Figure 60. Illustration of the connection between the subjective perceived similarity and manufacturing properties and surface roughness as an example of traceability and correlation. © IOP Publishing. Reproduced with permission. All rights reserved.

This is a good example where the ranking (perceived quality) of the component was linked to texture, material, and also the surface parameter 'Sa'. This link, together with other surface parameters from ISO 25178-2:2021, provided the team with a clue about how to frame the perceived quality of components in the project.

The link from customer acceptance (perceived quality or human response) to production is a combination of a structured framework, together with comprehensive tools. Figure 61 below illustrates the link between human responses to manufacturing, where different steps are required to achieve a significant correlation.

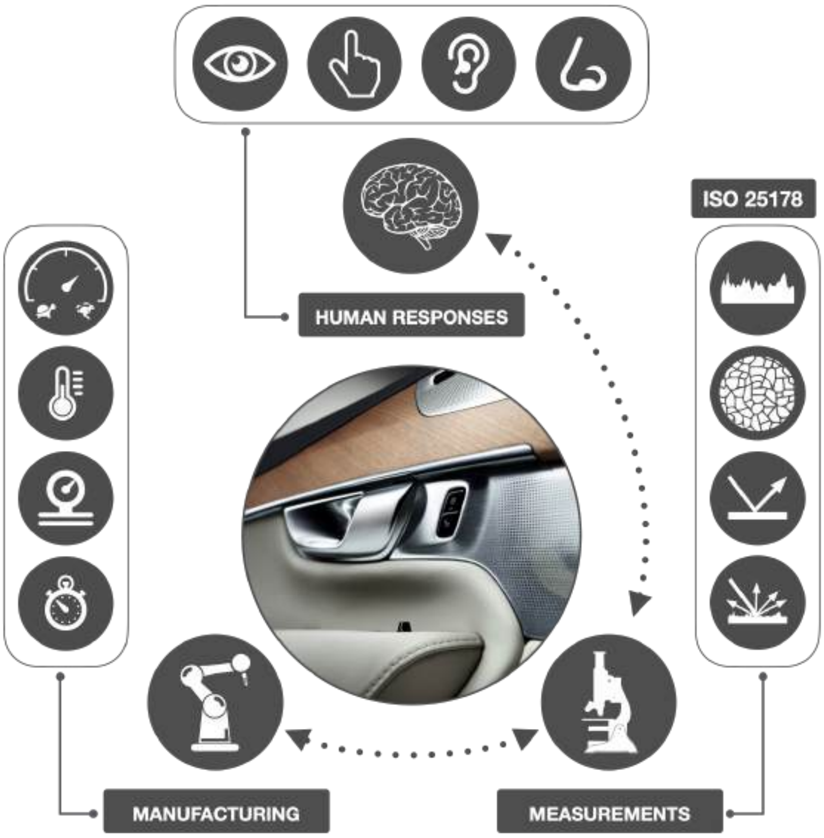

Figure 61. Illustration of the correlation of the soft-, hard metrology, and the process parameters.

Certain manufacturing properties, e.g., holding pressure, can alter the appearance, which in turn impacts human response and perceived quality. This will be traceable through customer reviews, user studies, and measurements, and further on linked to standards and back to production. The loop is closed.

The identified needs

- The need for increased transdisciplinary collaboration between industrial design and engineering design activities for a holistic approach**.**

Regarding different approaches within design, it is clear that we need a holistic approach to cover the variety of focuses on development projects. Diversity in a project group with different approaches is usually needed. However, it is of great interest and importance to utilize the variety of professions effectively to achieve a novel and robust development process. From personal experience within the industry, transdisciplinary teams (so-called T-shaped teams) work more effectively within the innovation process compared to more homogenous teams with, e.g., a design background only. Research supports this matter as well (Brown, 2009).

- The need to understand perceived quality from a sustainability perspective

Perceived quality of products has always been important. The idea of appealing products is not a new thing at all! However, what could be considered fairly new is how the industry tends to work with it. Traditionally, within the artistic and industrial design society, the *'perception of things'* is a natural part of the education and occupation, and could eventually be considered as tacit knowledge. However, the way of measuring *'sensation & perception'*, and creating traceability from perceived quality to production, is a separate thing. Now, combining the knowledge of perceived quality and the knowledge of sustainability creates a new dimension of wicked problems. Sustainability, as well as perceived quality, change in tandem with time as well as with each other. Today, sustainability is a driving force and a success factor for companies, reaching for global goals and the 'trust capital' of customers. However, the green transition is challenging a lot of the ways we have been manufacturing products. This fact should be taken into account when evaluating the total appearance and customer acceptance of future products.

- The vision of implementing a methodology regarding challenges in perceived quality and total appearance of materials and surfaces in the industry

The 'owners' of the matter of perceived quality within the manufacturing industry are usually a R&D department or similar, and the education level is usually a 'bachelor's degree' or higher. However, finding people with the competence, knowledge, and understanding of perceived quality is challenging. Implementing a methodology and creating a culture that controls total appearance and perceived quality is not only a matter of well-thought-out teams, such as T-shaped teams, but also a matter of management and conscious decision-making, as exemplified by the principles of DDC's 'design ladder' above.

- The need for a consensus regarding sustainability vs future trends and the control of perceived quality

There is an urgent need to reach a consensus on how to balance sustainability with rapidly evolving future trends, especially regarding our definitions and management of total appearance and perceived quality. For instance, the concepts of 'minimalism and dematerialization' contrast with 'traditional cues of quality,' where the trend favors designing products with fewer materials and simpler forms to reduce environmental impact. One concern regarding this statement is that consumers often equate, e.g., weight, density, and complexity with high quality. A lightweight, minimal product might be viewed as 'cheap,' even if it is more sustainable. For example, a solid metal/glass phone, which feels premium, may be favored over a biodegradable plastic one, despite the latter being more eco-friendly.

Thesis work objectives

- Study the influence of material/surface properties regarding total appearance, perceived quality, and customer acceptance.

This objective has proven to be both relevant and challenging, particularly because it is an interconnected issue of technology, design, and user perception. Throughout the research work, it became clear that material and surface properties are challenged by being evaluated in isolation; their influence on appearance and perceived quality is strongly dependent on context, user expectations, and even cultural or situational factors.

One key insight is that total appearance is more than the sum of measurable surface parameters (e.g., as defined in ISO 25178). While these technical descriptors provide an important foundation, they only partly predict how users interpret quality. The subjective dimension, which encompasses how smoothness, gloss, reflectance, temperature, and even sound contribute to the overall perceived quality, plays an equally critical role. This underlines the need to balance quantitative measurement with qualitative investigation, including perceptual studies and user feedback.

A key insight was that customer acceptance depends on how well material and surface qualities align with expectations for a specific product or context. Even high-quality surfaces can be perceived negatively if they feel inappropriate or inconsistent with the intended user experience.

Finally, the work reinforced the understanding that material/surface influence are essential early in the design process. Poor alignment, such as unnoticed wear patterns, unexpected gloss changes, or texture incongruities, can significantly undermine product perception later on.

- Study the sensation and perception of materials and surfaces, focusing primarily on visual stimuli.

This objective highlights the significant impact of visual cues on users' initial impressions of materials and surfaces. Sensation involves the raw visual information of color, gloss, texture, and pattern. Perception depends on how users interpret these cues, based on their expectations, previous experiences, and the context. This means that visual appearance alone can strongly influence judgments of quality, function, and even emotional response.

A key insight was that subtle visual variations, such as minor changes in roughness or reflectance, can significantly alter how a surface is perceived, even before users physically interact with it. This highlights the importance of understanding not only what a material is, but also how it is perceived.

Overall, the work reinforced the need to integrate knowledge from visual perception with material design choices to better predict how users will interpret surfaces and form opinions about product quality.

- Investigate the correlation of perceived quality and sustainability with sensation and perception in mind.

This objective exposed that perceived quality and sustainability are closely linked through how users sense and interpret materials. Visual cues strongly influence whether a product is judged as durable, trustworthy, or environmentally responsible. However, sustainable materials do not always appear sustainable or high-quality to users, which can create tension between actual performance and the perceived quality.

A key insight was that users often rely on familiar cues, such as surface finish, color, or material weight, to understand the sustainability, even when those cues may not reflect the true environmental impact. This demonstrates that sustainable design must consider not only material choices, but also how those choices are conveyed through the total appearance.

- Create a model for designing and analyzing materials and surfaces with regard to points 1-3.

This objective was a true inspiration and a key trigger for further developing the methodology presented in this thesis. One aspect was to understand the sensorial attributes on a more detailed level than before; however, it also involved digging deeper into how human perception works and triggers various behaviors. Combining this knowledge with current technology in hard metrology and ISO standards was a key aspect of the research work.

- Analyze how the product realization process relates to the perceived quality of sustainable materials and surface selections.

This objective highlighted that perceived quality is not determined only by the final material or surface choice, but by decisions made throughout the entire product realization process. Early choices, such as supplier selection, manufacturing methods, and surface treatment options, significantly influence how sustainable materials will appear and be perceived by users. Even small process variations can influence gloss and color consistency, as well as texture, which in turn affect the perceived quality.

A key insight, or clue, that could be important within future projects is that sustainable materials often require more careful process planning because they may behave differently during production, finishing, or even aging. What may work in a research lab may not work when scaling up the production. Hence, if these factors are not understood and controlled, the final appearance can conflict with user expectations and undermine both the perceived quality and customer acceptance.

Thesis work reflection

A product's technical functions should be developed and optimized to meet users' expectations about the product while also supporting its 'total appearance'. When mentioning 'total appearance', the primary definition refers to the experience of physical attributes and the aesthetics of the product. It is essential to manage the total appearance; therefore, products have requirements for both emotional and technical functions, as both play a central role in the product experience.

In this thesis, the influence of material and surface properties on total appearance and experience has been the focus. Regarding the results, it is clear that surface design matters. The understanding that a manufactured piece from the industry can be experienced differently based on surface quality must be addressed professionally and not overlooked. Even the slightest variation in surface appearance on a plastic component in a car interior, for example, could lead to a negative user experience. The technical functions are directly correlated to and impact the sensorial and perceptual systems, which in turn affect emotional responses. Although different properties of surface design relate to various appearance parameters, this must be handled with great precision, as the sensorial systems are extremely sensitive. If the sensorial system picks up signals that interfere with the product's original message, the cognitive message could fail, resulting in a negative product experience.

The synthesis of this matter is essentially this: by understanding the user and the needs of the emotional functions, we can optimize the technical functions, as shown in Figure 59 above. Therefore, if we can adjust the critical parameters that affect emotional functions, we can control a product's total appearance.

There is a major difference between controlling the total appearance of a product and measuring the experience it provides. While we may not be able to fully 'control' the experience due to its highly subjective nature, we can influence it by understanding how to manage the total appearance. Essentially, by enhancing the conditions under which users interact with the product, we can positively impact their experience.

However, how should designers (industrial, product, and engineering) adapt to this reality, and how can they collaborate not only with each other but also with the process technicians on the manufacturing floor producing those pieces? What do the different professions require in order to translate their respective properties of interest into actionable inputs for a successful manufacturing process while preserving the total appearance? First of all, we as designers need to soften our pride regarding our topic and accept that our approaches are different, and our focuses will differ as well. We should effectively use each other's differences by converting soft metrology to hard metrology and vice versa. This could be achieved through a methodology that encourages participants to implement 'design thinking' and 'design doing' outside of their comfort zone. Secondly, it is crucial to understand the connections between soft metrology, hard metrology, and manufacturing processes. If everyone involved in a process could agree that various treatments applied to a manufactured plastic piece, for instance, could alter the surface design parameters (and thereby influence the total appearance), we could effectively explore these connections. One phase of the methodology focuses on optimizing surface parameters according to ISO 25178-2:2021, which acknowledges that the relationship between surface design and process control has been established. The big question now revolves around repeatability and how to verify the total appearance in something like an 'in-line control station.'

The developed methodology for 'affective surface design' is working as intended; however, the content and implementation will always be project-specific and will yield unique results. The structure of the methodology requires awareness of both technical and emotional functions, as well as how to approach the implementation of combining them in an effective way.

5.2 NOVELTY AND VALUE OF RESEARCH RESULTS

The discussion about novelty and the value of the research is partly dependent on time and trends in the topical research field. The evaluation should be viewed as a continuous, ongoing process, both in terms of time and trends, throughout the research and future work. Implementing research without regularly reflecting on its significance, novelty, and value for stakeholders would be akin to navigating blindfolded. Questions as; "Where did I start my research, what is my current position, in which direction am I heading, and what obstacles will I face?" are important to be able to evaluate if the research is (or is not) novel and valuable.

One of the research objectives was to "create a model for designing and analyzing materials and surfaces in regard to emotional- and technical functions". Since there were a limited number of existing methodologies, methods, or models in that area when my research was initiated, and parts of the industry had expressed a need for framing experiences and perceived quality and linking it to production, I aimed to develop a methodology and framework in this topical area.

The results of the research carried out to this point have been implemented with the objective of developing a methodology and toolbox based on 'Kansei Engineering', an acknowledged approach that has been proven effective. In the initial research work (around 2011), there was a handful of researchers and companies worldwide (e.g., Mazda, Honda, and Sony) that continuously worked with Kansei Engineering in the field of product development as a leading strategy, and even fewer who have developed it further for a topical research field such as 'surface design'. With that in mind, the research work and the developed methodology presented in this thesis can be considered novel and a significant contribution to the market. The developed methodology, in light of the discussion above, could also be considered valuable in future development projects, as it offers a new approach to addressing the issue.

Contribution to the field of 'Mechanical Engineering'

The research extends the field of mechanical engineering by advancing the understanding and quantification of surface texture as a bridge between material processing and functional performance. By applying ISO 25178-2:2021 parameters and statistical methods to identify functionally significant surface features, the work enables engineers to move beyond average roughness (Ra-value) indicators toward a multi-dimensional understanding of surfaces. This contributes to a more predictive and knowledge-based approach to surface engineering, where surface function (e.g., friction, gloss, or wettability) can be linked directly to manufacturing parameters. The work also strengthens the theoretical basis for functional surface optimization, enabling engineers to tailor surface properties to their intended use and environmental conditions, a vital step toward achieving high-precision, sustainable, and robust manufacturing.

Contribution to the field of 'Product Design'
In product design, research makes a distinctive contribution by integrating the user's perceptual and emotional experience with the technical attributes of materials and surfaces. The research position perceived quality not only as an afterthought, but also as a quantifiable design parameter that, in an early stage, can be specified, measured, and communicated across disciplines. The connection between soft and hard metrology enables designers to translate abstract intentions, such as "refined," "durable," or "premium", into measurable surface parameters. By developing a transdisciplinary framework that connects engineering analysis with design intention, the research work provides a foundation for experience-driven design that remains technically robust throughout the production process.

Contribution to the field of 'Manufacturing'
For the manufacturing industry, research provides tools and methodologies for robust and perceptually aligned production systems. Through surface characterization and optimization methods, the research provides an approach to link process parameters to both functional and aesthetic outcomes, thereby bridging the gap between design and manufacturing. The outcomes support data-driven decision-making, facilitate process stability, and contribute to the creation of products with high customer acceptance. Furthermore, research work makes a strategic contribution to sustainable production development by demonstrating how precision in surface design and control can reduce waste, enhance durability, and align production with long-term quality and circularity objectives. In doing so, it also strengthens the industry's readiness for e.g., AI- and automation-based quality assurance systems in the future.

From a sustainability perspective, the research also supports the development of more resource-efficient material and process alternatives. An improved understanding of surface performance enables the use of options with lower environmental impact, reduced chemical consumption during processes such as cleaning, and longer product lifetimes. By promoting surfaces that are easier to maintain and more durable, the work aligns manufacturing with circularity principles, contributing to reduced waste and lower energy use throughout the product lifecycle.

5.3 OUTLOOK

To date, the research results and the developed methodology are based on findings from case studies conducted in collaboration with the industry over a 15-year period. However, the final step is to make the methodology independent of me as an 'expert' in the implementation, and make it work in tandem with established frameworks and culture. The aim is to introduce the methodology in a workflow introduction, so the topical company can later prosecute the implementation on their own towards their internal objectives. To achieve this goal, there may be a need for industrial standards (e.g., ISO or similar) for perceived quality regarding material and surface appearance. However, we have also developed tools, such as ‘objective inline control’ of surface properties, linked to established standards like ISO 25178-2:2021. However, accurate predictive models regarding surface characterization linked to ‘perceived quality’ might also be needed to speed up the process, perhaps by means of AI machine learning. Figure 62 illustrates a schematic view of visionary planning to reach long-term goals.

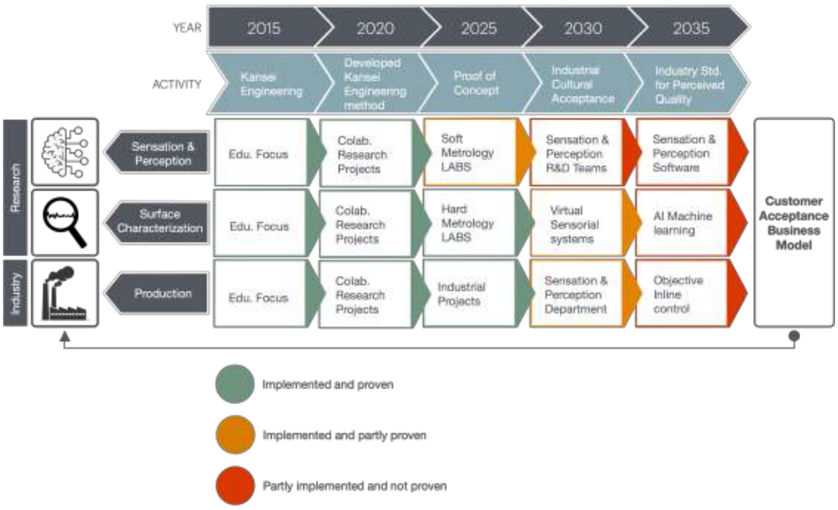

Figure 62. A schematic illustration of the research planning, what has been implemented, and what could be considered as a long-term goal.

To achieve these goals, a hybrid approach combining surface characterization, perceived quality, customer acceptance, and innovation management may be necessary.

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