UNIVERSIDADE DE LISBOA

INSTITUTO SUPERIOR TÉCNICO

An approach to identify the appropriate design requirements and specifications to define the target percept of an in-car interface: Case of Non-Visual Senses

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Abstract

An in-car interface is not limited to its utility, but has a broader scope that includes the need to address a desired feeling. Until now, after the selection of the desired feeling to be addressed, automotive companies (AC) “translate” it into a set of engineering parameters which is delivered as design requirements to the design process. Although supplier companies responsible for the design and manufacturing of the interfaces, are able to meet the design requirements, the percept may not be the one desired by the AC. This disparity is a result of an ill-defined nature of the problem. The current study explores how to define the percept of an in-car interface (ICI) push button, by integrating the kinesthetic and acoustic senses. Results indicate that the AC delivered design requirements are not enough to define the percept and that percept should be defined as an integration of acoustic and kinesthetic related engineering parameters, in order to be used as requirements in the design process. The contribution of each design requirement together with the interaction among them over the target percept of an in-car interface’s push button is assessed. Moreover, the proposed research framework focuses on the impact of the design on the percept, in order to adjust the percept through the design. Under that scope, the most critical design specifications were selected and through a designed experiment their impact on the acoustic and kinesthetic related design requirements was investigated. The results of the current study offers a valid tool for the design process of the ICI, to achieve the target percept, related to non-visual senses, as requested by the AC.

Keywords: Emotional Design; Human Machine Interaction; In Car Interfaces; Non Visual Senses Integration; Push Button Percept; Robust Design Methodology; System Analysis.

Resumo

Um interface num automóvel não está limitado à sua utilidade, mas antes tem um âmbito mais vasto que inclui a necessidade de responder a uma sensação desejada. Até agora as companhias automóveis (Automotive Company - AC) após a selecção da sensação que querem transmitir, "traduzem" a sensação desejada num conjunto de parâmetros de engenharia que são traduzidos como requisitos de modo a "transportar" essa sensação ao processo de fabrico. Apesar dos fornecedores automóveis conseguirem cumprir os requisitos, a percepção pode não ser aquela que as ACs pretendem. A disparidade resulta dum problema mal definido. O presente estudo explora num primeiro passo como definir a percepção correspondente a um botão duma interface automóvel (In-Car Interface–ICI), através da integração dos sentidos cinestésico e acústico. Os resultados indicam que os parâmetros de engenharia ''traduzidos'' em requisitos não são suficientes para definir a percepção e a percepção deve ser definida como uma integração de parâmetros de engenharia relacionados com valências acústicas e cinestéticas. Foi avaliada a contribuição de cada parâmetro juntamente com a interacção entre eles e a percepção alvo dum botão de premir duma interface automóvel (ICI). Numa segunda fase do estudo proposto vai ser estudado o impacto sobre a percepção de modo a ´´prever'' a percepção através das variáveis de projecto. Em primeiro lugar foram seleccionados os parâmetros mais críticos e posteriormente, através de uma experiência especificamente concebida, foi identificado o impacto sobre os parâmetros de engenharia relacionados com a acústica e cinestésica cinestesia que afectam a percepção. Os resultados do presente estudo oferecem uma ferramenta válida para fabricantes de ICIs para conseguirem ''prever'' a percepção alvo, relacionada com sentidos não visuais, tal como requerida pelas ACs.

Keywords: Analise de Sistemas; Integração de Sentidos Não Visuais; Interacção Homem-Máquina; Interface no Automóvel; Metodologia de Desenho Robusta; Percepção de Botão de Premir; Projecto Emocional

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SYMBOLS

dB	-	Decibel
Hz		Hertz
mm	-	Millimeter
N	-	Newton

ABBREVIATIONS

A	-	Acoustic related engineering parameters
AC	-	Automotive Company
AL		Actuator Length
ANC	-	Active Noise Control
ASTM	-	American Society for Testing and Materials
BIC	-	Best In Class
CG		Central Guide
CV	-	Coefficient of Variation
DAN	-	Dynamic Associative Network
DOE		Design of Experiments
DoF	-	Degrees of Freedom
DR	-	Distance to Release
DS	-	Distance to Stroke
FS	-	Force to Stroke
GG	-	Gap of the guides
HDD		Hard disk drive
HMI	-	Human Machine Interface
ICI	-	In-Car Interfaces
K	-	Kinesthetic related engineering parameters
LDA	-	Linear Discriminant Analysis
LG		Length of the Guide
LGL		Lateral Guide Left

LGR		Lateral Guide Right
LL		Loudness Level [Phon]
Lub		Lubrication
MI	-	Modality Identification
N	-	Loudness
NHRA	-	Noise-to-harmonic energy ratio
NQI	-	Noise Quality Index
p	-	Percept
PCB	-	Printed Circuit Board
PI		preference index
PL	-	Pre Load
PLL	-	Pre Load Length
r.p.m.	-	Rounds Per Minute
RDM	-	Robust Design Methodology
RE	-	Requirements Engineering
SA	-	Snap Action
SC	-	Spectral Centroid
SCN	-	Spectral center of gravity of the noise
SL	-	Slope of the force/displacement curve
SPL	-	Sound Pressure Level
SPL(A)	-	Sound Pressure Level A-weighted
SQ	-	Sound Quality
STFT	-	Short-Time Fourier Transform

TERMS & DEFINITIONS

Behavior or Performance corresponds to the physical performance.

Design parameters are the parameters that define the design.

Design specifications are the design parameters with impact over the design specifications

Design requirements are the engineering parameters that define the wanted performance

Distance to Release is the distance that the button has to run, from its initial position until it reaches the de-activation point.

Distance to Stroke is the length of the distance which the button has to run, from the initial position until it reaches the stroke, which is equal to the make distance and key travel.

Engineering parameters are all the physical parameters that typify how an interface performs (behavior).

Force to Stroke is the needed force which has to be applied, in order to activate the button's function (to reach the stroke), which is equal to the make and activation force.

Over travel is considered the distance between the stroke till the total travel.

Peak force is considered the maximum force that could be applied till the button stop moving, at the total travel.

1. INTRODUCTION

1.1 Overview

Cars are more than a product; they are symbols. Cars do not only fulfill the basic need of transportation, but, they are far beyond that. When the auto-mobile was introduced to the market, it brought with it a core benefit: its technical function, as valuable means of transportation (Karlsson, Aronsson et al. 2003). Nowadays, the role of “feelings” has become a major competitive factor in the automotive industry, as automobiles include cognitive and emotional aspects and arouse emotions and feelings (Desmet 2002, Norman 2004, Hekkert and Schifferstein 2007). Current demand for pleasure features triggered the evolution of design requirements from merely meeting functional aspects to emotional ones. Once issues such as utility, safety and comfort have been satisfied, the emphasis shifts towards the decorative, emotional and symbolic attributes of design (Crilly, Moultrie et al. 2004). The phase where a product should mainly fulfill ergonomic related design requirements such as usability has evolved to the concept of emotional design (Spielholz, Bao et al. 2001), that is, design with an emphasis on the emotional impact on users (Demir and Desmet 2009). Thus, aesthetics and design are decisive buy-arguments in markets in which the technical level of competing products is very similar (Demirbilek and Sener 2003). As a result, the design of pleasurable products is beginning to take center stage, as firms struggle to gain competitive advantages (Oh and Khong 2003). According to Walter and Spool (2011), to engage users emotionally, you must let your brand’s personality show and emotional design is the way to turn casual users

into fanatics, ready to tell others about their positive experience. This trend is more than obvious in the automotive industry and can be seen in current advertising slogans, like “ENJOYNEERING” from SEAT, which combine the words enjoy and engineering, or “motion and emotion” by Peugeot. The car as a symbol that carries all the values of the automotive company should express it in every sense. Consequently each Automotive Company (AC) targets a specific feeling that represents the core values of its brand (Lindstrom 2005). To trigger that specified feeling, ACs are moving forward to define the appropriate percept, by defining the corresponding design requirements and afterwards to pass to the design process, by defining the appropriate design specifications.

The car as a system consists of all its sub-systems and interactions among them. This system and its sub-systems should be shaped in such way as to emote consistently a specific feeling in the user: the one previously defined by the AC. The way a headlight switch looks, feels and sounds inside an automobile, for example, influences humans perception not only of the quality of the switch itself but also of the automobile as a whole (Hong 2008). Therefore all interior and exterior components of a car should follow specific design guidelines to achieve the appropriate percept and consequently trigger the appropriate feeling in the user. For this reason, ACs start by defining a target percept that carries the core brand’s values and character, followed by the generation of the set of design requirements which will shape the product in the desired way. These two phases are termed as emotion design and emotional design respectively. According to Ho and Siu (2009), the former is the design that contains the emotional concerns identified through interactions between the designers and the users and related to the latter can be viewed as the design that can motivate users/consumers’ emotion. The current study focuses on the second one, the

emotional design. At this point it should be noted that how human perception works and feelings are triggered or how ACs select a feeling (emotion design) is not analyzed, but what is focused on is rather how to design a product in order to achieve a percept that will arouse this particular feeling i.e. emotional design.

The interior of a car plays a vital role in triggering feelings; the importance of interiors can be highlighted by observing the latest car upgrades of some well-known brands, in which the changes are mainly cosmetic and mostly confined to the interiors. This fact is more than clear in several car brand advertisements, where the interior plays the central role. Car manufacturers are highly investing in research and development to improve the interiors of their existing models while focusing on innovative designs and unique interiors, both technologically advanced and aesthetically appealing, for their upcoming models. As key elements of the car interiors, the interfaces through which the user interacts with the different sub-systems are the subject of the current study.

An interface can be characterized by its behavior, which corresponds to its physical performance. The corresponding engineering parameters are factors that express the performance of an interface and could be used as design requirements. These engineering parameters can be measured instrumentally, for example in terms of the activation force of a push button or the sound pressure level of its activation point. Such parameters are currently used as design requirements by the AC companies to define the behavior of an interface and how it performs. In that sense, the physical parameters that typify how an interface performs are the engineering parameters used as design requirements for the detail design of the interface and its design for manufacturing. However, depending on motivation and context, a product's perceived attributes may have a greater importance than its tangible properties (Crilly, Moultrie

et al. 2004). What a user actually perceives is not these engineering parameters individually, but the outcome of the interaction between the interface's behavior and the user's perception. This outcome could be termed the percept of an interface and combine both, including the effects of the environment where the interaction is taking place. Hence, the behavior or performance of an interface is related only to the "object" interface and could be seen as something measurable, illustrating how an interface performs. However, the percept is something more complicated in terms of to how it merges, the interface's behavior, the user's perception of this behavior and the environment where the interaction takes place.

While ACs have precise expectations for the "feel" of a car (Cerrato 2009), the gap of integrating this feeling into the design solution and further on in the manufacturing process remains and creates a significant challenge. The lack of a robust method to "translate" a feeling into engineering parameters delivered as design requirements to the design process constitutes the stem of the problem. According to Hsu, Chuang et al. (2000) differences among designers and end users perception causes the problem of translating consumer's needs into design requirements and in turn into technical and design specifications.

On the other hand, an In Car Interface (ICI) supplier company responsible for the detail design of the interface and its manufacturing is not able to directly control the engineering parameters delivered as design requirements from the AC, as these parameters describe the performance of an ICI. By controlling certain design parameters (design specifications), customers emotion can be evaluated, designed, and fulfilled (Choi and Jun 2007) as the design regulates the performance of an ICI. Design specifications are the ones that define how an ICI will behave, i.e. the factors that regulate the design requirements which typify the percept of an ICI. Thus, the

design team should be aware of how to accurately control the performance of an ICI through the design, by identifying the impact of the design specifications over the design requirements.

As the visual channel is mainly dedicated to the driving task, for safety reasons non-visual senses play an important role as communication channels between the driver and in-car interfaces. Another reason to target emotions triggered by non-visual senses is the nature of the interaction. The triggered emotions when a user presses a button of an ICI, are generated through non visual senses. Thus, the current research is focused on the need to deliver a target percept in ICI, through non-visual senses.

1.2 Problem statement

ACs are increasingly moving forward in defining the appropriate percept of in-car interfaces, intending to evoke a specific feeling in users. This percept, together with the engineering parameters, is included in the design requirements set delivered to the design process, in order to provide a detailed design solution. Although through the design process it is possible to fulfil the design requirements, the percept is not fully controlled and so the AC expectation maybe only achieved after a long period of a cyclic process of prototyping by following the iterative design process. The inconsistency between the expected and achieved percepts is a result of the ill-defined nature of the problem. In fact, what ACs really want to achieve is the percept that the design requirements should allegedly provide. While AC requirements provide quantitative data the desired percept has an inherent qualitative nature.

Regarding in-car interfaces, ACs define which feelings/emotions they want to evoke by following interviews with their end users. After that, the ACs perform a “translation” phase, by decoding the chosen feeling into a set of engineering

parameters, in order to "pass" the feeling as design requirements to the design and manufacturing process. In another sense, ACs define the appropriate design requirements by selecting a set of engineering parameters which will be in position to evoke the chosen feeling to the user. This process could be seen as defining the percept of the interface, as they have predetermined the feeling and they convert it into a set of design requirements. This process is quite complex and critical, as a feeling is not a common function that interfaces usually perform. That process of "translation" is the main "gap" and the source of the problem. The complex nature of controlling user's perception through the design is of great interest for several researchers. The result of that ill-defined process, the AC's translation process, appears at the manufacturing level, where the produced ICI may not offer the wanted target percept. The appropriate percept of the interface is only achieved after a long process of design iterations and prototyping. Although the supplier company, which is responsible for defining the design solution of the ICI, is able to meet the design requirements of the AC, the outcome percept is not always what the AC desires. The set of design requirements does not supply the adequate information in order to fully design a percept. In simple words, the outcome of the translation phase, which is a set of design requirements given by the AC, are not enough to define the percept of an interface. For both ACs and ICI suppliers the emerging problem of translating a feeling creates the problem of designing an ICI which will be in a position to evoke a certain feeling. To overcome this issue, a series of prototypes are produced by following a trial and error method. This method besides being time and cost demanding, is also insufficient as, in the end, the achievement of the target percept is not guaranteed.

Once the product is prototyped according to the quantitative design requirements, the evaluation of the percept is performed in two phases. In the first the quantitative design requirements are evaluated and in a second phase a qualitative evaluation is performed by an AC expert team by using the ICI prototypes. Typically, when an AC expert evaluates the interface interacting with it, e.g. by pressing an interface’s push button, he/she assesses the triggered feeling and decides upon the acceptance or refusal of the interface. The presence of human evaluators, reflects the problem of the translation phase, as ACs are aware that the delivered design requirements are not enough to define the percept.

The issue with this procedure is that the evaluation of the design solution at the prototyping level, normally called pre-series in the industrial field, is performed based on a set of criteria different from those used by ACs: while through the design process the aim is to fulfill the quantitative design requirements, the AC aims for a qualitative percept. The source of the problem is mainly related to the assumption that if quantitative design requirements are met, so is the percept, even if experience shows that this is not true. At the design level, without any framework to approach the problem of satisfying a percept, the classic trial and error method is used, which means going through a quite costly and time-consuming iterative process: without adequate requirements, the ICI suppliers go through a series of design and prototyping cycles to find the proper percept almost by chance.

In order to approach this problem, it is important to understand the research approach followed by the ACs companies. Daimler AG (Enigk, Foehl et al. 2008) recently went through a research project on haptics, in which five phases were established. Basically, the phases incorporate the current method followed by ACs to define the target sound, with some alterations in the procedure. The first phase is the analysis of

the problem, by understanding the functional and constructional principles of controls in terms of physical engineering. It includes the analysis of different types of control with regards to the force/travel characteristics, and the identification of perceptual thresholds in order to specify the precision levels. In the second phase the aesthetic requirements together with the appropriate materials are defined accordingly in order to meet customers' expectations. The third phase consists of the design of the fully new controls or modification of the existing ones, based on the results from the two previous phases. A whole range of different prototypes is then made. Along this phase, user's qualitative studies are performed involving representatives of the target group. In the fourth phase, the "optimum" haptic parameters are identified and the design requirements are defined. By following an experimental customer trial, the optimum is determined empirically. By means of systematic experimental conditions variation and inferential statistical analysis of data, for example by means of regression, variance, cluster and factor analyses, ACs are able to make accurate statements about the acceptance of the models. Finally, the fifth phase is the definition of design requirements, i.e. the selected engineering parameters that define the percept. The outcome of the latter phase, the design requirements, is delivered to the design process for ICI production. ACs deliver the design requirements defined in the fifth phase, without providing any information about the way they were generated and selected. The gap between these design requirements were generated and defined (or valued), give rise to a lack of information on the manufacturing side and contribute to an ill-defined wanted percept. The problem of an ill-defined translation process from the AC appears when the prototypes are produced by the supplier company responsible for the design and manufacturing. To produce interfaces closer to the target percept, ACs should work together with the ICI supplier by following a

feedback procedure on the design requirements development phase (fourth phase), rather than the existing feedback procedure over the already defined design requirements, which is the outcome of the fifth phase. To deal with this complex problem ACs should enroll their suppliers in the design process earlier, integrating them into the "translation" phase, in order to identify together the appropriate design requirements which will be in position to define the percept of an ICI.

One case which exemplifies the problem is the AUDI AG practice (Mauter and Katzki 2003), which explains the selection process of a metal spring mechanism for push buttons instead of a silicone pad. The reason for that selection, takes place in the second phase as described previously. The selection criteria are not illustrated for their suppliers while it is highly significant the supplier company understand the advantages of that type of mechanism. According to AUDI AG, a linear connection (force/displacement) conveys the impression of comfort and high quality (metal spring behavior). A sagging (silicone pad behavior) force/displacement curve before the switching point is felt to be imprecise, whereas an inflated (convex) curve suggests sluggishness or reluctance. By pressing a radio station button with the arm almost fully extended whilst driving over an overcrowded uneven road is far more challenging than performing the same action at home on a personal stereo. AUDI AG (Mauter and Katzki 2003), reached the conclusion that in a car push button with an operational force of 5N to 6N (design requirement) and an operational travel displacement of 0.7 to 1.0mm, it feels comfortable as well as being conducive to the confidence of operation. Important criteria for the layout are the gradient of the curve at this point and the extent of the drop in force. This excludes the use of conductive silicone switch pads, as they can achieve neither the required force, nor the falling gradient of the force curve. In that case, supplier companies responsible for the design

and manufacturing, are not aware of the selection criteria of a metal spring instead of silicon pad and as a consequence they are not in a position to understand what the advantages of this selection are. The involvement of the supplier into the design requirements development phase, could give a better understanding of the importance of specific engineering parameters and, in sequence, to integrate that knowledge into the design process.

The proposed hypothesis for this problem is that a percept may be more than a linear combination of independent engineering parameters, following the human perception nature which is multi-modally unified (Wilson and Keil 1999). As such, the percept should be defined as design requirements by using a (possibly non-linear) function of the appropriate engineering parameters, including the interaction among them. Hence, in this study the involvement of the interaction among engineering parameters in human perception will be analyzed in order to identify its contribution over the percept of in-car interfaces.

1.3 Thesis objectives

The study aims to bring a deeper knowledge over the ICI percept in order to improve the design and prototyping process carried out by ICI supplier companies to achieve the target percept evoked by non-visual senses, as request by ACs.

The assumptions that the interaction between the user and an interface triggers emotions to the user and this interaction is clearly product-dependent (Schifferstein and Hekkert 2007) form the broad background of the study. The objectives are grouped into two main categories. The first one intends to bring a further understanding over the percept of an ICI by identifying the appropriate design

requirements to be used into the design process. The second one intends to identify the impact of the design specifications over those design requirements.

The objective of the first category is to contribute to the identification of the non-visual related engineering parameters that better describe the intended percept of an ICI, in order to be used as design requirements. Two main research questions arise from the fact that the wanted percept is not just limited to quantitative requirements and additional qualitative information is needed to define it; could the level of information provided by the quantitative requirements be considered enough to deliver the needed information to design an ICI with a target percept? And secondly, regarding the additional qualitative information; which engineering parameters affect the percept and should be included into the set of the design requirements in order to design ICIs achieving the target percept? The goal of the first category is to go further in identifying the interactions that exist among the engineering parameters and their contribution to the percept of an interface's element, such as a push button. To achieve it, an analysis was performed over non-visual behavior of an ICI and identified the engineering parameters with impact over the percept of an ICI. Through an experimental procedure and statistical analysis, engineering parameters which had an impact over the target percept were identified, and it was illustrated how these engineering parameters contribute over the target, in order to be considered as appropriate design requirements.

Moreover, regarding the second category of the objectives, the current research aims to answer the following research questions: which design parameters are the most critical regarding the effect over the percept of an ICI and should be considered as design specifications; and secondly; what the affection level of each design parameter is over the design requirements, in order to be used as design specifications for the

percept of an ICI. The goal of this category is to identify how design specifications affect the design requirements, in order to fully control the performance of an ICI through the design process. To address this objective an analysis over the architecture of the ICI system is performed in order to select the most critical design parameters and through an experimental procedure, the main design specifications which affect the percept are identified (i.e. affect each engineering parameter which is selected and included into the set of the design requirements). The outcome of this phase will offer to the supplier company the required knowledge to regulate the percept through the design, by tuning a set of design specifications to meet the appropriate one to define the target percept.

For both research and industrial application purposes, the objective of this research is twofold: to bring a further understanding over the percept of an ICI and to enlighten the impact of the design over it.

1.4 Outline of the Thesis

Chapter 1 presents an overview of the thesis as an introduction to the concept of applying feelings in the automotive industry and the importance of producing ICIs which will be in position to trigger a specific feeling as defined by the AC. It also discusses the problem of the current state by analyzing the path from the AC to the design and manufacturing process, and the associated root causes of the problem. Additionally, Chapter 1 summarizes the objectives of this thesis.

Chapter 2 presents the relevant background information related to the requirement engineering process, human perception and regarding the importance of non-visual senses, presenting the kinesthetic and acoustic related engineering parameters which could be used as design specifications.

Chapter 3 presents the research framework, which was developed to approach the problem of delivering a pre-determined feeling. Chapter 3 also presents the means and methods of the study, the selected method for each phase, the used material, the selected case studies and the procedures of the current research framework.

Chapter 4 presents the first phase of the research framework. It investigates how normal users perceive each engineering parameter which is delivered as a design requirement from the AC.

Chapter 5 addresses the second phase of the research framework, an approach to decompose the percept into non-visual related engineering parameters in order to identify the appropriate design requirements. It starts with the kinesthetic modelling and continues with an integrated model, by combining kinesthetic and acoustic related engineering parameters, in order to define the design requirements which will be in position to characterize the target percept of an ICI’s push button in an accurate level.

Chapter 6 presents the third phase of the research framework; an approach to define the impact of the design over the performance of an ICI’s push button. By following the Robust Design methodology, a designed experiment is performed, which aims to identify how each design parameter affects each engineering parameter selected to be used as a design requirement in the previous step of the framework (Chapter 5).

Chapter 7 presents the conclusions of this thesis and a general discussion, and Chapter 8 consists of the recommendations for future work.

2. STATE OF THE ART

The goal of this chapter is to provide the related background information. The chapter is structured in sections; the first approaches the requirement engineering process, to understand their levels and their role. The second section focuses on Human Perception, in order to give insights regarding how humans proceed with information processing and derive meaning from sensory experience. The section continues with the multisensory integration in order to highlight the importance of the sensory signals integration. The section Non-visual senses evinces their importance. Following are presented the Haptic and Acoustic sections, the two selected non-visual senses of the current study. Within each of these two sections (Haptic and Acoustic), their importance on the interaction between the user and ICI is highlighted and an investigation is performed regarding the engineering parameters that characterize in the best way their percept. In the last section the main findings and lacks found in literature are summarized.

2.1 Requirements

Due to their high complexity level, some design problems are hard to define as they consist of unreliable specifications, over or under constrained conditions, and implied information not readily available to the designer (Ozkaya and Akin 2006). Requirements may be considered as the foundation of every project, defining what the stakeholders - users, customers, suppliers, developers, businesses - in a potential new system need from it and also what the system must do in order to satisfy that need (Elizabeth Hull 2005). This two fold nature of the requirements, places their role as vital for the success of the system under-development. Due to the complex nature of "feelings", the definition of the appropriate set of requirements is the key to design

and manufacture an interface within the target percept, in order to trigger, through the interaction with the user, the wanted “feeling”. Under that scope, in order to understand how the requirements should be structured and which steps should be performed for their definition, a review is presented on the process of formulating requirements. The process of identifying requirements, analyzing them to obtain additional requirements, documenting them in a specification, and validating that specification to ensure that it meets user needs is known as Requirements engineering (RE) (Saiedian and Dale 2000).

2.1.1 Requirements engineering

Design proceeds from abstract and qualitative ideas to quantitative descriptions (Kreith 1999). It is an iterative process by nature: new information is generated in each step of the process. Thus, design process involves a continuous interplay between the requirements and how the designer wants to achieve these requirements. In order to describe the engineering requirements process, first we have to analyze the design development process. According to Kreith (1999) design process is made up of four domains: the customer domain, the functional domain, the physical domain, and the process domain (Figure 2-1). The customer domain is characterized by customer (stakeholders) needs or the attributes the customer is looking for in a product, process, system, or material. In the functional domain, the designer formally specifies customer needs in terms of functional requirements (FRs). In order to satisfy these FRs, design parameters (DPs) are conceived in the physical domain. Finally, a means to produce the product specified in terms of DPs is developed in the process domain, which is characterized by process variables (PVs).

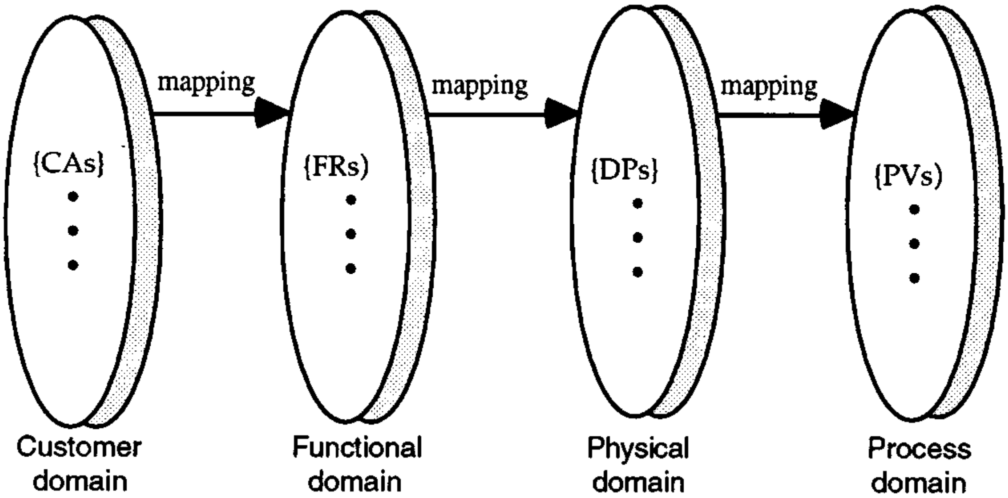

Figure 2-1 - Four domains of the design (Kreith 1999)

RE process follows the design process and for each domain a different level of requirements is created. The introduction into the design development process has to be with the definition of the problem. The problem is express by the statements of needs, which is the starting point of the Requirements Process. Stakeholders are stating a need or a set of needs, but that statement is not engineering requirements. A process with activities is going to transform that statement into engineering requirements. According to Sawyer (1997) the stakeholders requirements (some called user requirement), are the requirements written from the stakeholder's point of view, an informal high – level description which mainly is not expressed in great detail. Stakeholders are typically referred to anyone who is involved in the project or "whose interest the project affects" and could include the users, developers, marketers, procurers, QA, and any others who might be affected by the use of the system (Hofmann and Lehner 2001).

As the initial point of the Requirements process is the stakeholder's needs statement, it is a challenge to get as more as possible accurate needs, in order to have a clear objective of what the system has to perform. Thus, a critical point is to identify which

method or methods have to be chosen to capture requirements. There is a plethora of methods for capturing stakeholder's requirements as mentioned by the (Elizabeth Hull 2005) and listed above.

- interviews with stakeholders;
- scenario exploration (generally through stakeholder interviews);
- descriptive documentation (perhaps from studies or market research);
- existing systems which are being upgraded;
- problems and change suggestions from existing systems;
- analogous systems;
- prototyping, either partial systems, mock-ups or even simple sketches, of the product or the requirements themselves;
- opportunities from new technology (approved by stakeholders);
- questionnaires;
- anthropomorphic studies or analysis of videos.

Moreover, we pass from the customer domain to the functional domain. When stakeholder's requirements exist and it is known what the proposed system will be able to do, it is possible to start considering potential solutions, by defining what characteristics the system must perform. Before moving to the design process, it is recommended to determine first the outcome of the system irrespective of the final detailed design (Elizabeth Hull 2005). In other sense, those abstract requirements (stakeholder's requirements) develop into more detailed requirements, named as System Requirements and that consist of Requirement Specification, which is a collection of the set of all requirements, as a set of engineering parameters, which are to be achieved by the design and verification of the product. According to Sawyer

(1997), to elicit system requirements and define the requirements specifications, you must understand the problem to be solved, the business processes in an organization, the ways in which the system is likely to be used and the application domain of the system.

Furthermore, the systems design architecture takes place by identifying alternative design solutions with the objective to meet the system requirements. Design architecture is expressed as a set of interacting components (sub-systems) that collectively exhibit the desired properties. The design architecture defines what each system component must do and how the system components interact with each other to produce the overall effects specified in the system requirements (Elizabeth Hull 2005). Within design architecture, the Design Specifications are defined, in order to provide directions to the builders and coders of the product. The Design Specifications contain information about the product architecture and describe how each component will contribute to meeting the requirements.

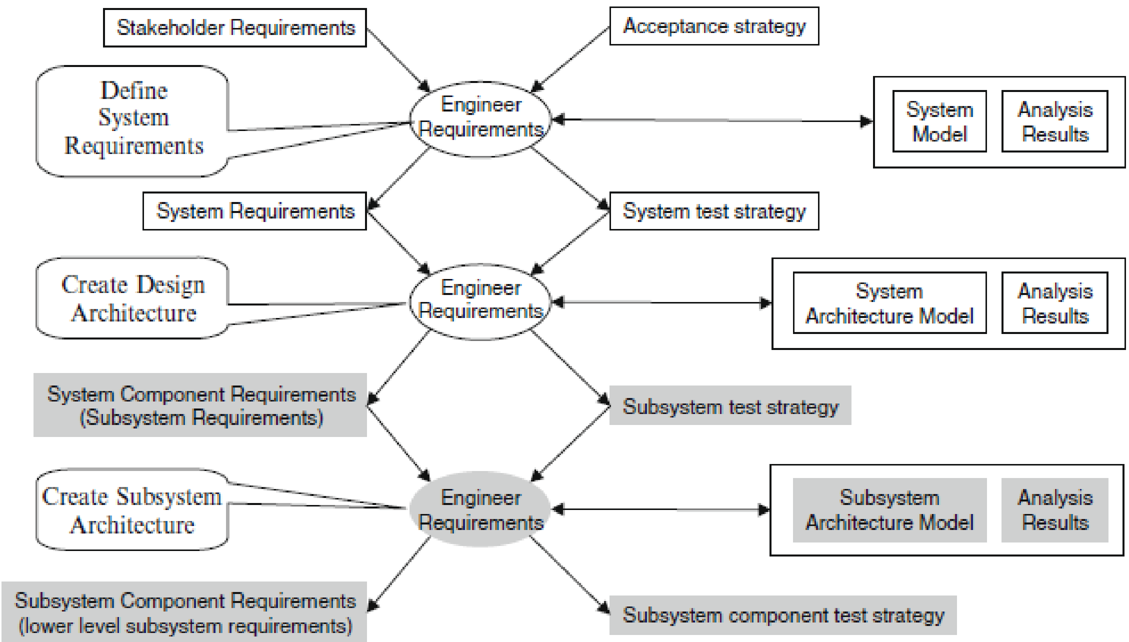

Figure 2-2 - Different levels of requirements engineering (Elizabeth Hull 2005)

It is important here to understand the role among each requirement layer (Table 2.1). According to Elizabeth Hull (2005), without a clear distinction between problem and solution, the following may result:

- Lack of understanding of the real problem
- Inability to scope the system, and understand which functions to include
- Domination of debate about the system by the developers and suppliers, because the only descriptions of the system are expressed in terms of solutions
- Inability to find optimal solutions due to lack of design freedom

Table 2.1 - Problem and solution spaces (Elizabeth Hull 2005)

Requirements layer	Domain	View	Role
Stakeholder requirements	Problem domain	Stakeholder's view	State what the stakeholders want to achieve through use of the system.
System requirements	Solution domain	Analyst's view	State what the system will do to meet the stakeholder requirements.
Architectural design	Solution domain	Designer's view	State how the specific design will meet the system requirements.

The arrangement between the requirement's layers is clearly illustrated in Figure 2-3, the Requirements V model (Elizabeth Hull 2005). The classic V-model, illustrates the relationship among each development stages. The V-model approaches the development in terms of layers, each layer addressing the concerns proper to the corresponding stage of development.

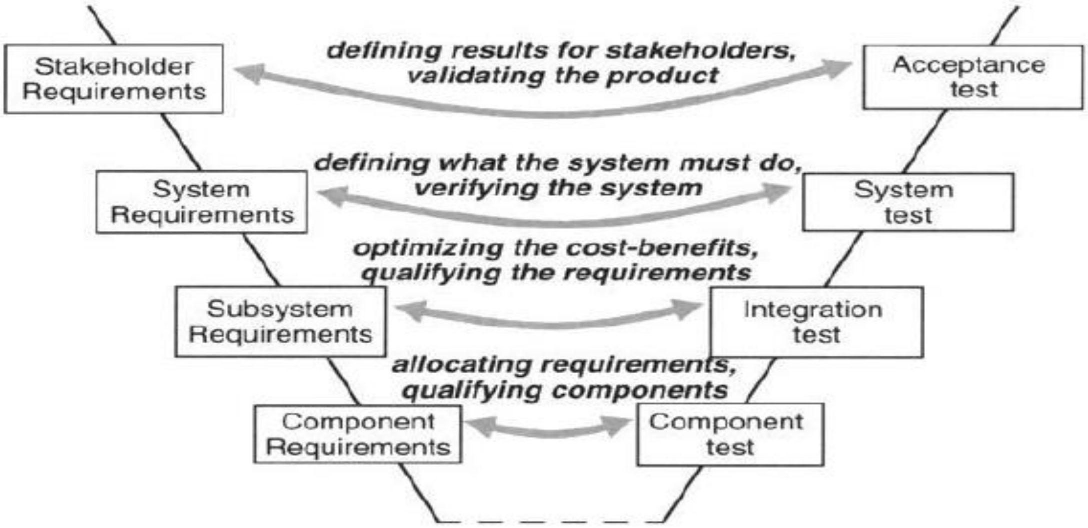

Figure 2-3 - Requirements V model (Elizabeth Hull 2005)

Moreover, following the engineering requirement process, it is clear that each level takes in input requirement and generates derived requirements, which will be used as input for the following level of the process. In Figure 2-4, it is presented which requirements are used as input for each process and in sequence feed the following process with derived requirements.

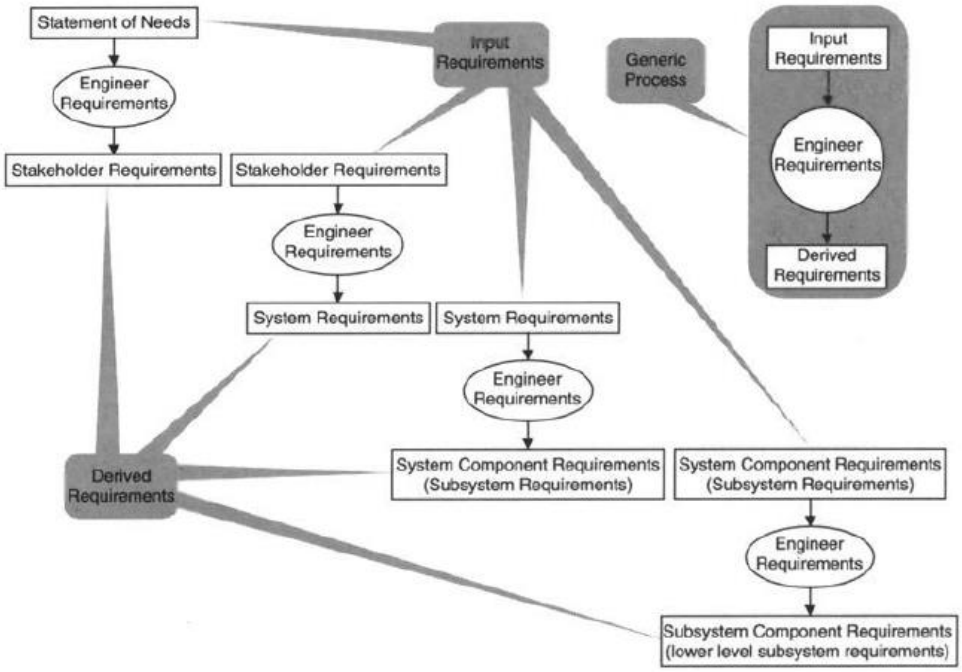

Figure 2-4 - Identifying input and derived requirements (Elizabeth Hull 2005)

Capturing requirements process followed by analysis, in order to recognize how each requirement is going to affect the system when it is in use. According to Sawyer (1997) the requirement analysis process objective is to identify missing requirements, requirements conflicts, ambiguous requirements, overlapping requirements and unrealistic requirements. The aim of this process is to avoid possible problems occurred by non – accurate requirements.

After that process is the negotiation process. According to Sawyer (1997), during that process it is intended to discuss the conflicts in requirements and to find some compromise which satisfies everyone involved. Requirements conflicts have to be resolved and should be decided if the benefits from requirements justify their costs.

According to Sawyer (1997) the elicitation analysis and negotiation processes may therefore be thought of as segments in a spiral, as presented at the Figure 2-5.

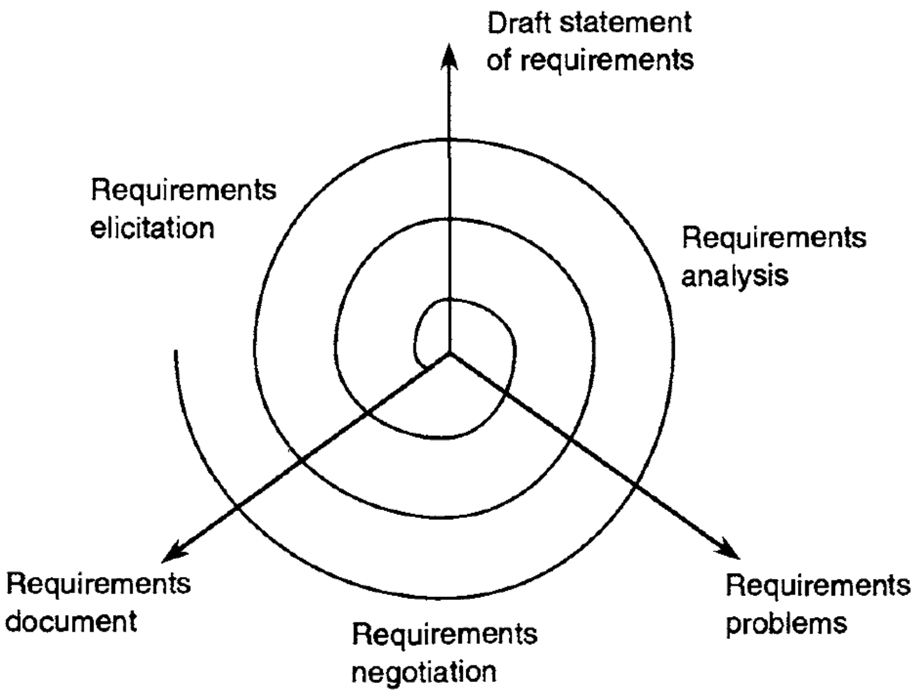

Figure 2-5 The elicitation, analysis and negotiation spiral (Sawyer 1997)

Summarizing this review on RE process, it is important to be clear the differences among the types of requirements and as well their role. Briefly, the RE process starts with a need or a set of needs. These activities, which transform a vague statement of need into a set of requirements that can be used as the basis for purchasing a system, constitute the process of developing the Stakeholder Requirements (Elizabeth Hull 2005). Stakeholders Requirements could be characterized as a process of mapping the problem domain. Besides the problem domain, it is the solution domain and the System Requirements, which define what the system has to perform to accomplish the Stakeholders Requirements, as defined at the previous step. In other sense, System Requirements are the proposed solution to the recorded problem (Stakeholders Requirements). The System Requirements consist of a set of Requirements Specifications, which define what characteristics the system must perform. Furthermore, how the system will meet the System Requirements, is defined by the System Architecture, where the design of the system takes place. System Architecture consists of Design Specification which states how the design will meet the wanted performance of the system, as defined by the System Requirements.

2.2 Human Perception

Dealing with the necessity of facing an interface as a communication channel which transmits "feelings", an engineering socially related problem surfaced: how to define a feeling as design requirements and how to integrate it into the design process by defining the appropriate design specifications? That need is clearly pointed out by Rossi and Berglund (2011) who mention the great importance of measuring characteristics related to human perception for scientific reasons as it is essential for the understanding of human perception and for practical reasons, as such

measurements are inherently appealing, since they are customer oriented, highly informative and provide direct information on the perceived quality of products. On the other hand, Rossi and Berglund (2011) suggest as a solution, to use a person as a measuring instrument, in properly designed and conducted experiments. The American Society for Testing and Materials (ASTM) has also launched sensory testing methods grounded in psychophysical research for industry. These include quality-control procedures similar to the ones used in the international system of metrology, such as inter-comparisons, after proper adaptation, and qualification of methods for measuring perceptual quantities. EU commission targets on that, with a research call under the topic “Measuring the impossible”, for advancing the measurement of multidimensional phenomena which are mediated by human interpretation and/or perception. EU commission supports interdisciplinary research and novel investigative methods that could advance the measurement of multidimensional phenomena which are mediated by human interpretation and/or perception(COMMISSION 2007).

To face the problem of delivering a predefined feeling, first it should be analyzed how a feeling is triggered. Everything starts with a human’s perception, a process by which an individual acquires knowledge, and interprets, selects, and organizes the sensory information of an objective world (Maund 2003). Perception reflects the ability to derive meaning from sensory experience, in the form of information about structure and causality in the perceiver's environment, and of the sort necessary to guide behavior (Wilson and Keil 1999). This process of evoking emotions and feelings in the user, a central quality of human existence and most of human’s behavior motivation, and thought is enriched with and influenced by emotions (Schifferstein and Hekkert 2008). Perception includes the five senses: visual, auditory, haptic,

olfactory, and gustatory and moreover includes cognitive processes required to interpret the information. Cognitive capacities link perceived information to stored knowledge to interpret the incoming information; they elicit memories of previous usage and evoke associations with other products (Schifferstein and Hekkert 2008). Several versions of information-processing approaches exist, starting from the classic one, the bottom-up processing, where processing is affected directly by the stimulus input and the top-down processing which is affected by the individual's knowledge and expectations rather than simply by the stimulus. Most human cognition involves a mixture of bottom-up and top-down processing (Eysenck and Keane 2005).

Another approach, in which some or all of the processes involved in a cognitive task occur at the same time is known as parallel processing, a most common form is called cascade processing, in which later processes begin before some of the earlier processes have been completed. Parallel processing occurs much more often when people are highly skilled and practiced in performing a task when they first encounter it (Eysenck and Keane 2005). In the case of an ICI, the type of information processing alters according to the target group of each automotive company, where some interfaces are developed for highly skilled and experienced drivers (i.e. luxury and classic cars mainly have more elderly users as target group, which are highly skilled and experienced) or for new drivers without prior knowledge and expectations about the product (i.e. small and economic cars target mainly targeted to new car drivers). In other sense, each automotive company targets on the needs and the wants of the particular target group they aim to cover.

Although some of the chosen feelings, as defined by the ACs are identical, the way an AC adopts to deliver it through the design process, differs as the information processing differentiates among the users of different target groups. For example, to

give the impression of safety surely an automotive company should develop much more complex systems when they deal with an experienced person than a young new driver, as the experience does not only result from the interaction, but follows and guides it, ultimately affecting it (Schifferstein and Hekkert 2008). In this case, a target group with an advanced level of experience follows a different type of processing, i.e. parallel, than a target group with a lower level, i.e. bottom up. The result of this differentiation causes people to perceive the same stimulus in a different way, for instance an in-car interface. As pointed out by Crilly, Maier et al. (2008), interpretation cannot be reliably controlled because different people will construct different meanings depending on factors such as context, motivation and values. While the physical performance of two interfaces for example, could be the same, the percept alters as it involves human perception. According to this, the users of an interface are involved in two phases in two different levels: the first phase as part of the interaction and the second as receivers of the interaction. This twofold nature of the user is highlighted by Mono (1997), who adapted the very well know communication model from Shannon (1948) in product design. In Shannon's model of communication, an information source produces a message that is encoded into a signal and transmitted across a channel; a receiver decodes this signal and a message arrives at the destination. The communication model as adapted from Mono (1997) has the concept of having 'products as transmitters' and includes five elements: source, transmitter, channel, receiver and destination. According to Mono's adapted model the source is the designer, while the product is the transmitter and as channel is the market where the product will be launched. In that sense, the receiver could be considered the individual's sensory system and the destination (target) of the message (the outcome of the interaction between the user and the interface) the individual's

brain, where the emotion/feelings are triggered. Therefore, the user has a twofold nature: one regarding the perception of the product (as receiver) and other as the destination, the interpretation of the interaction's outcome.

2.2.1 Multisensory Integration

In order to pass to a level of performing research over emotions/feelings, a key issue is to approach to understand the nature of one element of the treated system; the human sensorial system and brain processes, which through the interaction with the second element of the system (the interface), evoke feelings. During the last decade, several researchers emphasize on merging senses, in order to understand the human perception. A plethora of studies provided evidence on the importance of the sensory signals integration (Ernst and Bülthoff 2004, Robertsson, Iliev et al. 2007, Besle, Fischer et al. 2008, Pennartz 2009, Stein, Stanford et al. 2009). The linkage among senses through brain processes is commonly accepted and under research as to how and which mechanisms are under that interaction.

Ernst and Bülthoff (2004), from a cognitive point of view, provide a review on sensory integration, by pointing out how the brain reduces the variance in the integrated estimate and increases the robustness of the percept by combining and integrating sources of sensory information from within and across modalities.

Pennartz (2009) approaches the issue of how information from different sensory modalities is integrated into a multimodal percept, termed as Modality Identification (MI) problem. The author already realized that the neural mechanism for sensory integration is aligned with two main principles: i) for each unique object percept, a unique state or configuration of neural activity is, ensuring that two different percepts cannot be represented by only one neural state, and ii) neurons engaging in one and

the same object representation must influence aspects of each other's neural activity. By following a reassessment of the classical framework for explaining the identity of sensory modalities – the 'Labelled-Lines Hypothesis', he concludes that classical neurophysiology and neural-network theory do not offer satisfactory solutions to the problem and propose a heuristic framework to address the MI problem. Moreover, the author proposes to approach the integration of inputs from different modalities by considering a multi-modal group of sensory systems as forming a Dynamic Associative Network (DAN) with globally coexisting attractor states. The DAN model includes the uni-modal sensory areas, vision, audition and touch, which by default (anatomically) are segregated. Despite that, these areas are functional highly connected something which is needed for conscious multimodal experiences as our perceptions are constantly influenced by all our senses and this is termed as the 'topological uniqueness of sensory modalities', which means that each sensory modality is unique in the way it is integrated with other sensory modalities.

A growing interest in exploring the linkage among senses, by testing the interactions from different sets of modalities, following a multimodal or a bimodal integration, shows how humans merge the information from different sources through separated channels. Although several researchers, through experimental procedures, explore brain mechanisms on how the user perceives the properties of a stimuli, the whole picture is still incomplete. A review on the experiment procedures will provide a deeper knowledge over the integration of senses and will be used to perform a comparison among the results.

Regarding bimodal integration of vision – haptic (Ernst and Banks 2002, Zuidhoek, Visser et al. 2004, Bergmann Tiest and Kappers 2007, Helbig and Ernst 2007, Helbig and Ernst 2007, Kumazaki, Terada et al. 2007, Helbig and Ernst 2008, Kritikos and

Brasch 2008, Whitaker, Simoesfranklin et al. 2008, Magosso 2010, Overvliet and Soto-Faraco 2011), researchers provide evidence on how brain processes the input information from the visual and haptic channel, in order to identify how the visual sensory affects the haptic and inversely on human perception. Several stimuli properties were explored such as the perception of roughness (Bergmann Tiest and Kappers 2007), shape properties like the length or the height (Ernst and Banks 2002, Helbig and Ernst 2007, Helbig and Ernst 2007, Kumazaki, Terada et al. 2007), the texture (Whitaker, Simoesfranklin et al. 2008), the naturalness (Overvliet and Soto-Faraco 2011) or even regarding the action comprehension and execution (Kritikos and Brasch 2008) and perception of space (Zuidhoek, Visser et al. 2004).

On the study of Bergmann Tiest and Kappers (2007), how physical properties of roughness are correlated with the perceived roughness was tested. Results indicate that the visual correspondence with the physical ordering is approximately the same as the haptic correspondence. The meaning of the results is that roughness is not only a haptic property but can also be perceived from the visual channel. The same question, but for the perceived length was tested by (Kumazaki, Terada et al. 2007). Results also suggest that visual and haptic sensation independently provide equal information of physical quantity. An explanation on this issue is coming from Helbig and Ernst (2007) where they study the perception of another shape property, the height. Findings of that research suggest that prior knowledge about object identity can promote integration, even when information from vision and touch is provided at spatially discrepant locations. The same was speculated as an explanation hypotheses by Bergmann Tiest and Kappers (2007), where, in the proposed experiment, the participants retrieve the haptic sense of the roughness from their memory. Helbig and Ernst and Ernst and Banks in their studies (Helbig and Ernst 2007) and (Ernst and

Banks 2002) respectively, provide evidence about visual and haptic size information in a statistically optimal fashion, in the sense that the integrated estimate is most reliable. The authors underline the importance of the fact that bimodal shape estimates are more reliable than shape estimates that rely on either vision or touch alone.

Moreover, Overvliet and Soto-Faraco (2011) approach another object's characteristic, the 'naturalness' and investigated whether it is possible to provide a measure regarding the construct "naturalness" of wood by cross-correlating several psychophysical measurement methods. The study has a twofold aim, one regarding the measuring method and a second one about the contribution of vision and touch when measuring the perception of naturalness. To approach the problem of measuring such 'ill-defined concept', as authors term it, a comparison was performed among four psychophysical measurement methods (labelled scaling, magnitude estimation, binary decision, and ranked ordering), throughout an experimental procedure where participants rated samples of wood or imitations of it. Results show that all methods provided high correlations as all were tapping into a common underlying construct. Moreover, regarding the contribution of vision and touch, results indicate that the physical properties that influence the estimation of naturalness are mostly of a multisensory nature, and as a consequence of this strong cross-modal correlation, it is difficult to assign weights to each modality in order to evaluate their relative importance.

2.3 Non-visual senses

Non-visual senses contribute to a better interaction between humans and ICIs, by enriching the communication with supplementary information. Many studies have recorded benefits from an interaction which use non-visual senses as communication

channels. A new way to interact which improves the performance is established by using non-visual senses.

According to Serafin (2007) users show a stronger preference on haptic displays than non-haptic touch panel interfaces, because the non-haptic interfaces lacks the mechanical confirmation which is an expectation from almost all users. Two studies were undertaken to investigate the addition of haptic feedback as well as auditory feedback on user perceptions of the touch screen experience. The first study was conducted in a desktop setting and the second study was conducted with the touch screen integrated in a vehicle. In both studies, participants assessed four different types of feedback conditions: visual feedback only (Sawyer 1997), auditory and visual feedback (AV), haptic and visual feedback (HV), and auditory, haptic, and visual feedback combined (AHV). The results of these studies support the claim that individuals strongly prefer touch screen implementations that incorporate haptic elements and also provide insights on regional differences in their perception.

The combination of haptic and audio senses could be seen in many studies, like the multi-modal experiment by the Lorna M. Brown (2007) for mobile interpersonal communication. The Shake2Talk system allows users to construct audio-tactile messages through simple gesture interactions and sends these messages to other people. Such messages could be used to communicate a range of meanings, from the practical (e.g. “home safely”, represented by the sound and sensation of a key turning in a lock) to the emotional (e.g. “thinking of you” represented by a heartbeat).

In the study of Jesse Dosher (2005) an investigation was undertaken concerning the ability of individuals to detect small haptic effects and the associated gains in performance tasks with various configurations of haptic stimuli. Variations in force amplitude, shape, and pulse duration used to create the effects are studied. According

to Dosher, tactile feedback can convey significant quantities of information and use does not need to be confined to simple notifications. They developed a fingertip tactile display that provided both kinesthetic and vibrotactile feedback, which varied in amplitude, wave shape, and duration during interaction with haptic icons. The authors report that observed throughput was positively correlated with tactile effect amplitude, with bit rate improvements of as high as 50%. They also report that rough feedback (high tactility) has a lower threshold of detection than smooth feedback (low tactility).

Apart from the haptic non-visual sense, there is also the acoustic sense. According to (Bender 1999) auditory feedback alone could not recover performance losses associated with movement time (time needed to move between keys) and contact time (time spent in contact with each key). However, auditory feedback did reduce error rates, especially for small key sizes. Bender concluded that for touchscreens that do not provide haptic feedback, it is important to provide some type of auditory feedback and to make keys as large as possible.

In a systemic approach, it is critical to take into account the role of the context of use, as the cost of the interaction among a device and its environment could become higher than the value of it (Ronkainen, Koskinen et al. 2010). Car environments are considered one of the most challenging areas regarding the development of user interfaces with emphasis on nonvisual senses. One main reason for that is related with safety issues. Inside a car, the primary task of the driver is driving and so the vision channel is committed to that task. Another reason is related with the fact that a car is regarded as something more than just a functional object in a literally way. The way a headlight switch looks, feels, and sounds inside an automobile, for example, influences perception of not only the quality of the switch itself but of the automobile

as a whole (Hong 2008). Furthermore, due to the fact that touch and sound play such an important role in perceiving a product as one's own versus 'foreign', the use of distinctive tactile and acoustic details may provide an effective way to generate differential advantages that operates on a more personal level than that obtained with visual features (Schifferstein and Hekkert 2007).

Approaching the in-car interaction has to deal with a major issue, safety. The driving task has been integrated with a plethora of new functions and this phenomenon will increase in the future. In recent times and along with traditional instrumentation, the dashboard has been burdened with providing space and mind share for infotainment devices such as GPS navigation and other information facilitators (Kenny T 2004). The new car environment has to be developed in a way to keep the driver on the primary task, driving.

Driving is a highly complex skill that requires the continual integration of interdependent perceptual, motor, and cognitive processes. Nevertheless, driving becomes routine enough that users can comfortably perform minor secondary tasks while driving — for instance, turning on headlights or adjusting the defogger. While it may be convenient to have devices such as cell phones available for driver use, safety is clearly the primary concern, and thus it is essential to understand the impact that in-car devices may have on driver behavior and performance (Dario D. Salvucci 2002).

The aim to promote better interaction between humans and electrical/mechanical devices will result in the driver reducing errors during communication in order to create a more efficient interaction.

Nowadays, drivers have to cope with a growing amount of information coming from on-board information messages, telematics and advanced driver assistance systems. The interaction between the driver and these systems is critical, since they may

distract the driver from the primary task of driving (A.Amditis 2006). While driving itself can be decomposed into subtasks, another common aspect of driver multitasking involves the integration of driving with some secondary task, such as the use of an in-vehicle device like a cellular phone or navigation system. The burgeoning use of such in-vehicle devices has begun to pose a serious safety risk(Salvucci 2005).

In order to keep safety at a high standard, the goal is to use as less as could be the sense of vision on the primary task, the driving, and to use as a communication channel for the secondary tasks alternative communications channels, such as non-visual senses haptic/kinesthetic and hearing. Thus, dealing with non-visual senses on the interaction of the secondary tasks, is fully connected with the safety issue. In order to optimize the interaction level and increase safety, interfaces have to be developed which can easily communicate with the user (driver) through non-visual senses.

The importance of non-visual senses has placed their contribution to the perception of In Car Interfaces (ICI) at a primary level. One of the main automotive industries, Audi AG, clearly state (Mauter and Katzki 2003) that objective, by pointing out that it has been working for several years on shaping the desirable haptic feel of the controls. In fact, Audi's goal is not merely to minimize distractions but, more important, to create one unique feeling for all controls with the emphasis on comfort and equality. A switch or button that feels inexpensive, even if it is technically perfect and functions properly, will create a negative impression to the customer. These objectives appear in other AC such as BMW, which argues that the creation of a direct mapping between 'doing' and 'seeing' reduces the attention and the focus level required to operate the in-car system and therefore it provides a greater safety and comfort and overall pleasure is reached in the driving activity. As they state: "after all, what BMW cares about, is to preserve the joy of driving" (Bernstein, Bader et al. 2008). All ACs are

aware of the role of the perception, as they do at Ford, who knows that prospective buyers primary feel the knobs of the radio, heating system and air conditioning device: those seemingly minor elements provide wide messages about a car (COMPANY 2009). At Ford, designers and engineers are not only aware of the importance of touch, but they are also using the haptics to study touch and its ability to evoke certain sensory and emotional responses, aiming to design vehicle features that make sense and feel right to drivers and passengers.

2.3.1 Haptic

The importance of the haptic sense is highlighted by several firms in a wide range of products as it is considered as carrier of subconscious messages for their users. When one turns the dial button, the fingertips and muscles can almost “feel” the stations being scanned (Moggridge 2007) or it could be mentioned here that one “feels” the brand of the radio. For example, Texas Instruments has developed an exclusive touch for the keys on their calculators. This is a branded enhancement that makes the feel of a Texas Instruments calculator completely different from that of any other calculator (Linstrom 2005).

Haptic is regarded as an umbrella term, which involves both tactile/cutaneous and kinesthetic perception (Loomis and Lederman 1986, Hatwell, Streri et al. 2003, Kortum 2008). Cutaneous refers to the sensation of surface features by tactile perception and is usually conveyed through the skin. Kinesthetic touch sensations, which arise within the muscles and tendons, allow humans to interpret where the limbs are in space and in relation to us. For the ICI, when the driver presses a button to activate a function, tactile and kinesthetic perception is employed by touching the button’s surface and pressing it, by applying force throughout the travel of the button.

Therefore, the perception of the user includes both cutaneous and kinesthetic sensations. In fact, the ISO standard (ISO, 1998) for keyboards kinesthetic named the sensations based on the cutaneous, joint, and muscle-spindle receptors of the hands, limbs and other body parts. Nevertheless, to Kortum, the human haptic perception (rather than sensing) is the process of acquiring, interpreting, selecting, and organizing haptic sensory information and it comprises tactile perception and kinesthesia (including proprioception) (Kortum 2008).

2.3.1.1 Parameters related with kinesthetic percept

The behavior of push buttons and the engineering parameters that characterize the kinesthetic percept of a bush button in the best way has been analyzed by several studies. Many researchers tried to decompose the kinesthetic behavior into psychophysical parameters, i.e. those that humans are able to perceive and carry the core of the percept.

A study by Weir et al (Weir et al., 2004) focused on the wanted "feeling" as requested by the automotive company and provide an example of a typical development process for a console switch at an automotive company. According to the authors, together with a set of engineering parameters, the AC provides as design requirements to its supplier a sample of the Best-In-Class (BIC) switch as a template for the future products. The supplier develops the design solutions and produces a prototype that is sent back to the AC. However, the prototype switch rarely "feels" like the selected BIC sample, as the percept differs from the wanted one. Thus, authors conclude that there are not quantitative metrics (i.e. appropriate design requirements) to characterize the switch-feel, and so, no complete description or method to verify conformity of the final product can be given to suppliers. According to this study, by measuring the

force, displacement and acceleration of three types of switches, which means identifying features in haptic profiles, the authors suggest that plot of force/displacement displays most of the fundamental switch behavior. Hong (2008) clearly stated that it is fundamental to identify which engineering parameters can predict the haptic percept of a switch and what makes a given switch different from another, even when all the other design requirements are met. This study targets into rotary switches and approach the problem from the end-user's perception, rather than the AC requested percept. Nevertheless, the problematic state of specification's tolerances and manufacturing noises that affect the production is the same and the authors tried to identify the detection thresholds from users. One step further, on the level of design parameters was conducted by Erdelyi and Talaba (2010) who link the feeling with the design process by using design parameters to achieve the haptic behavior of a car turn-signal switch. By developing a virtual prototype the study aims to provide a tool to the designers in order to determine the geometry of a turn-signal switch cam mechanism, which defines the haptic behavior, the feel of the switch. Their statement is quite important regarding the lack of research on the manufacturing aspect. As clearly mentioned, to approach the problem of delivering a specific feeling through a switch, for most of the studies, the internal mechanism of the switch was of no interest. This could be considered as lower level research, as it targets over the design parameters which affect the engineering parameters, i.e. the performance of the device.

2.3.1.2 Parameters related with force-displacement curve

Regarding the kinesthetic percept, the force-travel characteristic plays a key role as regards the overall haptic impression and the experienced percept of a switch. It

describes the force which has to be applied between touching the switch and triggering the pressure function along the distance to be covered (Enigk et al., 2008). According to the standard ISO for keyboards (ISO, 1998), a ramp action is the kinesthetic sensation during key actuation in which the force required to actuate the button increases as the button is displaced; however, a snap action is the sudden drop in force required to further displace the key. The initial resistance is named the starting force or preload and the activation point is named the snap point. Since the 1960s, studies conducted upon the characteristics of button (Deininger 1960), from the user's perspective, have tried to answer what the desirable characteristics of push buttons are by analyzing several features, including the force-displacement characteristics. At that time the aim was related mainly with ergonomic issues, like user's speed optimization, or accuracy, but also with emotional aspects as preference. Armstrong, Foulke et al. (1994) states that force-displacement curve is nearly static or quasi-static and is characterized by the preload (the minimum force required to activate the key), the breakaway force (the difference between the maximum and the minimum before and after the breakaway – the click), the make travel (the displacement corresponding to the make force), the total travel (the maximum distance between the highest and the lowest positions of the keys) and the over travel (the distance between the total travel and the make travel). That study provides evidence that the key force exerted by users is related to the design and stiffness of the keys.

As one can note, several names were adopted for the same engineering parameters. In the current study the terms as listed at the Terms and Definitions will be adopted as used commonly with in manufacturing companies.

2.3.1.3 Kinesthetic parameters interaction

From a different perspective, studies on muscle activity for prevention of injuries related with the use of keyboard push buttons provide evidence on the interaction of these kinesthetic related parameters and their effect on the human nervous system.

Studies of Lee, Kuo et al. (2009) and Radwin and Ruffalo (1999), pointed out that changes on the behavior of a push button affect fingertip force and muscle activity. Fingertip force is considered the one that is applied by the user. These studies found out that Force to Stroke and Distance to Stroke affect the muscle activity and both are related with the force applied by the user.

Jindrich, Balakrishnan et al. (2004), regarding single finger tapping, tested the hypothesis that joint torques, stiffness and damping parameters differ for keyswitch designs and finger postures are typical as those observed during computer keyboard typing. Subjects tapped in three postures on four different keyswitches (two buckling-spring and two buckling rubber-dome). Results indicated that both finger position and keyswitch affected joint kinematics and torques.

The study of Nagurka and Marklin (2005) shows the influence of speed on the force displacement characteristic. For the rubber-dome keys, the peak force in general increases with the speed of depression. Although the increase in peak force for rubber-dome keys, may seems small (0.05–0.1 N for speeds up to 80 mm/s), the percentage increase in peak force approaches 14% above the quasi static peak force.

While studies for keyboards focus on ergonomics and usability rather than design for emotions and affections (Schutte and Eklund 2005), due to their different environment and functionality, studies for switches target a more customer oriented perspective, taking into account the feelings generated through the interaction of the user and the interface. In a study on rocker switch (Schutte and Eklund 2005), the researchers

followed Kansei Engineering to investigate how engineering properties influence the perception of rocker switches. A Kansei engineering process includes three phases: the first to define the semantic space, which is a set of words (kansei words) that describes the object; the second is to collect product properties (the most important physical properties) and the third step is the synthesis, in which the interactions between Kansei words and product properties are analyzed, and participants are expected to rate the product samples on a scale for one Kansei word each. They conclude that the semantic space for the particular type of switches could sufficiently be described by the four factors: Robustness, Precision, Design and Cheapness/Stiffness. After this characterization they were in position to identify which parameters are connected to these four factors. A similar procedure to the Kansei process was adopted by Hatzfeld, Kern et al. (2010) by contacting an experiment on household light switches, where force /displacement curves were recorded and weighted and then participants were asked to rate the switches on nine Semantic Differential scales. Moreover, in the study of Sekiyama, Ito et al.(2008), the authors, introduced as hypothesis that before pressing a switch, one predicts what muscular force is going to be needed. The difference between the predicted and the real needed force creates a feeling of comfort or discomfort, accordingly. The predicted muscular force was estimated from EMGs and they derived the difference between the predicted muscular force and the actual reactive force of the switch. Authors built a Kansei model for the kinesthetic sense with two units: the prediction unit and the feeling generation unit on comfort and discomfort. Experimental results showed correlation between evaluation by the proposed method and participants' subjective evaluation.

2.3.2 Acoustic

Product sound is emerging as an important marketing factor, as is the case with the famous Harley Davidson motorcycle sound, for example (Fog and Pedersen 1999). It is a generally accepted and proved fact - by a vast amount of studies - that the sounds a product makes characterize and represent its quality and this quality contributes to its usability, enjoyment and brand identity. Product sound is used as a carrier of specific information to the user of the product, which stand for the quality of the product (Blauert and Jekosch 2003). But what is the Sound Quality (SQ)? As clearly stated by Bodde (2000) SQ contradicts with Sound Engineering as it considers human perception. Thus, according to Blauert and Jekosch (1997), Bodde (2000), and Jekosch (2004) SQ is a multidimensional, complex and dynamic issue which consists of three different factor groups, physical, psychoacoustic (see (Fastl and Zwicker 2007) and physiological factors. In a further discussion over the definition of the SQ, Blauert and Jekosch (1997) and Jekosch (2004) mention the importance of the product usage and context as sounds are signals and signs of activities in the environment. This means that each product has its own SQ which is defined by its usage, environment and prior experience. As a result, it is not possible to define a set of physical and/or psychophysical metrics that describe the SQ of all products, but one has to focus over the particular under-study product or focus more on the product's class. Several researchers tried to evaluate the SQ of several products and define the appropriate set of sound related parameters that influence the percept and quality, in terms of preference or annoyance index, rather than evoke a specific target feeling, as defined by the AC.

The current study approaches the SQ from the perspective of achieving a specific percept, as defined by the AC. The goal is to identify a set of acoustic and/or psychoacoustic parameters that contribute to the percept of in-car interface's push button and evaluate their contribution on it.

2.3.2.1 Parameters related to the Sound Quality

Several researchers have tried to evaluate the SQ of several products and define the appropriate set of sound related parameters that influence the percept and quality, in terms of preference or annoyance index. Mainly for the evaluation, a semantic differential procedure is employed to examine the relationship between the subject's evaluation and acoustic and/or psychoacoustic parameters. A common evaluation procedure over SQ mainly consists of three phases: the first part comprises of acoustic measurements in order to extract a set of physical and/or psychoacoustic parameters. In the second phase, subjective measurements take place by using jury tests in order to record the perception of corresponding sound. At the final phase, the correlation between acoustic (and/or psychoacoustic) parameters with the subjective measurements is performed. Such examples on product sound quality evaluation of hard disk drives (Choi, Moon et al. 2004), air condition units (Susini, McAdams et al. 2004) or vacuum cleaners (Altinsoy, Kanca et al. 1999), aim to identify the preference and annoyance index, respectively.

In the study of Choi, Moon et al. (2004) the noise produced by hard disk drives (HDDs) was researched. While the evaluation of the HDDs performed over measurements of the Sound Pressure Level (SPL – dB(A)), this study investigated if the subjective human perception, which is in fact what they do care about, could be predicted more accurate with a psychoacoustic parameter, the Loudness Level (LL –

[Phon]. By measuring the A-weighted SPL and calculating the LL (by following the Zwicker method) of eight HDDs, they performed a preference pairwise comparison with fifty-six participants, in terms of loudness and annoyance for each HDD (preference test as the optimum for HDD sound design is the noise reduction). Key findings were that the 'noisiness' index constructed from the jury tests showed a stronger correlation with the LL than the SPL. Also authors noted that the preference index (PI) cannot be predicted only by the LL and mention the importance of adding more psychoacoustic parameters to predict the PI of HDDs, (e.g., Sharpness, roughness, and fluctuation strength). Susini, McAdams et al. (2004) presented a useful method for sound evaluation to characterize listeners' preferences of indoor air-conditioning units in order to validate the hypothesis that the dissimilarity and the preference judgments are based on the same acoustic or psychoacoustic parameters. Each sound sample was perceptually characterized by three common dimensions, by using the multidimensional scaling analysis program CLASCAL and correlated with the A-weighted noise-to-harmonic energy ratio (NHRA), spectral center of gravity of the noise part (SCN), and loudness (N). Results showed two classes of listener's preference, the one canceled primarily with loudness while the other with the SC and NHR. Altinsoy, Kanca et al. (1999) performed a study over sound quality of vacuum cleaners. The psychoacoustic parameters (Zwicker loudness, sharpness, fluctuation strength, roughness, tone-to-noise ratio and prominence ratio) of six types of vacuum cleaners were correlated by following a regression analysis, with the results of a subjective acoustic evaluation performed by a jury of sixteen participants, who ranked each sound in a nine point scale, over a number of adjective pairs (powerful/powerless, acceptable/unacceptable, booming/not booming, bass/high pitched, comfortable/disturbing, loud/weak, soft/hard, harmonic/discordant,

regular/variable). The results of the subjective evaluation, statistically analyzed and a "perceived annoyance factor" were obtained and used in the regression analysis. The results indicate that the annoyance index is directly affected by Zwicker loudness (R-squared coefficient equal to 0,85), the Sharpness (with R-squared coefficient equal to 0,78) and the Prominence ratio and tone-to-noise ratio (with R-squared coefficient equal to 0,53 and 0,70)respectively. The Roughness (with R-squared coefficient equal to 0,15) and Fluctuation strength (R-squared coefficient equal to 0,45), were found to affect significantly less.

From the automotive industry perspective, SQ is considered as highly important issue. Numerous amounts of studies have been conducted within the framework of car interior sound quality. Studies were undertaken regarding car power windows (Lim 2001, Nykanen and Sirkka 2009), car doors (Parizet, Guyader et al. 2008) or car engines (Pinero, Gonzalez et al. 2002, Gonzalez, Ferrer et al. 2003, de Oliveira, Janssens et al. 2009). Lim (2001) performed a study on the SQ of power windows in order to identify the principal attributes that affect their perceived annoyance and related them with sound parameters. Each attribute analyzed as design requirement (technical attributes) and preference criteria, as design specifications, defined. In other terms, authors defined a set of design specifications which affect the sound percept of power windows and defined their values in order to achieve higher preference. For example, they identified that the attribute Seal Separation Noise, which is caused by the static friction between the seal and the glass, should be valued as Smax<30 sones or LA<63 dB(A). The full list of attributes is clustered into four groups, defined as: overall intensity or loudness, the sensation of squeal/squeak, by sounds with distinct impulses, and lastly the dominating, time-varying effect. According to the authors, within the same category, the attributes share similar generic temporal or spectral

structures that clearly define their character. Nukannen and Sirkka (2009) modelled annoyance and perceived product quality as functions of subjectively measured qualities and of acoustic quantities. For the first model as subjective measured qualities (independent variables), they used the means of subject's judgments for the attributes dull, loud, steady, powerful and under-powered and as dependent variables the means of all subject judgments of annoying and overall product quality. For the second model the same parameters were used as independent parameters (SPL, Loudness, Sharpness, Roughness, Fluctuation strength, Tonality, Prominence ratio, Specific prominence ratio, Tone-to-noise ratio and Time for window opening). Three perceptual qualities: loud, dull and steady were identified as important for the impressions of annoyance and overall product quality. Annoyance was also predicted with high accuracy by a model based on loudness and sharpness of the motor sound. Overall product quality was well predicted by a model based on loudness, sharpness and speed variations of the motor.

Regarding the door sound, Parizet, Guyader et al. (2008) performed an analysis over perception of the noise coming from a car's door closure. A paired comparison for similarity and quality ratings were linked with signal parameters and perceptual dimensions. As a result, four timbre parameters were identified as most important, the frequency balance of the sound and its cleanness, sharpness and the spectral centroid respectively.

Engine noise is considered to be essential for vehicle interiors SQ. Pinero, Gonzalez et al. (2002) approach the evaluation of car engine noise by correlating psychoacoustic parameters with signal characteristics extracted from time signal in order to generate a Noise Quality Index (NQI) according to previous jury tests. The analysis was performed over two groups of diesel engines, with low r.p.m. (900 and

1500) and high r.p.m. (3000). For the TF analysis the signal spectra was divided in four different frequency bands covering the human audible range (from 20 Hz to 16 KHz). First, signals were demodulated to an appropriate frequency in order to translate the band of interest to base band. Next, demodulated signals were decimated by a suitable factor and then modulated again to adjust the band of interest to the whole range of the normalized spectrum. Finally, the Short-Time Fourier Transform (STFT) was calculated for every signal. For each of these four bands, the average and standard deviation of the energy was extracted, as well the average and the standard deviation of the instantaneous frequency. Regarding the psychoacoustic parameters, the loudness, sharpness (according to Zwicker and Aures definitions), roughness and fluctuation strength were calculated. By following multiple linear regression authors obtained the NQI by using psychoacoustic parameters which explains the 88,6% of the variability of the jury score, with the loudness, sharpness (according to Zwicker's method) and fluctuation strength to have significant contribution for noise perceived quality. Moreover, authors performed multiple regression analysis over each psychoacoustic parameter by using TF parameters in order to identify their relation. For the Low r.p.m sample it was discovered that the 98% of the variability of loudness depends only on the average energies of bands 1 and 3. The sharpness (Fastl and Zwicker) is related to medium band energies and instantaneous frequencies of highest bands, while the sharpness (Aures) only depends on the TF parameters of the highest frequency band. In Roughness and fluctuation strength relations, the corresponding significances were found to be the lower ones. Regarding the High r.p.m. sample, the loudness and sharpness were discovered to have the same relationships observed for low r.p.m., while there was no adequate model found in relation to the roughness and fluctuation strength.

Gonzalez, Ferrer et al. (2003) and de Oliveira, Janssens et al. (2009) applied active noise control (ANC) to engine noise in order to evaluate its effect on the SQ. Gonzalez, Ferrer et al. (2003) investigated the influence of active noise control techniques over sound quality. Authors approach the SQ through the evaluation of the sense of comfort, by using car noises case study. First, the authors studied the effect of ANC on psychoacoustic parameters (Loudness, Roughness, Tonality and Sharpness). ANC directly influences the loudness level, while the remaining parameters are not so clearly controlled by ANC. As ANC reduces low-frequency components that makes sharpness increase, which tends to decrease roughness after ANC operation. Tonality also decreases, but that is due to the fact that ANC reduces the spectral peaks of the sound. The second part of the study was the prediction of the sense of comfort by using two psychoacoustic parameters Loudness and roughness and as result an improvement of comfort for car engine noise is achieved using these descriptors, after ANC application. At the final phase, a subjective method using a jury test was conducted and results showed that comfort is directly related with the subjective sense of quietness. Nevertheless, the predictive comfort model failed to predict the jury test result for these signals.

2.4 Main findings from literature review

In summary, the literature review approaches the percept of an ICI by analyzing several related aspects, starting with the requirements engineering in order to illustrate the differences among the types of requirements and as well their role. The definition of each type of requirement is provided and as well where they are used in the product development procedure. Continue with the human perception to understand how a user receives information and which processes are taking place in order to construct a

feeling. Some basic information processing is presented, in order to demonstrate that each human interprets the physical properties of an object, such as an ICI, they interact with differently, and this variety of interpretations elicits different feelings.

Focusing on how feelings are triggered, the section 2.1.1 reveals the importance of sensory integration. In this section, the reviewed studies related to sensory integration several stimuli properties, such as roughness, length or height, naturalness or even action comprehension and space perception. Results indicate that senses are highly connected regarding the perception, and regarding auditory and haptic actions, used in the current study, are found to go beyond mere cue combination to an integrative nature (Sotofaraco and Deco 2009). While until now the delivered set of the design requirements were independent among them, these indications lead the analysis of the current study to structure the hypothesis that the integration of the engineering parameters used as design requirements should be investigated to define the percept of an ICI.

Moreover, this section exemplifies the importance of using non-visual senses, by recording their benefits over the interaction that takes place between humans and ICIs in its context: the in-car environment. This section is followed by the sub-topics related to the selected non-visual senses; the haptic and acoustic sense. Within these sub-topics a general overview for each sense is presented, and the broadly used engineering parameters related to them were revealed. This section is quite critical, as the engineering parameters used by several researchers to characterize the kinesthetic and acoustic percept are going to be the base for the selection process which is going to follow at the modeling phase of the current study. At this point, it should be noted ,as found to be the case in the presented review, that while several engineering parameters are already identified for both of the selected senses, according to our best

knowledge there is not yet any standard set that could be used as design requirements to characterize these senses accurately.

3. RESEARCH MEANS AND METHODS

This chapter presents the research framework to approach the issue of decomposing a feeling into appropriate design requirements and, in sequence, to investigate which design parameters should be used as design specifications, in order to achieve the target percept. The development of the framework was performed with extensive analysis and research over the presented problem (as presented in section 1.2) alongside the research affiliated company, the ACs supplier company which is responsible for the design and manufacturing of the ICIs. It was crucial to fully understand the nature of the problem and identify the root causes, in order to structure a comprehensive approach to deal with the objectives of the current study, as defined in section 1.3. To achieve it, a long term internship and visits to the first TIER company were conducted, to understand the path; starting from the initial point of receiving the design requirements from the AC, followed by the development phase and building prototypes, till the evaluation phase performed by the AC.

While focusing on the objective to approach the issue of how to decompose a feeling into appropriate design requirements and apply it to the design process, a wide range of scientific tools, methods and materials were used. The nature of the presented problem required a broad scientific research, covering areas from engineering such as Design of Experiments, manufacturing prototypes and statistical analysis, research tools from sociology regarding the interviews with normal users for the pair wise comparison. The construction of the framework comprises also the use of prototypes, which were used as case studies in each phase of the conducted research and off course materials regarding the instrumental measurements and software tools which were used for analysis purposes. The selection of the proper scientific tool and

material was a result of analysis of the needs and objectives of each step of the adopted framework.

3.1 Research framework

To approach the presented problem, the research focused on the wanted outcome, which was the percept of the ICI. The research framework was structured in three main phases (Figure 3-1).

The first phase was to approach the presented problem by investigating how normal users perceive each design requirement in order to identify which factors affect their perception. Moreover, the second phase was to investigate which acoustic and kinesthetic related engineering parameters indeed affect the target percept and should be included into the delivered design requirements.

As third phase of the proposed framework, was to identify which design parameters affect the design requirements and should be included into the set of the design specifications regarding the percept of an ICI.

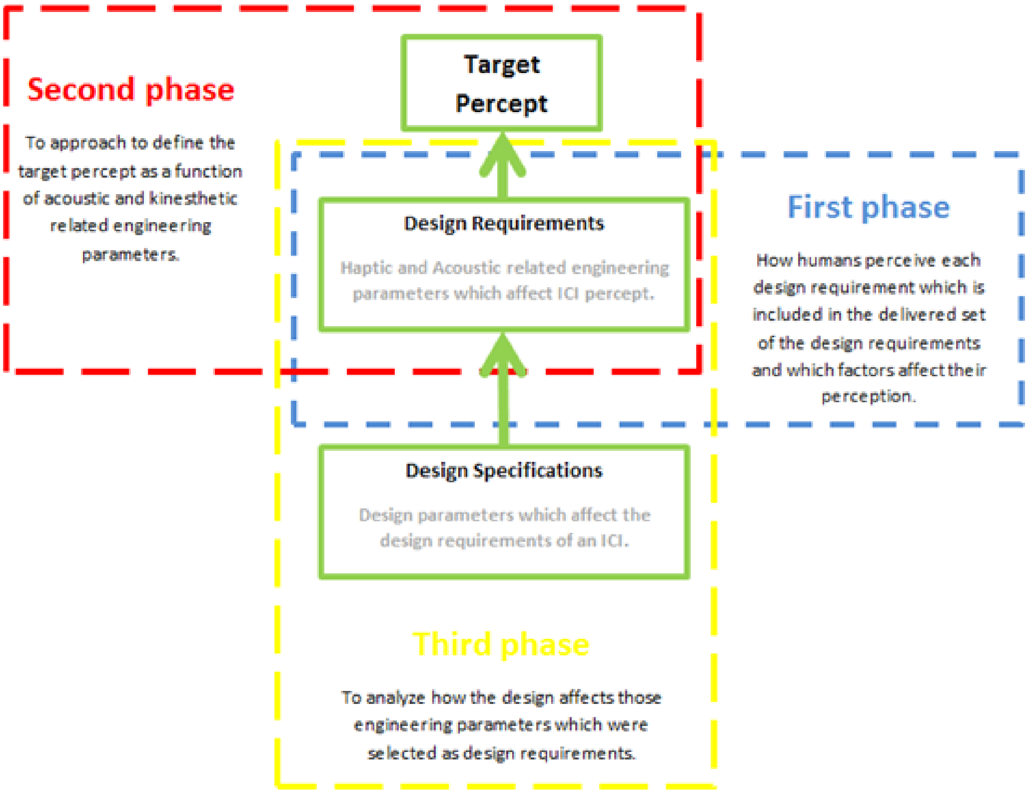

Figure 3-1 Research Framework

3.1.1 First phase – How humans perceive each design requirement

The first phase of the methodology was to understand why there is that inconsistency between the expected and the achieved percept, as formed by fulfilling the delivered design requirements. Based on the fact that the evaluation by the AC is performed by perceiving a button of an ICI (by pressing it) and the evaluation criteria for the AC's judgment were the delivered set of the design requirements, the first step was to investigate if normal people estimate the magnitude of each design requirement in a different manner than measured instrumentally. For instance, a judgment of an evaluation could be as rejected for the reason that AC's evaluators perceive one design requirement, for instance the Force to Stroke, with a lower value (i.e. lower force) than expected to be, even if the measured value of the Force to Stroke is within

the specifications bandwidth. As matter of fact, what is really important is not the measured value as measured instrumentally, but its percept when the evaluator presses the button.

As human perception works in an integrative way, by combining sources of information from several sensory channels, it was hypothesized that such way of processing should be present in a lower level, meaning at the level of each sense. For example, human perception over weather temperature, is not just defined by the measured temperature, but is also affected by the humidity, the wind, or other factors. The combination of different factors makes humans to perceive the measured temperature as colder or warmer. Hence, all parameters related to ICI percept interact among them and that interaction affects the human perception in a holistic manner. The proposed hypothesis was that humans when evaluating the magnitude of an engineering parameter, i.e. by pressing a button, are not only affected by the measured magnitude of the corresponding parameter, but also from the interaction among all or a set of engineering parameters that affect its percept. For instance, regarding the engineering parameter Force to Stroke, the proposed hypothesis is that a human does not perceive the same value with the instrumentally measured Force to Stroke, but their perception is affected by the combination of all the parameters which affect the percept and included into the delivered set of design requirements. For this reason, as first step to approach the problem was to target on human perception and to investigate which factors affect normal users when they estimate the magnitude of each design requirement which is included into the delivered set of the design requirements.

An experiment was conducted, to investigate how normal users perceive each engineering parameter, which until now is delivered as design requirement from the

AC. As the percept includes both the physical performance and human perception, the aim of this phase was to define the measured physical performance, as humans perceive it. In another sense, to define a perceived value for each design requirement, as a function of the factors that affect their perception, i.e. the engineering parameters that characterize the percept (design requirements) as measured instrumentally.

The goals of this phase are two. Firstly, to investigate how normal users perceive the magnitude of each engineering parameter, which is included into the delivered set of the design requirements as measured instrumentally. The second one, is to approach the hypothesis that the perception of each engineering parameter is being affected by the others engineering parameters which affect the percept. In other sense, the aim of was to define a perceived value for each engineering parameter as a function of the measured values of the all or a set of the engineering parameters which affect the percept of an ICI, in order to be used as design requirements.

3.1.2 Second phase - Defining the target percept as a function of acoustic and kinesthetic related engineering parameters

Each company aims to deliver to its users a specific feeling that represents the core values of the brand (Lindstrom 2005) and in automotive sector this feeling could be triggered through the interaction with an ICI with a specific percept. Following this, the second phase of the research framework aims to decompose the AC's predefined target percept into a set of design requirements that will be in position to deliver accurately the target percept as requested by the AC.

Although several kinesthetic and acoustic related engineering parameters have already been identified as critical regarding their impact over the percept of an ICI push button, according to the best of our knowledge, they have not been linked to metric

units in order to be considered as accurate design requirements. A lack of understanding remains, on how these engineering parameters interact among them of the percept of an ICI. The importance of selecting the appropriate engineering parameters and quantifying their contribution forms the objectives of the current phase, which is to approach decomposing the target percept as a function of a well-defined set of design requirements [Eq. 3-1].

Hence, the target percept p can be expressed as:

$$p = f(K_{1,} K_2, \dots K_{n,} A_{1,} A_2, \dots A_{m,}) \qquad 3\text{-}1$$

Where, $K_{(i=1,\ n)}$ represent the kinesthetic related engineering parameters and $A_{(i=1\ ,\ m)}$ represent the acoustic related parameters, which affect the percept of an ICI and should be included into the design requirements.

Primary was needed to define the first element of the function, the target percept p as requested by the AC. Existing prototypes, which were designed, manufactured and evaluated by the AC, were used as case study. The evaluation by the AC's evaluators over these samples was used as a criterion for achieving or not the target percept. Prototypes which were (judged as) accepted, meaning that they conformed to the target percept and as rejected prototypes which do not achieve the proper percept. Thus, the target percept p in Eq. 3-1 is a binary one, valued as 1 for the accepted prototypes (achieving the target percept) and 0 for the rejected ones. At this point should be noted that the conducted experiment at this phase was based on prototypes produced by the AC's supplier company which is responsible for the design and the manufacturing of the ICIs, by following the trial and error method as described in the section 1.2. These prototypes were evaluated by the AC, and their kinesthetic and acoustic physical performance was instrumentally recorded for the current study.

From these measurements, through a selective method (see section 5.2.1 and 5.3.2) several engineering parameters with physical meaning identified as critical and recorded. Finally, a statistical analysis was performed in order to identify which of the selected engineering parameters $K_{(i=1,\ n)}$ and $A_{(i=1,\ m)}$, as measured, indeed affect the target percept and also to quantify their impact ($coeffiecients$ a, b, c, . . , n) and their interaction among them [Eq. 3-2], in order to be considered as design requirements. As presented in section 5.3.3, interactions between engineering parameters have been removed, in order to use a linear relationship between the percept and the engineering parameters.

The target percept p could be expressed as:

$$p = \pm aK_1 \pm bK_2 \pm \cdots \pm cK_n \pm dA_1 \pm eA_2 \pm \cdots \pm nA_{n,}) \qquad 3\text{-}2$$

The analysis was performed step by step, starting with the modelling of the kinesthetic sense and then introducing the acoustic sense. For that reason, first a kinesthetic model (section 5.2) was developed to identify which kinesthetic related engineering parameters affect the percept of an in car interface [Eq.3-3]. The kinesthetic percept could be expressed as:

$$p = \pm aK_1 \pm bK_2 \pm \cdots \pm cK_n \qquad 3\text{-}3$$

In turn, an integrated model was developed (section 5.3.3), including both the acoustic and the kinesthetic related engineering parameters and as an output, as expressed in [Eq.3-2]. Figure 3-2 illustrates the research path of the research framework’s second phase.

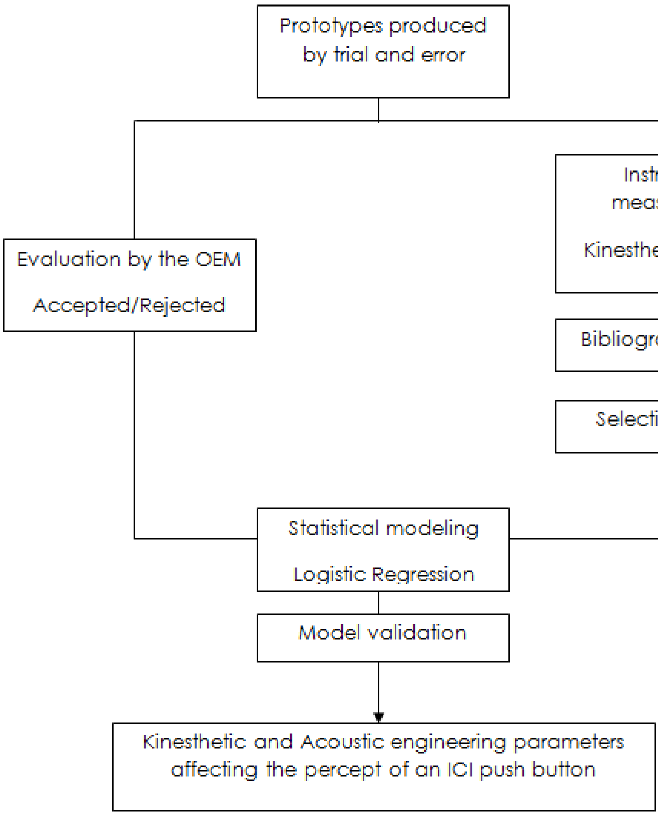

Figure 3-2 Research path to approach to define the target percept as a function of acoustic and kinesthetic related engineering parameters in order to be considered as design requirements

By this way within this phase will be investigated how each engineering parameter impacts the target percept and which is its contribution on it. To develop that function, first it should be identified which engineering parameters indeed affect the percept of a push button and then to define the connection among them and their contribution weight. Accordingly, existing prototypes of push buttons were collected, which were produced by the supplier company, by following the common trial and error method. Some existing prototypes had their kinesthetic and acoustic percept on target (accepted) while some others were out of the target (rejected), according to the AC judgment. The kinesthetic and acoustic behavior of the collected push buttons were measured instrumentally and, by following a statistical analysis, were identified as of

which and how kinesthetic and acoustic related parameters affect their percept on the AC judgment of being on target or not.

The goal of the second phase was to approach to identify which and how kinesthetic and acoustic related engineering parameters affect the percept of an interface. The aim was to define the target percept as a function of engineering parameters [Eq.3-2]. The result of the analysis of this phase will show which engineering parameters indeed affect the percept and will point out which of them should be included into the delivered set of the design requirements.

3.1.3 Third phase – Identifying the influence of the design on the performance of an interface

From the first prototype version, till the final approved one, the supplier company proceeds with design modifications by following the trial and error method in order to achieve the wanted percept. A critical point is to make clear that the design requirements "define" the percept but cannot be controlled as they correspond to the interface's performance. A supplier company affects the performance of an interface (the design requirements) through the design, by directly changing a set of design parameters (design specifications). To follow up the process, a supplier company has the ability to modify the design through the design specifications, and through the design alterations they affect the performance of an interface (the design requirements) and the performance combined with the human perception, defining the percept of the interface. Design specifications are the most fundamental characteristics of a design and the design requirements and constraints flow from them. The objective of the current step of the research framework is to approach to define the target percept from the design process point of view, meaning to provide at

the initial stage of the design process the knowledge and the ability to fully control the percept through the design. Thus, it is vital to analyze how the design affects the performance of an interface's push button. From the previous phase of the presented framework, it was approached to be identified which and how haptic and acoustic related engineering parameters affect the percept in order to be regarded as appropriate design requirements. In this phase of the framework, what will be analyzed is how the design affects those engineering parameters which were selected as design requirements. This phase shifts the analysis a lower level, as the design is the one that affects the performance.

The design of the mechanism beneath an interface affects its performance; for instance, the length of the button's guides affects the travel of the button. This example shows how a design parameter (length of the guide) affects a design requirement (distance to stroke- DS). The problem that the study deals with is the impact of each design parameter over each design requirement. Following the previous example, one could note that the design requirement DS, except the design parameter length of the guide could also be affected by another one, for instance the gap of the button's guide, which if it is too narrow it might not leaving the button to travel all length of the guide and as outcome it might have a button with a different percept. This issue is the objective of this phase: to identify which design parameters and how affect each design requirement, in order to be considered as design specification [Eq. 3-4 and Eq. 3-5] and could be expressed as:

$$K_{i=1,\ n} = \pm aD_1 \pm bD_2 \pm \cdots \pm nD_w \qquad 3\text{-}4$$

$$A_{i=1,\ m} = \pm dD_1 \pm eD_2 \pm \cdots \pm fD_w \qquad 3\text{-}5$$

Where $K_{(i=1,\ n)}$ and $A_{(i=1,\ m)}$ denotes the kinesthetic and acoustic related design requirements, respectively. The $D_{(i=1,\ w)}$ represent the design parameters that affect the design requirements and in sequence the performance of the ICI. The contribution of each design parameter is dedicated with the coefficients $a, b, c, \ldots n$. The design parameters which indeed impact over the design requirements ($D_{(i=1,\ w)}$), will be considered as design specifications.

To proceed into the modelling phase, a designed experiment was performed with new prototypes specially designed and produced for this step of the research framework. At this phase the use of existing prototypes, as used in the previous one, was inadequate as the changes on the design parameters were performed by following a trial and error method which was not designed. At this point it was needed to perform specific changes over a set of the most critical design parameters in order to record their impact. Design of Experiments (DOE) techniques enables designers to simultaneously determine the individual and interactive effects of many factors that could affect the output results in any design. First, an analysis performed over the under-analysis element, an ICI push button, as a selection process to identify which design parameters are the most critical and usually used by the supplier company to adjust the behavior of an interface. Moreover, basic levels selected for each design parameter and the design matrix were structured. Although, the production of the prototypes was a quite costly procedure, as specially designed tooling was needed, the necessity to identify the impact of the design over the performance forced the supplier company to proceed with this investment. Moreover, instrumental measurements were performed over the new prototypes, in the same method as followed in the previous phase of the research framework. The results of the measurements value each design

requirements that affects the percept $A_{(i=1\,,\ m)}$ and $K_{(i=1,\ n)}$, and the analysis performed to identify the impact of the design parameters $D_{(i=1\,,\ w)}$ on them.

3.2 Methods and material

This section presents the methods and the materials which used in each phase of the research framework.

3.2.1 Methods

For the first phase of the research framework, an experiment with normal users contacted in order approach to understand if they perceive the magnitude of an engineering parameter which is included into the delivered set of design requirements, as measured instrumentally. In other sense the objectives of this study were to: 1) to evaluate correlations between the perceived engineering parameter and the corresponding parameter as extracted from the force-displacement curves; 2) to evaluate predictive models by using multiple instrumental parameters as predictors.

The goal of this phase is not to identify which percept is the target one, as this decision was already defined by the AC with specially selected focus groups. The goal is to identify which factors affect the perception of a normal user.

As it was impossible to give to each participant an interface and to ask directly by following the method of direct questioning (Edwards 1983), for example how much force you applied to activate a button, the route was the design of the experiment to a comparison method. In such case, a participant would have to judge for example if a button needs a higher force, in comparison with another button, in order to activate it. In that sense, through an experiment, participants would have to compare ICIs with different performance (different measured values for each engineering parameter which are included into the design requirements), and to distinguish which ICI has a

greater/lower magnitude for each engineering parameter. In that sense, the aim is to identify which factors (measured values of engineering parameters) affect participant's judgments. According to Edwards (1983), the ordering of objects according to their measured value is said to be on a *physical continuum* while the ordering basis on judgments is said to be on a *psychological continuum* and the methods used for studying these relationships are known as *psychophysical methods.* Everything starts from the pioneer Louis Thurstone, an American psychologist, who developed the law of comparative judgment (Thurstone 1927), provides a method to convert subjective paired comparisons into one-dimensional quality scores. Since Thrustone method new methods for scaling a stimuli have been developed, known today as psychological methods as the interest shifted to the psychological scale values (Edwards 1983). Psychophysical models were originally intended to relate a single sensory attribute to a single instrumental measurement and the assumption was that the instrumental measurement was a direct measure of the corresponding sensory modality. To proceed with this experiment we target on Sensory Analysis. Sensory analysis include two main parts, the laboratory sensory analysis where a trained panel is used to measure sensory properties of products, and the consumer analysis, where consumer population is used to predict consumer responses for products (Bi 2006). Discriminative analysis and descriptive analysis are the main methodologies used in sensory analysis. According to Bi (2006) there are six standard discrimination methods:

- The 2-Alternative Forced-Choice method (2-AFC) or pairwise comparison, where the panelist receives a pair of coded samples, A and B, for comparison on the basis of some specified sensory characteristic is asked to select the sample with the strongest (or the weakest) sensory characteristic.

- The 3-Alternative Forced-Choice method (3-AFC), where the panelist receives three samples of the product and the two of them are the same and is asked to select the sample the strongest (or the weakest) sensory characteristic.
- The Duo–Trio method, where the panelist receives three samples of the product and the two of them are the same, while the one is labeled as 'control' and is asked which one is the same as the control.
- The Triangular (Triangle) method, where the panelist receives three samples of the product and two of them are the same and is asked to select the odd sample.
- The A–Not A method, where the panelist first take time to familiarize with the 'A' and 'Not A' samples. One sample which belongs to the category A or Not A is presented to the panelist and the panelist has to choose in which category the presented sample belongs.
- The Same–Different method, where a pair of samples is presented to the panelist. Each pair could be as AA, BB, AB and BA. The panelist has to choose if the two products of the pair are the same or different.

In our case, consumer sensory was selected in order to identify how normal users perceive the engineering parameters which are used as design requirements. To proceed with the consumer sensory analysis as a closer method to the nature of our comparison and the goals of the study, the pairwise comparison method was selected. Moreover, the multiple regression was chosen to perform the analysis as it is quite useful in sensory science where one of the main focus points is to find relations between data sets, for instance between perceived and the corresponding measured data (Næs, Brockhoff et al. 2011).

For the second phase of the research framework, as previously stated, the target percept p has a binary nature, valued as 1, the ICI which achieving the target percept and as 0 those which their percept is not the desired one. As one of the common approaches to model a binary dependent variable is the logistic regression, it will be considered that the response of an individual unit (i.e. a push button from an ICI) can take one of the two possible values (1 = accepted and 0 = rejected). Hence, the logistic regression takes the form:

$$\log(\frac{p_i}{1-p_i}) = a + \beta X_i \qquad 3\text{-}6$$

In which: $p_i = P[Y_i = y_1[X_i]$ – response probability to be modeled; a - intercept parameter; β - vector of slope parameters; X_i - vector of explanatory variables.

Or in other form (Kleinbaum and Klein), the logistic model may be written as:

$$p_i = \frac{1}{1 + e^{-(a+\beta X_i)}} \qquad 3\text{-}7$$

Besides the Multiple Logistic Regression, there are other statistical methods that may be used to find the importance of each engineering parameter in the acceptance/rejection of a push button in an ICI. A very well-known statistical method is the Linear Discriminant Analysis (LDA). LDA is generally used to analyze the impact of several normally distributed covariates in the discrimination of groups (in this case 2 groups: accepted vs. rejected). However, as Table 3.1 shows (see section 5.2.2), the hypothesis that each covariate under analysis is normally distributed is rejected at the 10% significance level for the variables PL and DS. As one of the main assumptions of LDA is violated – normality of covariates, the proposed methodology will focus on logistic regression to explore the contribution of each covariate. Note that logistic regression is more flexible in terms of assumptions as normality is not required, though it can only discriminate between 2 groups. As in this case, two

groups are in interest: accepted versus rejected push buttons, thus logistic regression the classification method was chosen to pursue the analysis.

Table 3.1 – Normal distribution

Variable	Description	K-S test p-value	Result at 10% significance level
PL	Pre-Load	0.006	Reject
FS	Force to Stroke	0.977	Do not reject
DS	Distance to Stroke	0.081	Reject
FR	Force to Release	0.979	Do not reject
DR	Distance to Release	0.657	Do not reject
SA	Ratio of FS over DS	0.418	Do not reject
Sl	Ratio of FR over DR	0.275	Do not reject

For the third phase of the research methodology, the experiment was performed at the research affiliate company's plant. Hence, to follow a full factorial experiment was quite time and cost demanding and moreover, in our case the higher-order interactions (third-order and higher) are not important, as the wanted was the information on the main effects and the two-order interactions, which can be extracted by a fraction of the full factorial experiment. A type of orthogonal array design which allows experimenters to study main effects and desired interaction effects in a minimum number of trials or experimental runs, termed as fractional factorial design selected for this phase of the research methodology. The Orthogonal Array (OA) designs and Robust Design Methodology recommended by Dr Taguchi.

Robust Design Methodology (RDM) is a quality improvement engineering method that seeks the lowest cost solution to develop product design specifications based on customer requirements (Chen and Chuang 2008). Pioneered by Dr. Genichi Taguchi,

RDM is a powerful method to optimize the quality of a system and in parallel reduce cost and development interval. Taguchi found that developing robust product designs was often less costly than controlling causes of manufacturing variation and hence it is often possible to simultaneously improve product quality and decrease manufacturing costs (Moeeni, Sanchez et al. 1997).

According to Taguchi, Chowdhury et al. (2007), when a product does not work properly under different conditions, design constants (design specifications) have to change so that it would function well. This is considered parameter design in the old sense. In quality engineering (QE), to achieve an objective function by altering design constants is called tuning. Under the Taguchi method, functional improvement using tuning should be made under standard conditions only after conducting stability design because tuning is improvement based on response analysis.

Robust Design methodology is one phase of the Taguchi method, a three-step strategy for the development of high quality products: the system design, parameter design (robust design) and tolerance design, by pointing at the importance of using experimental methods regarding the parameter and tolerance design (Arvidsson and Gremyr 2008). Depending on what the AC wants the product to perform, the objective function, there are several technical means to achieve it. The selection of the mean for this objective function is called system design (Taguchi, Chowdhury et al. 2007). It is the phase where the architecture of the system is defined, in order to meet the objective function and fulfill the delivered design requirements. In system design, the product and process design stage are involved, where the selection of materials, components, process analysis and manufacturing process, etc. are included. Within this phase, the parameters levels of the subsystems are defined. In order to perform an optimization in terms of quality, analysis must be performed by varying parameters

levels. This is the second phase: the parameter design. The optimum levels for the control factors that do not affect the manufacturing cost and minimize the quality loss are defined (Phadke 1995). The objective of parameter design is to optimize the settings of the process parameter values for improving quality characteristics and to identify the product parameter values under the optimal process parameter values (Chen and Chuang 2008). As a final step is the tolerance design, a phase where product quality limitation is set and the tolerances around the optimum levels of the control factors are defined. This phase could be seen as a trade of between the reduction of the quality loss and the manufacturing cost, as the reduction of the tolerances being performed regarding their cost effectiveness(Phadke 1995).

Parameter design is the core of quality engineering, as it is used to improve a system and to find the ultimate functionality of a system (Taguchi, Chowdhury et al. 2007). Within the framework of the current study, in order to explore which and how design parameters affect the performance of an interface in order to be considered design specifications, the parameter design was adopted.

Robust design methodology begins with the idea of designing an engineering system to achieve the desired objective function. Passing from the system design, implies that the required understanding of the system has been acquired, in order to start the tuning process. The basic idea of the Robust Design methodology is that through the analysis of the design parameters over the objective function of the system, could lead to the optimization of the design to achieve the objective function.

Robust design methodology includes the following steps:

1. Identification of the objective function and assignment of the Signal to Noise ratio
2. Selection of the design parameters

3. Determining the number of levels for the design parameters
4. Selection of the appropriate orthogonal array
5. Conducting experiments
6. Analysis of the experimental results using the Signal to Noise ratio and ANOVA analyses
7. Validation

The two main tools used in Robust Design methodology are: signal to noise ratio for measuring the quality and orthogonal arrays in order to study many parameters simultaneously. A key point of the Robust Design methodology is the use of orthogonal arrays, a statistical tool which allows the study of a large number of decision variables with a small number of experiments.

3.2.2 Material

Regarding the prototypes used as case studies for the three steps of the research framework, it should be noted that all of them are real case studies and provided by the research affiliate company. The instrumental measurements were performed in the Instituto Superior Tecnico and the needed software to perform the analysis was also provided by the faculty.

3.2.3 Prototypes

As case study, an ICI push button (with metal springs support) was selected. For the first phase of the research framework, nine buttons of the bezel of the AUDI A3 were used for the pairwise comparison. A scheme of the bezel is illustrated in (Figure 3-3).

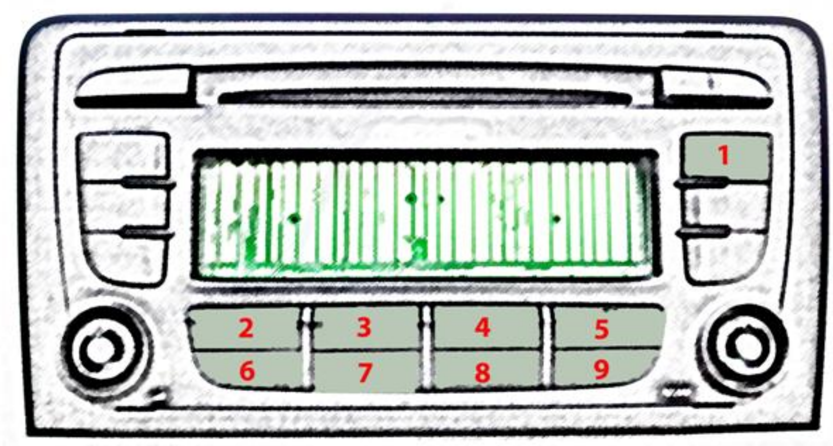

Figure 3-3 Case study of the first phase - AUDI A3 radio bezel

For the second phase, the AUDI A1 bezel was selected, which includes 16 buttons (Figure 3-3). Nine prototypes from different development phases which were produced by trial-and-error method were used (144 buttons). The prototypes were evaluated by the AC and judged as accepted and rejected, in sense of conforming with the target percept or not.

Figure 3-4 Case study of the second phase - AUDI A1 radio bezel

For the third phase, and for practical reasons, as a case study only one button of the A1 bezel was selected (the same as used in the second phase of the framework) the eject button (Figure 3-5).

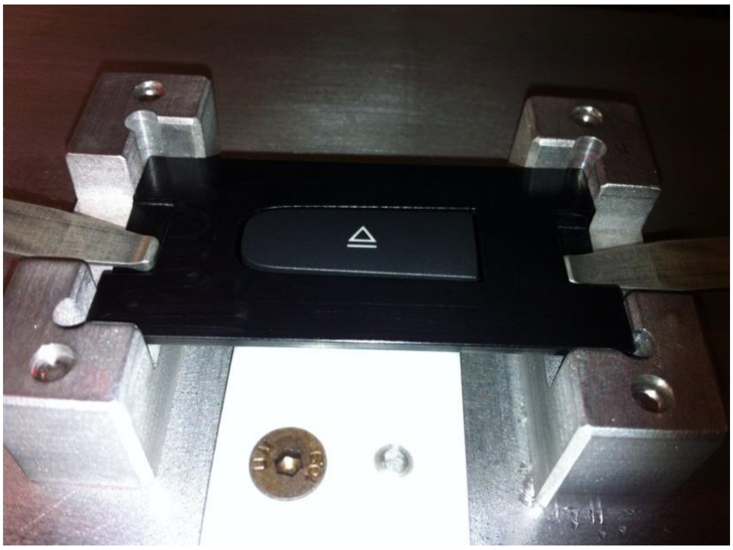

Figure 3-5 Case study of the third phase - AUDI A1 eject button

3.2.4 Instrumental measurements

Kinesthetic measurements

To measure the physical kinesthetic behavior of the buttons, an INSTRON 5544 (Figure 3-6) universal testing machine was used.

Figure 3-6 INSTRON 5544 - kinesthetic measurements

To perform the kinesthetic measurement and to extract the force/displacement curve from each push button of the ICI, the following procedure was used:

- The ICI was placed on the INSTRON base, supported by a jig to guarantee that the surface of each button is perpendicular to the machine. The machine was set into the "zero" position adjusting the pin of the machine on the center of the button’s surface, in a way that any slight movement against the button would start recording a load.
- The machine controller was set to start the movement of the button until reaching a specific force value (7 N) with a specific speed (3mm/sec). When the machine stops, its position kept as the start one for the release movement.
- The machine controller was then set up to make the movement in inverse direction and to stop when a force value of 0.1 N is reached (the theoretical value should be 0, but 0.1 was adopted to assure an adequate contact between

the pin and the button), keeping the same speed as used for the press movement.

Acoustic measurements

To measure the acoustic behavior of the interface a Larson Davis Microphone (Figure 3-7) with the associate pre-amplifier as shown below was used. The sensitivity of the system is 47,63 $\mathrm{Pa.mV^{-1}}$.

Figure 3-7 Larson Davis Microphone

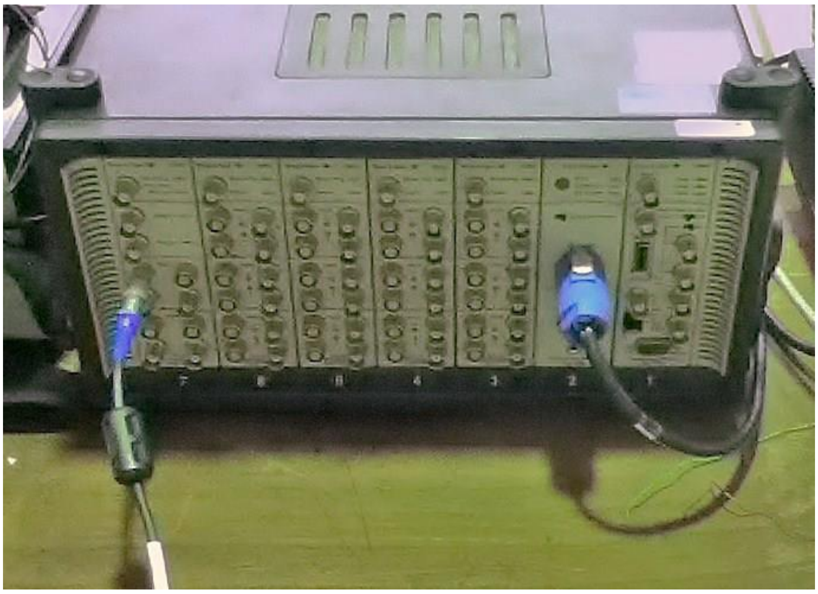

Figure 3-8 B&K 3560D Pulse

The microphone was supported by a tripod and linked to an Acquisition front-end to an Input Module, B&K 3560D Pulse (Figure 3-8).

The software "Pulse LabShop" was used to perform the measurements and obtain the data. All the acoustic measurements were performed in an anechoic chamber with absorbing materials (Figure 3-9).

Figure 3-9 Performing measurements in the anechoic chamber

For the acoustic measurements the following procedure were used:

- In order to perform the measurements, two persons were needed, one inside the chamber who had to press the buttons of the interface and the other one outside controlling the software. With a light signal the person outside the chamber informs the person inside to press or release the button in order to perform the measurement.
- The interface was placed in the anechoic chamber on a base covered with absorbing material base. This base was stood upon a tripod and above it was placed the microphone with 3mm distance from the interface.
- The acoustic measurements were performed for the two phases of the button independently: the pressing and the releasing one. Thus, two signals were obtained for each button, respectively.

4. FIRST PHASE – DEFINING A PERCEIVED VALUE FOR EACH DESIGN REQUIREMENT

Under the scope of the current study, the first phase of the research framework approach to understand how normal users perceive each engineering parameter which is delivered as design requirements by the AC and to see if the perception of an engineering parameter is a result of all or a set of the engineering parameters which impact the percept of an ICI as measured instrumentally. For instance, the perception of an engineering parameter if can be estimated as a function of the engineering parameters which are delivered as design requirements as measured instrumentally.

The engineering parameters which are delivered as design requirements were taken, a priori, as the most relevant kinesthetic related engineering parameters for an effective communication channel with the driver.

To address this issue, the kinesthetic sense was first explored. An experiment was performed to investigate how humans perceive each of the three main kinesthetic-related engineering parameters, which are used as design requirements: the Pre-Load (PL), the Force to Stroke (FS) and the Displacement to Stoke (DS).

4.1 Experimental methodology

A car's control interface (with metal springs) was chosen as a representative element in order to perform the analysis; the kinesthetic and the objective associated parameters of the interface push buttons were studied. Nine buttons in the ICI were selected for study. The selected method to perform the experiment was a pairwise comparison and the use of nine buttons had as an outcome 72 pairs, 36 of which were

different (excluding the inverse pairs i.e. comparison between button 1 and button 2 assumed to be equal with the comparison between button 2 and button 1). That sample (36 observations) was considered enough for investigating three independent parameters (lower than the 10% of the sample). Instrumental measurements were performed and the force/displacement curve of each button recorded in order to extract from those engineering parameters which are delivered as design requirements. Moreover, an experiment with normal users was performed, in order to create a perceived value for each engineering parameter. The perceived value of each engineering parameter is represented with the abbreviation of the name of the parameter with the indicator *p*, (for example PL_p) while the measured value of each parameter is represented with the name of the parameter the indicator *m*, for examplePL_m.

Finally, a statistical analysis was performed with the data obtained from the instrumental measurements and the experiment with normal users, in order to evaluate correlations between the perceived engineering parameter and the corresponding instrumental parameter as extracted from the force-displacement curves and to evaluate predictive models by using multiple instrumental parameters as predictors. The methodology includes two main parts. The first one is to identify if the perception of an engineering parameter is affected only by the corresponding engineering parameter as measured. The second part is to explore if the perception of an engineering parameter is being affected also by the other engineering parameters which are included into the design requirements, except the corresponding parameter.

4.2 Extracting the engineering parameters

Force/displacement curve deploys the mechanical behavior of a push button, as illustrated in Figure 4-1. The upper line (blue) represents the pressing movement and the lower line (Zuidhoek, Visser et al.), the release one. Only the pressing curve was used to identify the parameters relevant to kinesthetic.

The pressing curve starts from the 0.0 N and 0.0 mm with an abrupt slope, reaches a force value bellow 1.0 N and remains steady for a while. The point of the curve where the first derivative changes the sign is considered as the first kinesthetic related engineering parameter, the Pre-Load (PL [N]); in other words, the load peak of this abrupt slope is taken as the value for the parameter. The perceived feeling of this parameter is the initial hardness of the button, when someone tries to press it. This parameter is currently used as design requirement from the AC.

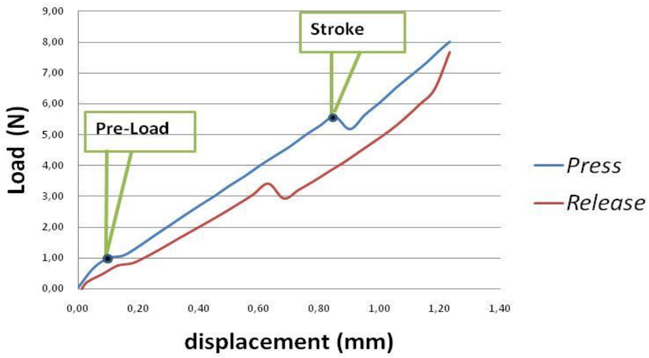

Figure 4-1 Mechanical behavior of an interface push button

After the second inflection point (end of the Pre-load duration), the curve follows a constant slope, which ends at the stroke point. The stroke point is the activation point of the button (click point). The stroke is another critical point that defines the main purpose of the button: it is its activation point. The stroke point is analyzed in two components: the Force to Stroke (FS (N)), the needed force to reach the activation

point, and Displacement to Stroke (DS (mm)), the distance the button has to run to reach the activation point (the travel of the button). Both FS and DS are used currently as design requirements.

Considering the parameters that are specified as affecting the kinesthetic sense (as delivered design requirements) a simplified model can be considered as in Figure 4-2.

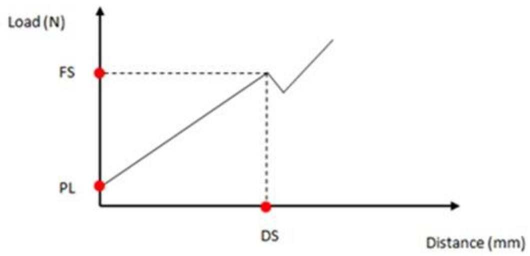

Figure 4-2 Kinesthetic sense parameters PL, DS and FS

4.3 Interviews methodology

In order to identify how a human perceives each engineering parameter, a pair comparison experiment was performed on a sample of 32 individuals. Participants were normal users, 17 of them were from the University (PhD students and Faculty members) and the other 15 were employees (engineers, operators,..) from the research affiliate company. The experiment was performed in two different places, following the same identical procedure. For the 17 members of the University, interviews were performed inside the campus, while the interviews with of the workers were performed at the affiliate's company plant.

Each individual had to compare each pair of buttons and to assess each parameter with three possible options: higher/longer, equal or lower/shorter (higher/ lower for the PL and FS because their value is force, and longer/shorter for the DS because the value is distance). The higher/longer, equal and lower/shorter were given the values 1,

0 and -1, respectively. As participants had to make a comparison between pairs of buttons (button i and button j), the results from the experiments were 32 matrices (one per participant) with the results of the comparison for each sense parameter, PLp_{ij}^{k}, DSp_{ij}^{k} and FSp_{ij}^{k} respectively. Where first is the abbreviation of the parameter's name, *p* indicates that it is a perceived parameter and the *ij* represents the pair of the comparison. The *k* stands for the participant identification number.

All participants were explained and asked to evaluate the three design requirements, the Pre–Load (PL), the Displacement to Stroke (DS) and Force to Stroke (FS), as shown below:

1) Pre-load: force needed to make the button start moving (*Figure 4-3* a).

2) Displacement to stroke: displacement of the button, from its initial position until it reaches the activation point (to set up for the click point) (*Figure 4-3* b).

3) Force to stroke: force needed to activate the button's function (to trigger the click point) (*Figure 4-3* c).

In order to have accurate results and keep the experiment under controlled conditions, a standard procedure was set-up. The experiment took place in an isolated room where only the participant and the observer were present. Each parameter was tested on a different day to avoid any misjudgment caused by factors like fatigue or boredom. The participants were trained for these tests and their preparation involved an initial process of sensing, in terms of mental state (focus and concentration; instructions to use the same procedure and time limits):

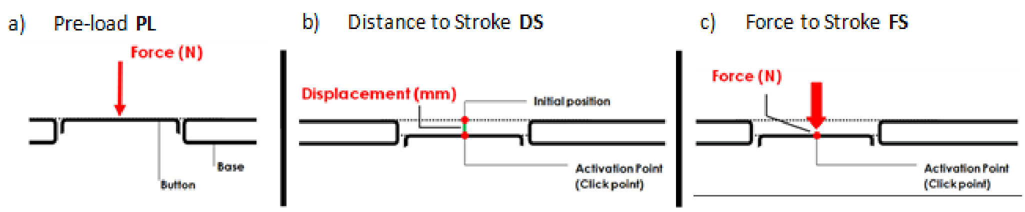

Figure 4-3 a) Pre–Load, b) Displacement to Stroke, c) Force to Stroke

Each participant was placed on a comfortable seat located in front of a table on which the ICI was located. All the elements, the seat, the table and the interface had fixed positions. Also, the position of the participants' hands was defined as a specific place marked on the table.

The observer explained to each participant what parameter he had to evaluate using an illustrated explanation for each parameter, in order to be clear what the participant had to "feel".

Specific instructions for each parameter were provided. Each participant was asked to perform a pairwise comparison involving all the buttons in a specific order (each button was compared against all the others),

Before starting the comparison, participants had one minute to touch, press and understand what was supposed to be done. Then, a maximum time interval of ten seconds was given to evaluate each pair of buttons.

Participants compared each pair of buttons (button i compared to button j) and reported to the observer his assessment. Each button i was compared to buttons j (j > i) in terms of higher, lower or equal feeling for the parameter under analysis.

The observer was recording all the answers of the participants in matrix format, where PLpij, DSpij and FSpij, standing for the comparison of button i and button j, can

assume the values of 1, 0 or -1, meaning that the feeling of the parameter (PL, DS or FS) for button i is higher, equal or lower than for button j, respectively.

4.4 Survey reliability

Reliability of a survey is the measure of whether the survey is measuring things consistently, and whether the results obtained from the survey can be relied upon. A survey's reliability affects its validity, as a survey that is not reliable in its measurements cannot produce fully valid results. While there are a number of quantitative reliability measurement techniques for survey design, especially in psychology and sociology, the two most common reliability measurement techniques used in HCI research are internal and inter-rater reliability techniques (Julie and Andrew 2003). The internal reliability technique is whether participants respond to the same question the same way when it is asked the second time, in a similar form. These types of questions are termed as "duplicate questions". The latter one is concerned about the consistency among responses given by different participants to the same question, which in opinion surveys, as in our case, it is arguable that the inter-rater reliability coefficient is a valid measure.

In order to investigate the reliability, a logic test was used over participants assessments to prevent biased responses. The test was based on internal validity technique, by using a sort of opposite questions. As it was quite time demanding for the participants to judge a pair ij and then the reversed pair ji, the logic test was based on the idea that when a participant judges that button 1 has for instance a higher Force to Stoke, between a pair button1 vs button2 and the same participant (for the same engineering parameter) judges that button 2 has a higher value between the pair button2 vs button3, then automatically it means that button1 should be judged as

higher at the comparison of the pair button1 vs button3. This simple test was performed (results presented in Appendix 1 - Table 8.1) and the results showed that: regarding the engineering parameter PL, twenty participants were found to have not made any mistake, regarding the engineering parameter DS, eleven participants and regarding the third engineering parameter, the FS, 15 participants. This indicates that the evaluation of the DS was the hardest one, as only the ~ 33% (11/32) of the participants were found to be consisted. The reliability of the other two parameters was also found to be low with ~ 47% (15/32) and ~62% (20/32), a fact that shows the difficulty for normal users to evaluate the measured values of the received design requirements. As result of this reliability test, only participants' judgments without mistakes were used in the modeling procedure. That means that the perceived parameter $\mathrm{PLp_{ij}}$, was a result of the sum of 20 matrices, $\mathrm{DSp_{ij}}$ was a result of the sum of 11 matrices and $\mathrm{FSp_{ij}}$ was a result of the sum of 15 matrices. Hence, for the $\mathrm{PLp_{ij}}^{\mathrm{k}}$, k is equal to 20, for the $\mathrm{DSp_{ij}}^{\mathrm{k}}$, k is equal to 11, and for the $\mathrm{FSp_{ij}}^{\mathrm{k}}$, k is equal to 15.

4.5 Data processing

The perceived global value for the differences for each parameter was taken as the sum of the 20, 11 and 15 matrices, $\sum_{\mathrm{k=1}}^{20} \mathrm{PLp_{ij}}$ (Appendix 1, Table 8.3), $\sum_{\mathrm{k=1}}^{11} \mathrm{DSp_{ij}}$ (Appendix 1, Table 8.4) and $\sum_{\mathrm{k=1}}^{15} \mathrm{FSp_{ij}}$ (Appendix 1, Table 8.5), and named as $\Delta\mathrm{PLp_{ij}}$, $\Delta\mathrm{DSp_{ij}}$ and $\Delta\mathrm{FSp_{ij}}$, respectively.

The measured parameters were transformed in an equivalent form as the perceived parameters. As the initial form was a specific value for each button *i*, for each measured parameter $\mathrm{PLm_i}$, $\mathrm{DSm_i}$ and $\mathrm{FSm_i}$ ($\mathrm{i = 1\ to\ 9}$) (Table 4.1), the difference Δ

was obtained for each pair of buttons, as performed for the perceived parameters. As a result, measured parameters will be considered as the ΔPLm_{ij}, ΔDSm_{ij} and ΔFSm_{ij} respectively (*j* is the second button of each pair) (Appendix1 Table 8.2).

Table 4.1 Measured values of the the engineering parameters PL, DS and FS

Number of button	PLm (N)	DSm (mm)	FSm (N)
1	0.451	1.000	5.208
2	1.115	0.700	5.221
3	0.541	0.950	5.399
4	1.319	0.949	6.548
5	0.995	0.850	5.578
6	1.398	0.700	5.367
7	0.763	0.950	4.698
8	0.520	0.900	4.875
9	1.014	0.901	5.611

4.6 Modeling

To test the proposed hypothesis, that users do not perceive each engineering parameter as instrumentally measured, but when are asked to evaluate one engineering parameter their perception is being affected by all or a set of the engineering parameters that affect the percept of an ICI, first a linear regression for each of the perceived parameter was performed against the corresponding measured parameter. As illustrated in the plots of the Figure 4-4, Figure 4-5 and Figure 4-6, a positive linear relationship identified for all the variables. That shows that the perception of each engineering parameter is being affected by the corresponding measured value. A weak relationship with outliers found for the PL and DS, with the coefficient of determination (R^2),to be 0.223 and 0.289, respectively. Regarding the FS, a relative strong relationship observed, with R^2 equal to 0.75. This indicates that for the PL and DS, participants assessments did not affected only by the measured

value of the corresponding engineering parameter, while regarding the FS, found to be more reliable such connection, even with a relative low $R^2 = 0.75$.

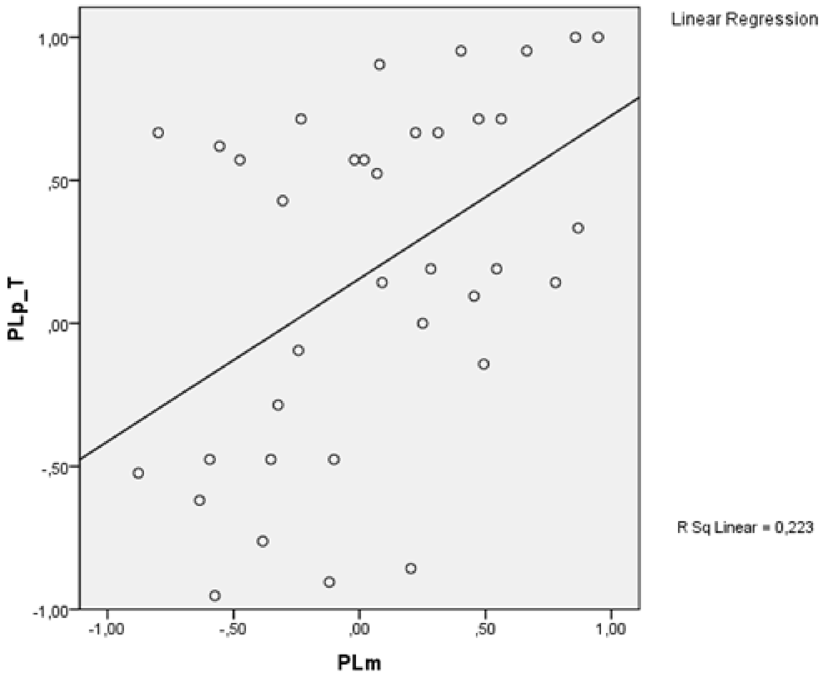

Figure 4-4 PLp against PLm

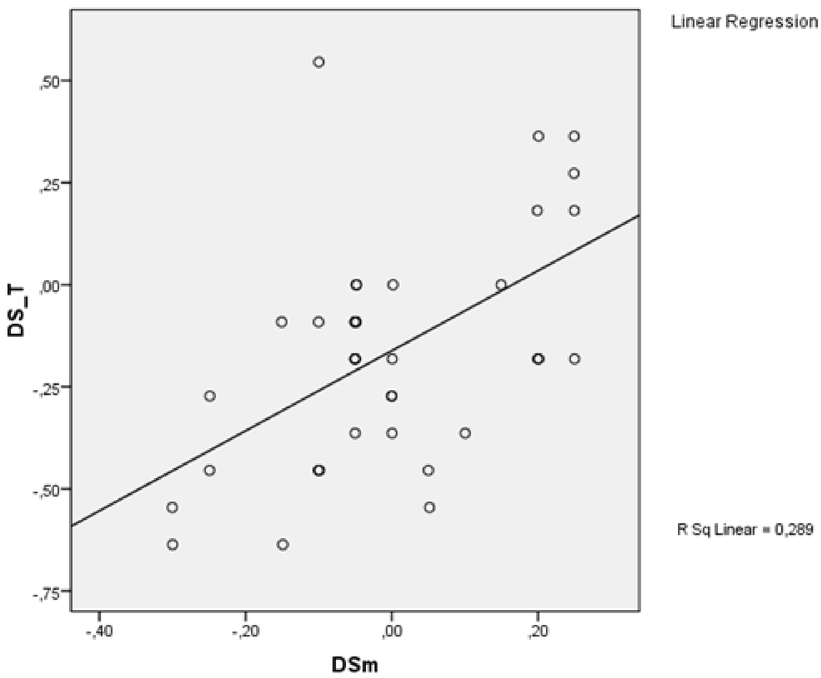

Figure 4-5 DSp against DSm

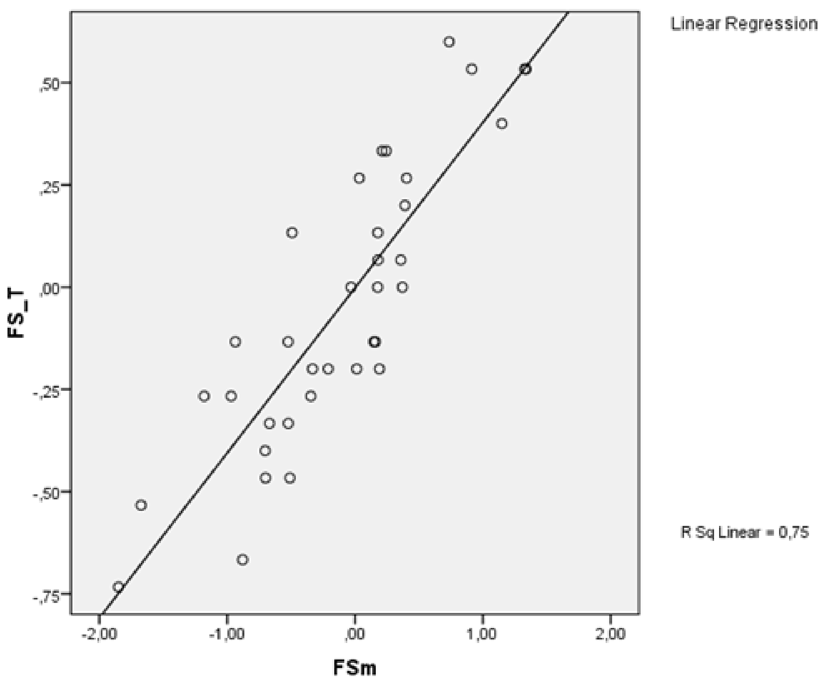

Figure 4-6 FSp against FSm

As next step to test the hypothesis, another regression analysis was performed for each perceived parameter against all the three measured engineering parameters. *Table 4.2* presents the linear regression of the dependent PLp against the independent PLm,DSm and FSm. As shown at the *Table 4.2,* the DSm presents a p value greater than 0.5, showing that is not significantly related with the dependent variable PLm. Hence, the predicted model which use only the independent variable PLm and FSm, presented at *Table 4.3*, Eq 4-1. As illustrated, both independent variables are significant ($p<0.5$) and the 77,6% of the variability of the perceived PLp is explained by the variability of the measured PLm and FSm. The model for the PLp can be expressed as:

$$\mathrm{Plp} = 1{,}261\mathrm{Plm} - 0{,}761\mathrm{FSm} \qquad 4\text{-}1$$

Moreover the Coefficient of the Variation (CV) Eq. 4-2 , in order to see if the model is powerful enough to be used for prediction purposes. CV is defined as the ratio of the sample standard deviation to the sample mean:. For the model calculated as:

$$CV_{reg} = \frac{S_{PL_p}}{PL_p} = \frac{0,3}{0,19} = 157 > 10\% \quad (4\text{-}2)$$

As observed the predictions intervals are quite wide (>10%), a criterion that shows that this model is not considered useful for prediction purposes.

Table 4.2 - Linear regression PLp against PLm,DSm and FSm

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	0,075	0,053		1,406	0,169
PLm	0,844	0,234	0,699	3,614	0,001
DSm	-1,184	0,598	-0,307	-1,979	0,056
FSm	-0,57	0,12	-0,706	-4,742	0

a. Dependent Variable: PLp

Table 4.3 – Linear regression PLp against PLm and FSm (DSm removed)

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
PLm	1,261	0,121	1,002	10,411	0
FSm	-0,761	0,08	-0,911	-9,459	0

a. Dependent Variable: PLp

Table 4.4 – Summary of the model PLp against PLm and FSm

R	R Square	Adjusted R Square	Std. Error of the Estimate
0,888	0,788	0,776	0,2957

Table 4.5 presents the linear regression for the dependent variable DSp against the independent PLm,DSm and FSm. As shown at the *Table 4.6*, the DSm presents a p value greater than 0.5, showing that is not significantly related with the dependent

variable DSm. This is a quite strange, as it shows that participants when were asked to evaluate the DS, their perception mainly was affected by the measured PL and FS and not the corresponding engineering parameter DSm. Hence, the predicted model which use only the independent variable PLm and FSm, is presented at *Table 4.6*, Eq 4-3. As presented, both independent variables are significant ($p<0.5$) and the 35.2% of the variability of the DSp is explained by the variability of the PLm and FSm. This is quite low and do not allow to be used as a predictive model. The model for the DSp can be expressed as:

$$\mathrm{DSp} = -0.44\mathrm{Plm} + 0.198\mathrm{FSm} \quad (4\text{-}3)$$

Table 4.5 - Linear regression DSp against PLm,DSm and FSm

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-0,118	0,044		-2,715	0,011
PLm	-0,437	0,191	-0,766	-2,289	0,029
FSm	0,195	0,098	0,512	1,989	0,055
DSm	0,019	0,489	0,01	0,038	0,97

a. Dependent Variable: DSp

Table 4.6 - Linear regression DSp against PLm and FSm (DSm removed)

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-0,118	0,04		-2,945	0,006
PLm	-0,444	0,097	-0,777	-4,567	0
FSm	0,198	0,065	0,519	3,055	0,004

a. Dependent Variable: DSp

Table 4.7 – Sumary of the model DSp against PLm and FSm

R	R Square	Adjusted R Square	Std. Error of the Estimate
0,624a	0,389	0,352	0,23

Table 4.8 presents the linear regression of the dependent FSp against the independent variable PLm,DSm and FSm. As shown at the *Table 4.8*, the DSm presents a p value greater than 0.5, showing that is not significantly related with the dependent variable FSm. Hence, the DSm removed, but as the *Table 4.9* presents, PLm presents a p-value greater than 0.5, showing that is not significantly related with the dependent variable FSm. Thus, PLm also removed and as presented at *Table 4.10*, the only significant important parameter to explain the FSp, it is its corresponding measured value the FSm. At table *Table 4.11* illustrated that the 75% of the variability of the perceived FSp can be explained by the variability of the measured FSm (as presented at *Figure 4-6).* The model Eq.4-4 for the FSp can be expressed as:

$$\mathrm{FSp} = 0.44\mathrm{FSm} \tag{4-4}$$

Moreover the Coefficient of the Variation (CV) Eq. 4-5, for the model calculated as:

$$CV_{reg} = \frac{S_{PL_p}}{PL_p} = \frac{0{,}174}{-0{,}0463} = -377\% > 10\% \tag{4-5}$$

As observed, predictions intervals are quite wide and this model cannot be considered useful for prediction purposes.

Table 4.8 - Linear regression FSp against PLm, DSm and FSm

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	0,027	0,032		0,843	0,405
PLm	-0,286	0,14	-0,41	-2,051	0,049
DSm	-0,503	0,358	-0,225	-1,405	0,17
FSm	0,526	0,072	1,128	7,325	0

a. Dependent Variable: FSp

Table 4.9 - Linear regression FSp against FSm and PLm (DSm removed)

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	0,011	0,03		0,35	0,728
FSm	0,451	0,049	0,967	9,235	0
PLm	-0,118	0,073	-0,169	-1,617	0,115

a. Dependent Variable: FSp

Table 4.10 - Linear regression FSp against FSm (PLm and DSm removed)

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
FSm	0,404	0,039	0,868	10,361	0

a. Dependent Variable: FSp

Table 4.11 – Summary of the model FSp against FSm

R	R Square[b]	Adjusted R Square	Std. Error of the Estimate
0,868	0,754	0,747	0,1748

4.7 Discussion

As a matter of fact, the hypothesis that humans do not perceive each engineering parameter as instrumentally measured, but their perception is being affected by all or a set of the engineering parameter that affect the percept of an ICI, proved to be true only for the engineering parameters PL and DS. On the other hand, regarding the perception of the engineering parameter FS, found to be affected only by the corresponding measured value. For all the cases prediction intervals were found to be quite wide, which points out that these models would not be useful for prediction purposes. Hence, the general outcome of this section could be that for all the cases, participants were not able to feel difference in an accurate level, in order to define perceived values for the design requirements to predict the wanted percept as ACs

desire. This result raises some important questions about the way design requirements are selected to ensure the percept of a push button.

The outcome of this experiment highlights the need to shift our research to the target percept as ACs experts define it. As Gerhard Mauter, manager of the AUDI "Control Haptics Team" in 2001 stated: "It's important to take haptics seriously, and a certain degree of sensitivity is also required. This kind of sensitivity is not really based on physical properties such as the way the fingertips react; it is more of a process of awareness that takes place in your brain".

5. SECOND PHASE - DEFINING THE ACOUSTIC AND KINESTHETIC RELATED DESIGN REQUIREMENTS OF THE ICI TARGET PERCEPT

Following the outcome of the previous phase of the research framework, the aim of this phase is to go further on the target percept with objective to identify all those engineering parameters which will be in position to define accurately the target percept of ICI and should be used as design requirements. At this phase of the research framework, a broader investigation was performed over the engineering parameters which define the percept, in order to identify all the possible affecting factors and detect their affect.

To widen the analysis, a deeper investigation was performed over the kinesthetic sense, in order to identify if there are more kinesthetic related engineering parameter which affect the percept and until now are not included in the delivered set of the design requirements. Moreover, the ACs used to deliver to the design process only with kinesthetic related engineering parameters as design requirements, leaving the sound percept only with qualitative descriptions as requirements, such as “no strange sounds”. The hypothesis of the current study is that the percept, the ‘feel’ of a button, cannot be just considered as a single dimension one, meaning that it is not being affected only by the kinesthetic behavior and the acoustic sense also affects the perceiver and in sequences his judgment. Thus, under the scope of the current phase, were also analyzed the effect of the acoustic sense on the percept, always with objective to identify all those acoustic related engineering parameters which affect the

percept of an ICI. In that way, the analysis aim to cover the whole picture of the percept, in order to approach the percept in a broader view and identify all the possible, kinesthetic and acoustic related engineering parameters which affect it and should be included into the design requirements.

The analysis was performed in two steps, started with the kinesthetic modelling in order to identify all the possible kinesthetic related engineering parameters and then followed by the acoustic modeling in order to identify which acoustic related engineering parameters impact over the percept as well, in order to fulfill the whole picture of the percept.

The order of the analysis is first to define the target percept by using only kinesthetic related engineering parameters, as the delivered design requirements till now are concerned only with kinesthetic related parameter and then to incorporate the acoustic ones. Accordingly the structure of the analysis first proceeds with the modelling of the kinesthetic sense and afterwards as additional information, it introduces the acoustic impact over the percept, by integrating the kinesthetic and acoustic related parameters.

By analyzing the impact of the acoustic and the kinesthetic related engineering parameters, the aim is to define the target percept as a function of the integration of the senses. The outcome of that final step is to define the most appropriate non-visual related engineering parameters (acoustic and kinesthetic) which should be included into the design requirements of an ICI push button.

5.1 Case study

A car control's interface push button (with metal springs) was chosen as a representative element in order to perform the analysis; Nine prototypes were tested.

Each button of each prototype evaluated by the AC and identified which buttons have their percept on or off target (accepted/rejected) (Appendix 2. That gives us a sample of 144 push buttons, in which 51 were found to be accepted (≈35%) and 93 were rejected (≈64,5%). To perform the analysis, the sample was split into two subsamples: the training sample (≈70% of the total sample - 103 observations) and the validation sample (≈30% of the total sample - 41 observations), as defined in (Hair and Anderson 2010). As the total sample is unbalanced (51 accepted and 93 rejected), two subsamples were randomly selected by using SPSS random selection and kept approximately the same ratio between accepted and rejected observations (for the training sample: 39 accepted and 64 rejected observations and for the validation sample: 12 accepted and 29 rejected). The analysis will be performed over the analysis sample and the function that will be obtained will be applied to the validation sample and the hit rate will be compared.

5.2 Kinesthetic modeling procedure

The kinesthetic curves (force/displacement) of the collected push buttons were measured instrumentally and a statistical analysis followed based on the measurements and the AC evaluation, in order to identify which and how kinesthetic related parameters affect their percept on the AC judgment of being on target or not.

The kinesthetic modelling process includes three phases: first, a selective method was performed; to choose which engineering parameters have physical meaning and should be included into the analysis. Second, a statistical analysis was executed following Multiple Logistic Regression, by using as a dependent variable the AC's evaluation (accepted/rejected) and as independent variables the kinesthetic related

engineering parameters. Lastly, the selected model was validated and the standardized coefficients were calculated.

5.2.1 Kinesthetic selective Method

In order to perform a broader analysis over the kinesthetic sense, a selective method was performed with aim to identify all the possible engineering parameters which could affect the percept.

Exploiting the force/displacement curve of an ICI push button will show which engineering parameters carry the needed information to represent the behavior of a push button. The selected parameters would be extracted from the instrumental measurements and used as inputs in the modeling procedure in order to validate if they are indeed statistically significant and affect the percept of a push button and should be considered as design requirements.

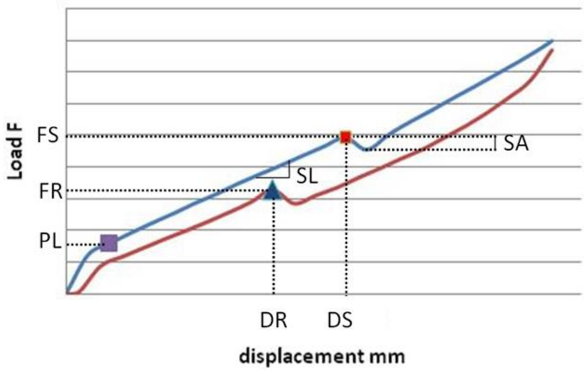

Figure 5-1 - Force/displacement curve of a push button and the kinesthetic related engineering parameters. Blue line corresponds to the pressing phase and red line to the release phase of the button

Figure 5-1 illustrates the force/displacement curve of a button with a metal spring support. Apart from the delivered design requirements (Pre-load (PL), Distance to Stroke (DS) and Force to Stroke (FS), will be studied a possible gap of missing information, between the engineering parameters, which are used as design

requirements, and the desired kinesthetic percept, by adding “extra” parameters with a physical meaning regarding human perception. Regarding the push button movement and the delivered design requirement, one could easily note that the release phase remains unexploited. In fact, the requirements delivered do not carry any information regarding the release phase. At a perceptual level, by following the act of a human who interacts with a push button, during the activation phase, when the user presses a button until it reaches the activation point (click) in order to enable the function of the button, he receives a feedback and that feedback by some means is defined by the delivered design requirements PL, FS and DS. Moreover, after the activation, the finger of the user moves upwards and a second event happens (un-click). In fact, the release phase carries the end of the overall feedback of what a user experiences and as a consequence that could be considered as the last or the overall impression of the interaction with the button. From the human perception point of view, this last part of the interaction (release phase) is quite possible to affect the user, but until now the contribution of the release was considered irrelevant as there are no design requirements related to it. Hence, in order to take account of the impact of the release phase, two engineering parameters are introduced: the Force to Release (FR) and the Distance to Release (DR). At the level of design requirement development, by following the same line as used from the AC regarding the push phase, where the force and the displacement at the activation point were used as characteristic parameters FS and DS, two engineering parameters related to the release phase were defined, the Force to Release (FR) and Distance to Release (DR), respectively.

One more parameter to be studied is the snap action (SA). As noticed previously, several studies indicate the importance of that parameter on the percept of a push

button. Higher values indicate a higher difference of the sudden drop at the activation point, as this parameter is defined as the difference in Force ΔF.

Moreover, it will be studied if the decline of the slope (Besle, Fischer et al.) also affects the percept. The slope of the curve could be used as an indication of the stiffness of the button, following an analogy with the behavior of a normal spring. Although, at the spring case there is absence of activation (snap action), the friction, the backlash, the detents, and other effects appears in both of cases and of course the main characteristic of increasing force while the distance increases too. For the spring the slope is defined by the spring constant K and at a perceptual level this K defines the stiffness of the spring. By following that analogy, it will be investigated if the stiffness of the push button reflects more accurately the behavior of the button. Higher values of SL indicate higher stiffness as the force increases and the distance decreases.

Summarizing, the selective method concluded with a set of engineering parameters with physical meaning which could define the kinesthetic behavior of a push- button and apart from: Pre-Load (PL), Distance to Stroke (DS), Force to Stroke (FS), Force to Release (FR), Distance to Release (DR), Snap Action (SA) and Slope. In Appendix 2, Table 8.6 presents the results of the kinesthetic instrumental measurements of the above mentioned engineering parameters and the AC judgment of each button.

5.2.2 Kinesthetic modeling

The presented analysis will be performed in three steps. The first step will start by looking at the existing process, i.e. a model to predict the acceptance by using the received design requirements, as delivered by the AC, the engineering parameters PL,

FS and DS. Then, in the second step, a model developed by including as independent variables the engineering parameters which were defined and explained at the selective method: PL, FS, DS, FR, DR, SA and SL.

Model 1

As a first step of analysis, a logistic regression analysis was conducted to predict the target percept as requested by the AC using as predictors those engineering parameter which delivered as design requirements to design process from the AC, i.e. the engineering parameters PL, DS and FS. Table 5.1 provides the estimated logistic regression using as explaining variables PL, FS and DS and including an intercept constant. It also includes the estimated coefficients, associated standard errors and p-values of significance. Moreover, two statistics of goodness-of-fit for model comparison are presented: the -2 log likelihood value and the Nagelkerke R-Squared. Finally, the associated p-value for the Likelihood ratio Chi-Square test contrasting a constant only model with the estimated logistic model is also presented.

Table 5.1 – First model

	Coefficients	Std. Error	Significance (p-value)
PL	0,072	0,798	0,928
FS	-0,605	0,704	0,390
DS	-3,364	4,566	0,461
Intercept	5,056	2,218	0,023
-2 log likelihood	125.411		
Nagelkerke R-Squared	0,141		
Chi-Square test (p-value)	11,248 (0,000)		

From this first model, it is learned that comparing it to a constant-only model, it is statistically significant with a Chi-Squared p-value 0,010. However, none of the engineering parameters is statistically significant at the 10% significance level, so it is not at all clear how PL, FS and DS are influencing the probability of acceptance of a button. In fact, take for example the linear coefficient associated with PL, its standard error is 10 times higher than it absolute value. Moreover, it should be noted that the Nagelkerke R-Squared indicates a low value of 14.1%. Finally, at this stage it is expected that the additional parameters may provide more insight on the effect of each parameter at the acceptance/rejection of a button.

Model 2

In the second step of the analysis, the multivariate logistic regression is estimated again including all the possible engineering parameters, as identified from the selective method, the PL, FS, DS, FR, DR, SA, SL.

Table 5.2 presents the estimated logistic regression with all explaining variables and an intercept, whereas Table 5.3 presents the estimated logistic regression removing all covariates that are not statistically significant at the 10% significance level. Regarding the likelihood ratio Chi-Square test, both regressions exhibit statistically significant ratios when contrasted with a constant only model, showing that both sets of covariates significantly contribute to distinguish accepted versus rejected push buttons.

Table 5.2 – Second model

	Coefficients	Std. Error	Significance (p-value)
PL	2,377	1,305	0,069
FS	-2,461	1,317	0,062
DS	-25,929	13,752	0,059
FR	0,510	0,780	0,513
DR	30,693	13,621	0,024
SA	-4,336	2,471	0,079
SL	1,416	0,814	0,082
Intercept	1,709	5,121	0,739
-2 log likelihood	112,898		
Nagelkerke R-Squared	0,280		
Chi-Square test (p-value)	23,761 (0,000)		

For the first estimated logistic regression (Table 5.1), all parameters present statistically significant coefficients at the 10% significance level, except for the FR and the intercept. Significantly that comparing this model to the initial model in Table 5.1, it exhibits a better fit with a higher Nagelkerke R-Squared of 28.0% compared to 14.1%, or a lower -2 log likelihood of 112,898 compared to 125,411.

Regarding the individual contribution of each parameter, as PL, FR, DR and SL exhibit positive coefficients, their increase seems to have a positive effect on the probability of acceptance of a button. Similarly, as FS, DS and SA exhibit negative coefficients, their increase appears have a negative effect on the probability of acceptance of a button.

By removing FR and the intercept from the set of predictor (Table 5.3) all remaining parameters present statistically significant coefficients at the 10% significance level. Moreover, though the -2 log likelihood value increases slightly, the Nagelkerke R-Squared exhibit a higher value. Regarding the individual contribution of each parameter, their effect is consistent with the previous logistic regression, with positive

effects of PL, FR and SL and the negative effects of FS, DS and SA on the probability of acceptance of a button.

Table 5.3 – Second model, after removing the non-significant covariates

	Coefficients	Std. Error	Significance (p-value)
PL	2,833	1,046	,007
FS	-2,605	1,011	,010
DS	-24,358	10,362	,019
FR	32,031	11,783	,007
SA	-4,052	2,414	,093
SL	1,659	0,514	,001
-2 log likelihood	113,757		
Nagelkerke R-Squared	0,327		
Chi-Square test (p-value)	29,032 (0,000)		

In order to avoid problems on the prediction and classification ability of the presented model, in this third step of the analysis, the existence of collinearity will be examined.

Table 5.4 – Correlation matrix

		Constant	PL	FS	DS	FR	DR	SA	Sl
Step 1	Constant	1,000	-0,557	0,615	-0,649	-0,396	0,422	-0,160	-0,777
	PL	-0,557	1,000	-0,868	0,165	0,068	0,259	-0,233	0,693
	FS	0,615	-0,868	1,000	-0,405	-0,372	0,046	0,144	-0,792
	DS	-0,649	0,165	-0,405	1,000	0,352	-0,897	,477	,282
	FR	-0,396	0,068	-0,372	0,352	1,000	-0,401	-0,021	0,291
	DR	0,422	,259	0,046	-0,897	-,401	1,000	-,534	-0,032
	SA	-0,160	-0,233	0,144	0,477	-,021	-,534	1,000	-0,250
	Sl	-0,777	0,693	-0,792	0,282	0,291	-0,032	-0,250	1,000

The correlation among the covariates presented on Table 5.4, shows that two pairs of covariates exhibit highest values in absolute value: the Distance to Stroke (DS) with the Distance to Release (DR) with a correlation of -0.897 and the Preload (PL) with the Force to Stroke (FS) with a correlation -0.868. These collinearities influence the estimates of each covariate and may lead to wrong ceteris paribus conclusions. For

that reason, it was replaced each pair by a new variable with a physical meaning, formed by the combination of each former covariate. Regarding the pair DS and DR, from the model 2 it can be seen that they have opposite signs in their coefficients and thus, a possible physical explanation could be that the real influencing factor is how close the activation is from the deactivation point, and not the DS and DR independently. Therefore, the difference in distance between DS and DR (DS-DR) was chosen.

Similarly, regarding the pair PL and FS which also exhibit opposite signs in their coefficients in Model 2, a possible physical explanation could be that the contributing factor is actually the amount of force you apply since the button start moving till it reaches activation (i.e. FS-PL), and not PL and FS independently by themselves.

The correlation between these two new coefficients is comparatively low: 0,237. In that way, collinearity problems are avoided by replacing each pair with the new defined covariates DS-DR and FS-PL, which have a physical explanation at a perceptual level.

Table 5.5 illustrates the model by using the engineering parameters DS-DR, FS-PL, FR, SA. Finally by following stepwise backwards regression, Table 5.6, concludes that only DS-DR and FS-PL remain statistically significant, while the others are excluded.

Table 5.5 – Second model by using the new defined covariates FS-PL and DS-DR, instead of the corresponding FS, PL, DS and DR.

	Coefficients	Std. Error	Significance
FS-PL	-1,470	0,468	0,002
FR	0,434	0,607	0,475
SA	-4,275	2,406	0,076
SL	0,986	0,616	0,109
DS-DR	-31,232	10,851	0,004
Intercept	4,162	4,188	0,320
-2 log likelihood	113,602		
Nagelkerke R-Squared	0,273		
Chi-Square test (p-value)	0,000		

Table 5.6 – Final integrated model

	Coefficients	Std. Error	Significance
DS-DR	-23,534	8,642	,006
FS-PL	-0,884	,287	,002
Intercept	6,757	1,974	,001
-2 log likelihood	118,300		
Nagelkerke R-Squared	0,222		
Chi-Square test (p-value)	0,000		

5.2.3 Kinesthetic model validation

To cross validate the selected model, the validation sample will be used. In order to test the predictive power of the model, the function obtained from the analysis sample will be applied to the validation sample and the hit rate will be compared. Table 5.7 presents the classification matrix which contains the number of correctly classified and incorrectly classified cases, from the training and validation sample. For the validation, it would be based on the overall hit ratio which is the total number of correctly classified divided by the sample size. Due to the reason that the overall hit rate is almost the same for both samples 70,6% and 73,1%, cross validates the model and proves that in both sample samples the predictive power is on the same level and that fact contributes to the confidence of the model.

Table 5.7 - Hit rate classification matrix of the training and validation samples with cut off value 0.5

		observed	Predicted		Total
			Accepted	Rejected	
Training set	Count	Accepted	17	22	39
		Rejected	8	56	64
	%	Accepted	56.4	43.5	100.0
		Rejected	12.5	87.5	100.0
Validation set	Count	Accepted	4	8	12
		Rejected	3	26	29
	%	Accepted	33.3	66.7	100.0
		Rejected	10.3	89.7	100.0

Overall hit rate:
Training set 70.9%
Validation set 73,1%

5.2.4 Parameters contribution

One more issue regarding the contribution of each covariate is the non-standardized values which were used in the presented modeling procedure. Hereupon, non-standardized values were selected for a straightforward interpretation of the metric of each covariate and this fact does not allow us to understand the contribution of the selected parameters on the judgment of being accepted or rejected. To overcome this matter, the standardized coefficients of each covariant will be used. Although there are controversial opinions as to calculating standardized logistic regression coefficients (see (Menard 2004)), the *fully standardized logistic regression coefficient method* was adopted for this study and is presented at Table 5.8 for the final model. The standardized coefficient shows that the contribution of the DS-DR (-1,635) is almost at the same level as the FS-PL (1.766). The meaning is that both engineering parameters almost equally affect the kinesthetic percept of a push button.

Table 5.8 - Unstandardized and Standardized absolute coefficient of each covariant

	Unstandardized absolute coefficients	**Standardized absolute coefficient**
DS-DR	-23,534	-1.635
FS-PL	-0,884	-1.766

5.2.5 Discussion of the kinesthetic modeling

Taking into account the restrictions of the presented analysis, results provide evidence regarding the engineering parameters that contribute to the percept of a push button, as requested from the AC and also show the contribution of each engineering parameter and the interaction among them. As proved, the set of the engineering parameters that delivered as design requirements could not be considered as adequate information to define the percept. This proves the reason why AC follows a different evaluation method, than the regular one of measuring the specified parameters.

Results are shown that could fairly drive to the conclusion of having a lack of information regarding the design requirements that define the percept of a push button, as received from the AC and delivered to the design process. The delivered set of design requirements does not offer a sufficient level of information through the design is not able to be achieved the wanted percept. The contribution of the DS-DR and FS-PL fulfill the potentials to be considered critical engineering parameters to characterize the kinesthetic behavior of a push button and to be included into the design requirements. These two parameters could be characterized as psychophysics parameters as they are based at a perceptual level.

DS-DR at a perceptual level has the meaning of how close (in distance) the activation is to the deactivation. Results indicate that the selected case study's AC, AUDI, wants the user to perceive the activation as close as could be with the deactivation. Similarly, FS-DS indicates that the difference between the needed force that should be applied in order to make the button start moving till the needed force which is required to reach the activation point should be also as little as possible. Of course this relationship for both of the selected parameters (FS-PL and DS-DR) is limited on the treated sample range for each engineering parameter. Thus, it cannot conclude that the

difference between FS and PL or DS and DR should be equal to zero as such cases were not included at the treated sample.

Furthermore, the prediction power of the model, although it increased compared with the one that uses the delivered design requirements, still remains in low levels (70.3%). A possible explanation could be the contribution of other non-visual senses, i.e. the acoustic sense, into the judgment of achieving the target haptic percept. Non-visual senses are mentioned as the evaluation by the AC was performed just by pressing the button without taking into account visual deficiencies. Parameters related to the acoustic sense could be proven contributors to the percept of a push button as during the evaluation, AC experts receives information also from the auditory channel and form their judgment.

5.3 Integrated model

The current step focuses on the audio/kinesthetic interaction with objective to identify which and how acoustic and kinesthetic related parameters affect the decision of the AC's evaluation. Passing from the kinesthetic modeling phase, in which kinesthetic related engineering parameters that affects the percept of an interface push button were identified, and substantiate which kinesthetic related engineering parameters should be considered as design requirements, this phase approaches the impact of the acoustic related engineering parameters. As discussed previously, the predictive power of the model by using kinesthetic related engineering parameters could reach a relative low level 70,3%. It is believed that a broader analysis by developing a sensory integrated model (kinesthetic and acoustic) will advance current knowledge and provide a more complete understanding of the percept. By using the same case study

as used with the kinesthetic modeling procedure, the impact of the acoustic sense over the percept of an ICI's push button is investigated.

5.3.1 Integrated modeling procedure

The acoustic behavior of the ICI push buttons was recorded and the Frequency Spectra and the Time signal for each of the buttons were obtained, as described in section 3.2.2 Instrumental measurements. The judgment of the each button as performed by the AC is the same as were used for the kinesthetic modeling procedure and the identical statistical analysis (Logistic Regression) followed.

The integrated modeling process follows the same path as used for the kinesthetic one, which includes three phases as well. A selective method performed, to identify which acoustic related engineering parameters have a physical meaning and could affect over the percept. Second, the same statistical analysis was adopted, the Multiple Logistic Regression, by using the AC's evaluation as dependent variable and the acoustic and the kinesthetic related engineering parameters as independent variables. Regarding the kinesthetic ones, the FS-PL and DS-DR as identified by the kinesthetic modeling will be used and regarding the acoustic related engineering parameters they will the chosen from the selective method of the acoustic sense.

Finally, the selected model was validated and the standardized coefficients for each engineering parameter were calculated, in order to identify their contribution over the percept.

5.3.2 Acoustic Selective method

Following the State of the art, regarding the acoustic sense over the percept of a product, one could note almost the same issue as faced for the kinesthetic one; that of having a plethora of parameters which are used by several researchers and case

studies. Regarding the acoustic sense, the relative parameters are many more compared to the kinesthetic ones and could mainly be grouped into two main areas, the physical and the psychophysical. The latter category was missing for the kinesthetic sense and this is a simple indication of the extensive research that has been performed by several researchers over the acoustic sense, compared with the kinesthetic one. This gives the ability to choose from a plethora of sound parameters and use them in the modelling process. Dealing with short sounds, as a click at the push button, should target on those acoustic parameters that contain the appropriate information for sounds with this nature. Below are listed the selected parameters which are going to be used in the modeling procedure. As stated previously, for each button the phase of pressing and releasing was recorded independently and as a sequence for each parameter will be used two covariates in the modeling process, respectively with the two phases of the button. In Appendix 2 the Table 8.7 presents the results of the instrumental measurements of the bellow mentioned acoustic related engineering parameters.

Loudness

The standard sound measurement has been Sound Pressure Level measured in decibels, dB (SPL (dB)) and predicts the perception of loudness. For the purpose of the current study, A-weighted SPL(A) is applied, in order to use a metric for the relative loudness perceived by the human ear.

Another metric for the perceived loudness, N, is the psychoacoustic one, as defined by (Fastl and Zwicker 2007) and standardized in ISO 532B. In the present case, the

Loudness Model for Impulsive Sounds LMIS (Boullet 2006) was used. Boullet studied more precisely the loudness of the impulsive sounds, and presented a very fast transient response, which was immediately followed by an exponential decay.

The acoustic signal is filtered to obtain a temporal signal in each critical band. The following step of the model consists of calculating the energy and the decay time for each critical band. Mainly loudness is the product of energy (exponent alpha) and the duration of the impulse decay (exponent beta). Finally, the effect of simultaneous masking is taken into account as in (Fastl and Zwicker 2007). Specific loudness obtained this way and then summed over the 24 critical bands to obtain the overall loudness of the impulsive sound (GENESIS 2009). Figure 5-2 illustrate the LMIS model. The parameter calculated by following the Matlab code (Appendix 3) (Boullet 2006) as adopted from (GENESIS 2009).

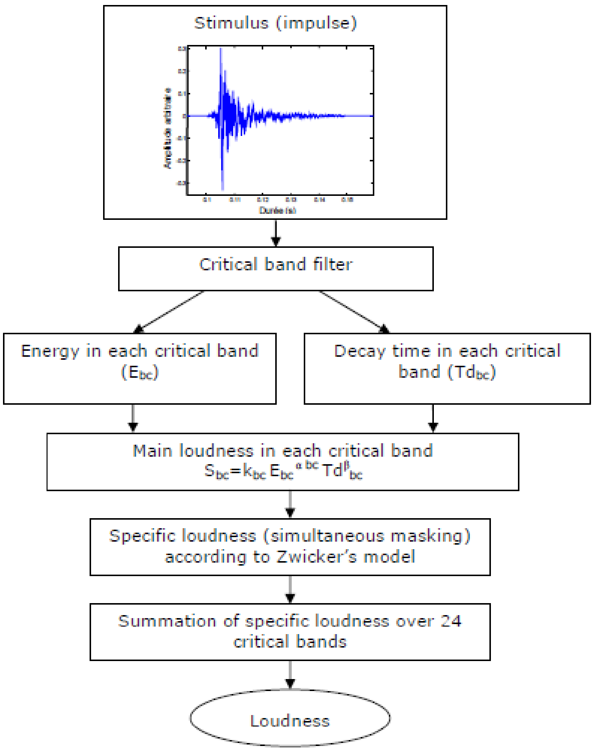

Figure 5-2 - LMIS (Boullet 2006) adopted from (GENESIS 2009)

Spectral Centroid

Dealing with short and impact sounds, like a click from a push button, a possible indicator could be as to how clear a sound is. A physical parameter associated with the brightness of the sound is the Spectral Centroid. This parameter, also used by Roberts, Jones et al. (2005) in a study over the golf club impact sounds, aims to identify the importance on golfer's choice equipment. This measure is obtained by evaluating the "center of gravity" using the Fourier transform frequency and magnitude information. The individual centroid of a spectral frame is defined as the average frequency weighted by amplitudes, divided by the sum of the amplitudes (Eq.5-1) (IRCAM 2003).

$$SC = \frac{\sum_{k=1}^{n} kF[k]}{\sum_{k=1}^{n} F[k]} \qquad 5\text{-}1$$

Tonality

One more parameter which was decided to be included in the analysis is the deviation of the signal as a sign of its tonality, Ton. As all the sounds have the same duration of 0,5 sec, it is thought that when the signal is dispersed it would have as a result a sound with low tone and inversely when the signal is concentrated it would have a sound with high tonality. This parameter is calculated as the Standard Deviation of the Amplitude, from the Frequency Spectra.

5.3.3 Results of the integrated modeling

Primary, the correlation among the covariates were analyzed, in order to examine the existence of collinearity, to avoid problems on the prediction and classification ability of the model. The correlation among the covariates presented on Table 5.9 shows that the pairs SPLa_press with Ton_press and SPLa_release with Ton_release present a quite high correlation (-0,941) and (-0,942) respectively. That means that for both phases (press/release) when the SPLa increase the Tonality decreases almost equally and for that reason it is not reasonably to let both covariates into the analysis as the one could be explained by the other. These collinearities are going to influence the estimates of each covariate and will lead to wrong ceteris paribus conclusions, because they are quite high. Thus, one of them should be excluded from the analysis. As the Sound Pressure Level considered as a standard sound measurement parameter, was decided to keep it into the analysis and to exclude the Tonality for the pressing (Ton_press) and release (Ton_release) phase.

Table 5.9 - Correlation Matrix

	FS_PL	DS_DR	SPLa_ Press	SC_ press	SPLa_ Release	SC_ release	N_ press	N_ release	ton_ press	ton_ release
FS_PL	1,000	,081	-,428	-,694	,322	-,037	,181	,326	,399	-,227
DS_DR	,081	1,000	,109	-,169	,458	,395	,134	-,404	-,069	-,540
SPLa_Press	-,428	,109	1,000	,184	-,037	,423	,124	,093	-,941	-,107
SC_press	-,694	-,169	,184	1,000	-,335	-,497	-,001	-,253	-,284	,363
SPLa_Release	,322	,458	-,037	-,335	1,000	,243	,082	-,074	,054	-,942
SC_release	-,037	,395	,423	-,497	,243	1,000	-,141	,276	-,252	-,509
N_press	,181	,134	,124	-,001	,082	-,141	1,000	-,299	-,394	,062
N_release	,326	-,404	,093	-,253	-,074	,276	-,299	1,000	-,013	-,072
ton_press	,399	-,069	-,941	-,284	,054	-,252	-,394	-,013	1,000	,020
ton_release	-,227	-,540	-,107	,363	-,942	-,509	,062	-,072	,020	1,000

For the first estimated logistic regression of the acoustic/kinesthetic integrated model (Table 5.10) with all the possible engineering parameters SPLa_press, SPLa_release, N_press, N_release, SC_press, SC_release, FS-PL and DS-DR. The parameters which

do not present statistically significant coefficients at the 10% significance level, are the SC_press, N_press and N_release. By following stepwise backwards regression, meaning to remove the non-significant variables step by step till all the remaining parameters to be statistically significant (p-value<0.10), it is concluded at the final model as presented in

Table 5.11. The only remaining statistically significant variables are FS-PL, DS-DR, SPLa_Press SPLa_release and SC_release while the SC_press and N_press and N_release are excluded as non-significant.

Table 5.10 – First integrated model with all possible covariates

	Coefficients	Std. Error	Significance (p-value)
FS_PL	-1,039	,410	0,011
DS_DR	-33,308	11,654	0,004
SPLa_Press	-0,535	0,319	0,094
SC_press	,001	0,001	0,131
SPLa_Release	1,888	0,421	0,000
SC_release	-,005	0,001	0,000
N_press	-1,130	0,876	0,197
N_release	-,541	0,535	0,312
Intercept	-41,526	12,722	0,001
-2 log likelihood	79,203		
Nagelkerke R-Squared	0,596		
Chi-Square test (p-value)	61,171 (0,000)		

Table 5.11 – Final integrated model

	Coefficients	Std. Error	Significance (p value)
FS_PL	-1,246	,401	,002
DS_DR	-28,139	10,545	,008
SPLa_Press	-1,135	,313	,000
SPLa_Release	1,442	,333	,000
SC_release	-,0024632	,001	,000
-2 log likelihood	81,846		
Nagelkerke R-Squared	0,607		
Chi-Square test (p-value)	63,715 (0,000)		

Comparing the integrated model with the kinesthetic one, improvements could be noticed, as it exhibits a better fit with Nagelkerke R-Squared of 60,7% compared to 22.0%, or a lower -2 log likelihood of 81,846 compared to 118,300.

The probability (P) of having the percept on target, is expressed in equation 5-2.

Equation 5-2:

$$\mathrm{P} = \frac{e^{\{(-1{,}25\ \mathrm{x}\ \mathrm{FS\_PL})+(-28{,}14\ \mathrm{x}\ \mathrm{DS\_DR})+(-1{,}13\mathrm{x}\ \mathrm{SPLa\_Press})+(1{,}44\ \mathrm{x}\ \mathrm{SPLa\_Release})+(-0{,}0025\ \mathrm{x}\ \mathrm{SC\_release})\}}}{1+e^{\{(-1{,}25\ \mathrm{x}\ \mathrm{FS\_PL})+(-28{,}14\ \mathrm{x}\ \mathrm{DS\_DR})+(-1{,}13\mathrm{x}\ \mathrm{SPLa\_Press})+(1{,}44\ \mathrm{x}\ \mathrm{SPLa\_Release})+(-0{,}002\ \mathrm{x}\ \mathrm{SC\_release})\}}}$$

Regarding the individual contribution of each parameter, the kinesthetic related covariates FS-PL and DS-DR continue to exhibit negative coefficients; their effect is consistent with the previous logistic regression, with negative effects. Regarding the acoustic related covariates, SPLa_Press exhibit a negative coefficient, while the corresponding SPLa_release exhibit a positive one. Thus, a decrease on the Sound pressure level of the pressing phase brings the percept closer to the target, while the opposite effect appears for the release phase, where an incensement of the SPLa_release raises the possibilities for the percept to be judged as accepted. The SC_release also exhibit a negative effect.

By analyzing the results one could stand at the point of having the A-weighted Sound Pressure Level of the press and of the release as significant, while psychoacoustic Loudness (N) for press and release were excluded as no significant factors. That means that the SPLa is a better indicator, in comparison with psychoacoustic Loudness (N), to define the loudness level of an ICI push button target percept.

Another point is that Spectral Centroid for the pressing phase excluded as no significant factor, while the respective for the release phase identified as statistically significant factor. This result indicates the importance of the sound produced at the release phase, as two related factors found to have an affect over the percept. An

explanation for this phenomenon could be that the produced sound during the release phase is the dominant one in comparison with the one at the pressing phase.

As final outcome, the integrated model indicate as statistically significant factor the FS-PL, DS-DR, SPLa_press, SPLa_release and SC_release.

5.4 Integrated model validation

Following the same procedure with the kinesthetic modelling, the selected model will be cross validated with the validation sample. By using the function obtained from the analysis sample (Eq. 5-2) and applying it to the validation sample, the hit rate of these two groups will be compared. On the classification matrix, Table 5.12 illustrates the correctly and incorrectly classified cases for both of the samples, the analysis and the validation. It could be mentioned that the model is cross-validated as the overall hit rate is almost the same, 83,8% and 82,5%. The predictive power is on the same level and that fact contributes to the confidence of the model.

Table 5.12 - Hit rate classification matrix of the training and validation samples with cut off value 0.5, of the final integrated model

		observed	Predicted		Total
			Accepted	Rejected	
Training set	Count	Accepted	32	9	41
		Rejected	8	56	64
	%	Accepted	87,5	12,5	100.0
		Rejected	22,0	78,0	100.0
Validation set	Count	Accepted	8	2	10
		Rejected	5	25	30
	%	Accepted	80	20	100.0
		Rejected	20	80	100.0

Overall hit rate:
Training set 83,8%
Validation set 82.5%

5.5 Parameters contribution

In order to identify the contribution of each covariate, the fully standardized logistic regression coefficient method (Menard 2004) will be followed, as it used for the

kinesthetic modeling. Table 5.13 presents the unstandardized and standardized coefficients for each covariant used in the final integrated model.

Results shows that the acoustic related engineering parameters are the main affect factors of the target percept. Particularly, the SPLa of the release found to have the highest impact among the others covariates with coefficient 6,771 and follows the SPLa for the pressing phase with -3.520 and the SC of the release with -2,962. The kinesthetic related engineering parameters FS_PL and DS_DR have the lowest impact with -2,313 and -1,881 respectively.

Table 5.13 Unstandardized and Standardized absolute coefficient of each covariant of the final integrated model

	Unstandardized absolute coefficients	Standardized absolute coefficient
FS-PL	-1,25	-2,313
DS-DR	-28,14	-1,881
SPLa_Press	-1,135	-3,520
SPLa_Release	1,144	6,771
SC_release	-0,0024555	-2,926

5.6 Discussion

The better fit of the integrated model and the increase of the predictive power, compared with the single kinesthetic one, prove the proposed hypothesis that the percept cannot be characterized as a single dimension system, as it is affected by the integration of the acoustic and the kinesthetic sense. The quite high increase of the predictive power from 70,6% to 83,8% indicates the importance of using both acoustic and kinesthetic related engineering parameters as design requirements to define the percept of an ICI. Results clearly demonstrate the lack of information between the delivered design requirements which are limited only on the kinesthetic related engineering parameters, and the wanted outcome. An ill-defined design requirements development process to express the wanted target percept is a fact, as

the percept proved to need more information, for example the integration of the acoustic and the kinesthetic sense. Until now this integration has been missing, and also the kinesthetic related engineering parameters provided as design requirements, were found to be insufficient. The result of this deficiency was a plethora of prototypes produced by trial and error method, with several design alterations in order to achieve the target percept. Results indicates that there is a gap between the provided information (design requirements) and the wanted outcome (target percept), with result of having a time and cost demanding trial and error process.

Regarding the integrated acoustic-kinesthetic model it is important to mention some basic limitations. Restrictions related with the under analysis case study element, an ICI bezel's push button with a metal spring supporting mechanism and the fact that the study conducted only over the same brand and bezel type, does not allow to come up with general conclusions over the universal percept of push buttons, not even for interfaces with a metal spring support.

Regarding the former, the difference between a push button's percept with a silicon pad and the ones with a metal spring as studied at the current study, is more than clear, as one offers a linear behavior in contrast to a non-linear one of the silicon pad. Different buttons design architecture, i.e. using silicon pad support, might show other engineering parameters than the selected set in the presented case study. This limitation requires a further analysis on different design architectures of supporting mechanisms, to conclude if the same set of engineering parameters, as identified at the current research, is sufficient to define the universal percept of push buttons and to be considered as design requirements.

Concerning the issue of conducting the experiment over prototypes of the same brand, to generalize the results to all push buttons with the same design architecture (metal

spring support), one more issue should be considered; the absence of a different AC target percept. The presented analysis was based on the judgment of a particular AC, and this represents the predetermined percept of that company, the specific target percept as requested (by the evaluation of the interfaces). The goal was to approach the problem in a holistic manner by identifying the possible acoustic and kinesthetic related engineering parameters that could affect the percept in order to be considered design requirements and develop a method that could be applied in general on that domain. In that sense, each supplier company which is responsible for the design and manufacturing of ICIs, could follow the presented method in order to create a pattern of the target percept for each of their customer (each AC). These aforementioned limitations of having as cases study an interface from a particular AC and as well their judgment doesn’t permit to widen the presented conclusions to all ICI even with the same design architecture (metal spring support). Dealing with another AC, meaning another target percept, might conclude into different set of design requirements or with different contribution. To overcome this issue it is proposed, a broader sample from several ACs, in order to shed light on the criteria that are used for the majority of the AC companies. In that sense, a pattern of each AC could be created and provide to the design process what the most appropriate percept for each of the ACs.

Despite the above mentioned limitations, from the results, one can arrive to the conclusion that the percept is being affected by the integration of the senses and to point out this multisensory nature. The difficulty to evaluate the relative importance of each sense referred also by (Overvliet and Soto-Faraco 2011) even for different senses (vision-haptic), regarding the estimation of ‘naturalness’. In our case, the wanted “feel” which is evoked by the act of touching, cannot defined just by the kinesthetic sense, but also the acoustic sense is needed as it contributes over the

percept in a holistic manner and the interaction between the two senses should be included into the delivering set of design requirements. This is also in accordance with (Bergmann Tiest and Kappers 2007) and (Kumazaki, Terada et al. 2007) who found that the roughness and perceived length, respectively, are not only haptic properties but can also be perceived from the visual channel and the sensation provides independent, equal information of physical quantity.

One possible explanation could be that the acoustic related engineering parameters, which are signals of the vibration, also convey some kinesthetic related information. The vibrations that were produced throughout the process of pressing a button and transformed via the acoustic signal could be characterized more accurately by the vibrations that a user receives through his finger when he interacts with the button. (Sotofaraco and Deco 2009) pointed out that close relationship between the senses of hearing and touch, as the two involved sensory modalities are sensitive to the same kind of physical property (mechanical pressure in the form of oscillations).

In that sense, the importance of the acoustic sense is not underestimated, but the importance of the integration between the acoustic and the kinesthetic sense over the percept of an ICI push button is highlighted.

As final outcome, the kinesthetic and acoustic related engineering parameters DS-DR, FS-PL, A-weighted Sound pressure level (SPLa) of the press and release phase and the Spectral Centroid (SC) of the release N, are considered as critical engineering parameters and convey a significant amount of information in order to define the percept of the ICI push button, in order to considered design requirements.

6. THIRD PHASE - IDENTIFYING THE INFLUENCE OF THE DESIGN ON THE PERFORMANCE OF AN ICI

The following chapter includes the third phase of the research framework and intends to explore the impact of the design over the percept of an ICI. At the previous phase of the research framework were identified which engineering parameters affect the percept in order to be included into the design requirements and at this phase the aim is to identify which design parameters affect the design requirements, in order to de considered as design specifications. It is critical to understand that the performance of an interface characterized by the engineering parameters, while the design could be defined by the design parameters. The engineering parameters which indeed affect the percept considered as design requirements and the design parameters with impact over the design requirements considered as design specifications. Therefore, the impact of the design over the performance could be seen as the impact of the design specifications over the design requirements. In order to make it clear, we are going to use as example a car. If the requirement is to be fast, as one design requirement will be the horse power of the engine and as design specification will be for example the size of engine. The size of engine is a design parameter which affects car's performance, the horse power of the engine.

Dealing with sensitivity issues of delivering a feeling as requested by the AC, it is critical to control the performance with high accuracy, i.e. to regulate the physical behavior of an ICI, through the design process. Furthermore, this need have becomes higher with the addition of new defined engineering parameters as presented in the previous step of the research framework, which had never before investigated their impact. Till now, as presented in section 1.2, by following the classic trial and error

method designers and engineers were trying to achieve the appropriate performance of an ICI, in order to attain the target percept as requested by the AC, by changing design parameters. This leads to a very long and expensive process, with results a non-optimal product design and as outcome delivers an inferior quality product at an inflated cost (Phadke 1995). Although it was identified which design parameters affect each engineering parameter, which was received as design requirement, it was never explored how a change of a single design parameter impact over the overall percept in a systemic way. A lack of information regarding the impact of each design specification over the overall performance creates an unstable environment at the design process, in which the design alteration is performed with the final goal of achieving the wanted target percept.

By following a holistic approach, this phase of the framework aims to identify how an alteration of a single design specification impact over each design requirements, as defined in the previous step of the research framework. The capability to control the performance through the prior stage of the design process will advance the ability to design and manufacture ICIs with the target percept as requested by the AC. This will bring a great reduction on costs and time as the production of numerous prototypes will not be required and most important of all, will offer the ability to achieve more accurately the target percept.

To perform that step, the Robust Design Methodology was applied, which is an engineering methodology for delivering products with in quality through the design process (Phadke 1995).

6.1 Method

Robust design methodology is based on the idea of designing an engineering system to achieve a desired objective function. Passing from the system design, implies that the required understanding of the system has been acquired, in order to start the tuning process. The concept of the Robust Design methodology is that through the analysis of the design parameters over the objective function of the system, could lead to the optimization of the design to achieve the objective function.

Robust design methodology includes the following steps:

- Identification of the objective function and assignment of the Signal-to-Noise (S/N) ratio
- Selection of the design parameters which will be used as control factors
- Determining the number of levels for the design parameters
- Selection of the appropriate orthogonal array
- Conducting experiments
- Analysis of the experimental results using the S/N ratio and ANOVA
- Validation

The two main tools used in Robust Design methodology are: S/N ratio for measuring the quality and orthogonal arrays in order to study many parameters simultaneously. A key point of the Robust Design methodology is the use of orthogonal arrays, a statistical tool which allows the study of a large number of decision variables with a small number of experiments.

6.1.1 Objective function and Signal to Noise ratio

The first step of the analysis is to define the objective function and calculate the S/N ratio for each of the conducted experiments. As described previously, the objective of

this framework phase is to approach to identify how the design specifications affect each design requirement. Accordingly, how control factors (design parameters) affect the objective functions (design requirements), have to be identified, accordingly. This implies what the objective functions will be as the number of the design requirements which will be used to define the percept of an ICI interface, as identified in the previous step of the research. Hence, what will be analyzed is how the selected control factors affect the objective functions FS-PL, DS-DR, SLPa_pressing, SPLa_release and SC_release.

The objective function, which is the response obtained from the experimental results is transformed into S/N ratios. Robust design recommends the use of the S/N ratio to measure the quality characteristics deviating from the desired values. Several categories of quality characteristics exist for the analysis of the S/N ratio. At the current case study, as defined by the integrated model, the contribution of each design requirement affects the percept in a negative or positive way. Thus, two types of problems exist, the *lower-the-better* and the *higher-the-better*. The S/N (η) ratio for these types is defined as (Phadke 1995):

The *lower-the-better*:

The *lower-the-better* is used when the objective is to minimize the output value. The goal is to minimize the mean square quality characteristic which is equivalent to maximize the S/N which is defined as:

$$\eta = -\log_{10}(mean\ square\ quality\ characteristic) \qquad 6\text{-}1$$

$$\eta = -\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right) \qquad 6\text{-}2$$

The *higher-the-better*:

The *higher-the-better* is used when the goal is to maximize the output value. The problem is transformed into the *lower-the-better*, by considering mean square reciprocal quality characteristic and the objective function to be maximized in this case is given by:

$$\eta = -\log_{10}(mean\ square\ reciprocal\ quality\ characteristic) \qquad 6\text{-}3$$

$$\eta = -\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right) \qquad 6\text{-}4$$

6.1.2 ICI push button design architecture analysis

In order to identify the design specifications, first it is needed to analyze the design architecture of the selected case study, the ICI push button. An ICI push button from the design process point of view could be seen as an arrangement of components which are integrated and work as a system, providing as outcome the function of the button. An analysis of the design architecture of a push button will illustrate how the components are integrated (Figure 6-1). The main components of an ICI push button are listed and analyzed below.

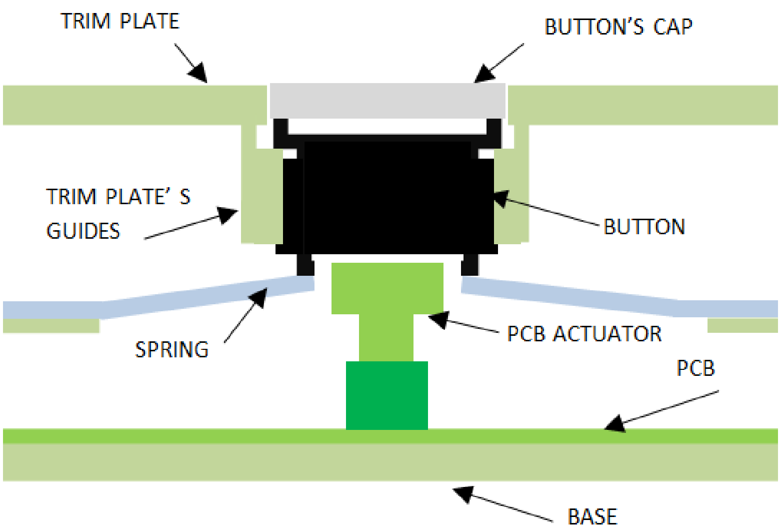

Figure 6-1 ICI push button design architecture

Trim plate: Trim plate is what a normal user call in-car interface, i.e. a radio bezel. All the related components are placed in it, such as the buttons, the display etc. The trim plate is mounted to a base. The base is an individual component, mounted on the car's dashboard.

Cap of the button: The cap is what users see and recognize as a button. The cap is only the contact surface where the user applies his force with his fingers, while the button is the component below the cap. The upper side of the cap is designed according to the trim plate design with the corresponding curvature, while its bottom side is flat with lateral grips in order to be attached on the upper side of the button which is placed below it. Commonly, on the upper surface of the cap relative information with the function of the button is illustrated.

Button: The button is the component which is placed in the trim plate and performs a linear motion. On its upper side the cap is attached. On its lateral sides guides are integrated, which work with the corresponding guides of the trim plate. Trim plate's guides keep the button on a track and make it to move only upwards and downwards, eliminating lateral movements (tilting). The bottom side of the button contacts with the spring, which feedback force keeps the button at the upper position, where its cap is tangent with the upper surface of the trim plate. When the user presses the cap of the button, the button moves down and reaches the PCB (Printed Circuit Board) actuator, till the activation point (stroke). When the user receives the message that the function of the button is activated (by kinesthetic sense with the snap-action and by the acoustic signal, 'click-sound'), the user releases the button and it starts moving upwards by the feedback force generated by the PCB actuator and the spring (providing also information to the user by the kinesthetic sense with the snap action of the release and by the acoustic signal, 'click-sound' of the release).

Metal Spring: At the back side of the trim plate the spring is attached, which is the supporting mechanism of the push button. This spring applies a force on the button to keep it at its initial position. The spring and the PCB actuator provide the feedback force when a user presses the button and are responsible to move the button back in its initial position, where the cap upper side is tangent with the front side of the trim plate. The spring is also responsible for the Pre-load of the button, which is the needed force which has to be applied, in order to make the button start moving. Regarding the other engineering parameter Force to Stroke, it is a combination of the spring and the actuator, as both push the button upwards.

There are several types of supporting mechanism for push button; the two main ones are the one with silicon pad and with metal spring. The selected case study has the metal spring support.

PCB Actuator: The actuator is the mounted tact switch, attached to the PCB. The push button is placed over the actuator and when one presses it, the push button moves down and touches the actuator and the actuator provides a feedback force. The actuator is the key element for the main function of a push button (i.e. switch on/off) as it transforms the movement into a signal through the PCB.

PCB: The printed circuit board (PCB), electrically connects the button with its main function, e.g. to switch on/off. The PCB is attached to the base.

Base: The base is the main component where the conducting parts are attached.

6.1.3 Design parameters selection

By analyzing the under analysis system, the ICI push button, the critical design parameters which affect an ICI push button performance will be identified in order to be considered as control factors in the Robust Design Methodology procedure. First

should be performed a separation among the components that affect the push button's behavior and are controlled through the design process and those components which also affect the behavior but are not control factors from the perspective of the study, because they are outsourced. Of course, one could note that even the outsourced components follow the design guidelines and fulfill the design requirements according to the AC, but our study will be focused over the components which are designed and produced in from the supplier company. As stated previously, from the study's perspective, which is from the point of view of the design process, these outsourced parts are going to be considered as 'fixed' and it will be investigated as of how the design of the components produced by an ICI supplier company, affect an interface's behavior. Of course, when all the possible design alterations are exhausted and the wanted outcome cannot be achieved, an ICI supplier company could request from the AC a modification on an outsourced part. However, under the scope of this study, the analysis will consider these components as standard and design parameters will be identified only to the parts which are produced and controlled through the design process.

The outsourced parts in selected case study are the PCB, the PCB Actuator and the spring. The controllable parts which are going to be investigated and from them will be extracted the design parameters are the button, the cap of the button and the trim plate.

By starting the analysis which aims to identify the most critical design parameters of a push button in order to define the design specifications, one of the most obvious element is the guides of the trim plate and the button. These guides are responsible for keeping the button on track for its linear movement, eliminating the tilting effect. This issue points the first selected design parameter which is the *Gap of the Guide (GG)*,

i.e. the space between the button's guide and the one of the trim plate. The tightening of the gap decreases the tilting effect, but simultaneously increases the friction, with result to cause a 'sticky' button. Thus, this decrease might cause a not smooth movement or it might cause a problem at the release after the pressing phase. Both of these two effects; tilt and sticky, are not acceptable and the gap of the guides should be tuned in such way in order to avoid such failures. Within the limits of having a tilting or a sticky button, it should be identified how the gap affects how a push button performs. By increasing or decreasing the gap (i.e. the friction), the kinesthetic and the acoustic emission of the button is affected and sequentially impacts over its behavior. The design parameter gap of the guides also affects the needed force to make the button starts moving (preload) and the needed force to reach the activation point (force to stroke).

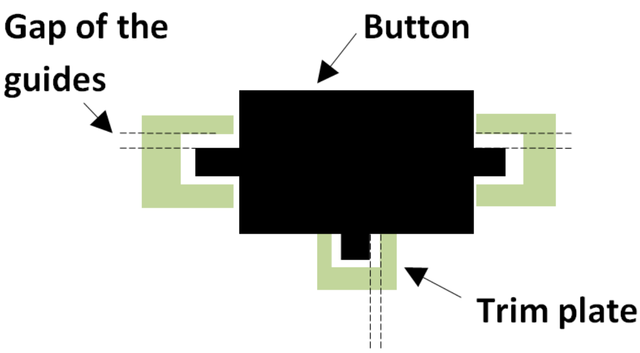

Figure 6-2 Design parameter Gap of the Guides (GG)

Another design parameter related also with the guides of the button and the trim plate, is the *Length of the Guide (LG)*. Following the same line of thinking regarding the alteration of the performance by increase/decrease of the friction, the length of the guide is also affected. As previously stated, when the button is pressed, the button's guide are ruled by the guides of the trim plate, but the guides of the trim plate do not track the button's guide for the whole travel, meaning from its initial position until the

activation point. For that reason, the design parameter LG, was selected in order to analyze how the length of the guide affects the behavior of a push button. In most cases three guides are used; two are placed at the lateral sides of the button, while the third is the in the middle and it is the longer one (compared with the other two). The length of the guide affects the percept of a push button, as it keeps the button more stable. Until now in the design process was used a “practical” law, which the length of the middle guide should be around 60% of the length of the button (bigger buttons needs longer guides). Due to technical reasons, i.e. lack of space, most of the times it is not possible to have a guide such long and designers are forced to reduce it. That causes mostly stability problems, the “tilting” effect. This parameter will be analyzed and will be valued with 3 levels and correspond to the length of the middle guide, as it considers the most critical parameter for adjusting the “stability” of a button.

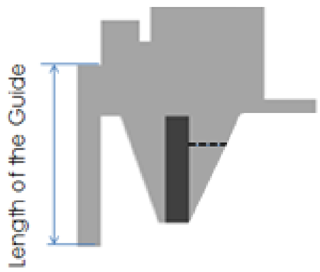

Figure 6-3 Design parameter Length of the Guide (LG)

Another parameter related to the guides is the use of *lubrication (Lub)*. The Lub is one more affecting factor over the friction, as it offers the ability to have quite tight gaps (no tilt) with no sticky effect and as an outcome gives a smooth movement, due to the lubrication that it offers. The main problem with the existence of grease as lubrication method, is the fact that it is not stable and it cannot remain for the entire lifetime of the product and in parallel is a cause of problems within the manufacturing process, as it collects dust and causes problems. It will be investigated how the Lub affects the

behavior of a push button, and to identify when it is possible to not use it by modifying the other design parameters. This parameter will be valued with 2 levels.

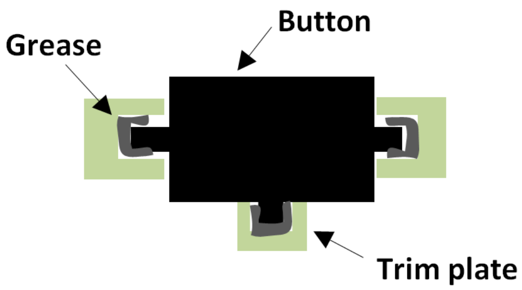

Figure 6-4 Design parameter Lubrication (Lub)

As stated previously, the spring is an outsourced part of the system. Although, the spring's constant and specification are fixed, its initial deformation (pre-load) when attaches the button is controllable through the design process. As described previously, the spring contacts with the bottom side of the button, and keeps its cap tangent with the trim plate. The initial deformation of the spring when the button is at the initial position is defined by the height of the button's surface were the spring contacts with. The height of this surface will be considered as another design parameter, the *Pre-Load Length (PLL)*, which defines the needed force in order to make the button and also increases the needed force to make the button to reach its activation. A higher value results in a greater pressure (deformation). This parameter will be valued with 3 levels.

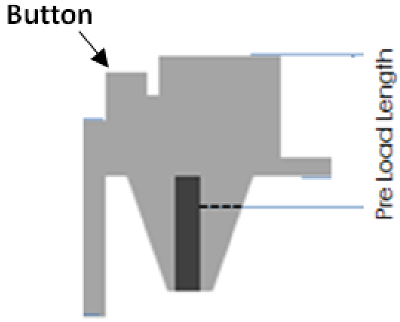

Figure 6-5 Design parameter Pre Load Length (PLL)

Finally, the last selected design parameter will be considered as the gap between the button at its initial position and the PCB actuator. The button at its initial position is not attached to the actuator. When the button is pressed down, it touches the actuator and in sequence it starts depressing the actuator, until it reaches the activation point. As illustrated at Figure 6-1, there is a space between the button and the actuator and that length is mainly defined in order to separate the preload feedback force, which is generated by the spring. The height of the button's area which comes in contact with the PCB actuator mainly affects the distance to stroke of the button. This parameter will be named the *Actuator length (AL).* Higher values of this parameters results a greater space between the button and the PCB actuator. This parameter will be valued with 3 levels.

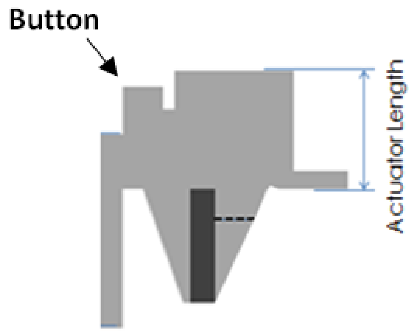

Figure 6-6 Design parameter Actuator Length (AL)

Although several other design parameters may affect the behavior of a push button and could be considered design specifications, technical limitations regarding the construction of prototypes limits the selected case study to take into account only the above mentioned parameters. These parameters are the most common control factors which are used in the design process as design specifications in order to 'tune' the behavior of an ICI in order to achieve the target percept. The selection of the

aforementioned parameters performed through analysis with the supplier company's design engineers.

Some other parameters were found to be critical with an impact on the performance of an interface, but due to limitations of the experiment, it was decided not to include them into the analysis. These parameters are listed below:

Material: The impact on the behavior of a push button of the material is one issue that is missing from the presented experiment. By changing the material of the button or the one of the trimplate, the friction changes, and the button's behavior changes spontaneously. To study the impact of that parameter, it was needed two molds (different shrinkage for each material). Thus, this parameter excluded due to the cost.

Another design parameter which also excluded due to cost is the position of the guides. Although the position of the two laterals and the center upper guide should be in the middle of the button's sides, due to technical reasons (lack of space) in some cases are their position is shifted from the middle point and are placed even in asymmetric positions. In order to examine the influence of such movements over the percept of a button, three more design parameters could be added. The two parameters regarding the position of the lateral guides, which could be named as Lateral Guide Left (LGL) and Lateral Guide Right (LGR) and one parameter regarding the position of the Central Guide (CG).

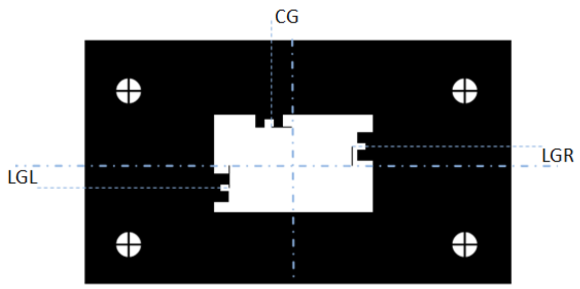

Figure 6-7 Design parameters LGL, LGR and CG, which are not included in the current study due to technical reasons

For future work, these two parameters are recommended to be included into the analysis as identified critical parameters throughout the analysis of the push button design architecture. Moreover, alteration on the specification of the outsourced parts could be also included in the analysis and is also recommended for future work.

6.1.4 Assigning levels for the selected control factors

In order to design the experiment, according to the Robust Design Methodology, first it is needed to assign levels for each one of the selected control factors. Table 6.1 illustrates the selected levels for each one of the control factors.

Regarding the control factor, Gap of the Guides (GG), which corresponds to the space between the guide of the trim plate and the guide of the button, three levels adopted; the first level A1 (tightest one), the one with a gap lower than 0,08mm. As second level A2, a gap was selected between 0,08mm and 0,15mm and the third level A3, the loosest one, corresponds to a gap between 0.15mm and 0.25mm.

Regarding the control factor, Preload Length (PL), which corresponds to the deformation of the spring at the initial position of the button (with the cap tangent at the trim plate), three levels selected. The selected levels are the B1, with deformation equal to 0,20mm, B2 with deformation 0,40mm and finally the one with the highest deformation: 0,60mm.

The control factor, Guide Length (GG), corresponds to the length of the central guide of the trim plate. Three levels selected, starting with the first level D1, 11,4mm which corresponds to 60% of the length of the button's size. The second level D2 corresponds to 55% and it is valued with 10,45mm and the third level D3 which is equal to 9,50mm corresponds to the 50%.

In order to assign tree levels on the parameter Lub, it was selected to have the first level E1 without any lubrication, the second level E2 by applying lubrication only on the central guide and a third level E3, by applying grease to all the guides.

Table 6.1 Control factors and their assigned levels

Control factors		levels		
		1	2	3
A	Gap Of the Guides (GG) (mm)	<0.08	0.08<x<0.15	0.15<x<0.25
B	Pre Load Length (PLL) (mm)	0,20	0,40	0,60
C	Actuator length (AL) (mm)	0,10	0,30	0,50
D	Length of the Guide (LG) (mm)	11.4	10.45	9.5
E	Lubrication (Lub) (grease appliance)	none	Middle guide	All guides

6.1.5 Matrix experiment design

In the next step, the experiment matrix was designed with the appropriate orthogonal array for the selected parameters and their levels. Taguchi provides many standard orthogonal arrays and the corresponding linear graphs (Taguchi, Chowdhury et al. 2007). The first step for selecting a standard orthogonal array, in order to fit the presented case study is the total degrees of freedom (DoF). DoF tell us the minimum number of experiments (trials) that must be performed to study the effect of all chosen control factors (Phadke 1995). The number of independent parameters associated with an entity like a matrix experiment, or a factor, or a sum of squares is called its degrees of freedom (Phadke 1995). One DoF is associated with the overall mean regardless of the number of control factors to be studied (Taguchi, Chowdhury et al. 2007). By following the general rule that the number of degrees of freedom associated with a factor is equal, to one less than the number of levels for that factor, plus the overall mean (Eq. 7.5) (Phadke 1995), at the current case study, with five factors of three levels each, gives a total number of DoFs equal to:

$$DOF = Number\ of\ factors\ \times (level - 1) + overal\ mean \quad (6\text{-}5)$$

$$DOF = 5 \times (3 - 1) + 1 = 11 \quad (6\text{-}6)$$

The 11 DoF indicate that at least 11 experiments have to be conducted. The smallest possible standard arrays that meets the requirements of the current case study is the L_{18}. The L_{18} has eight columns and that represents the maximum number of factors that can be studied. At the present case, with five factors, some columns will stay empty, something that does not violate the orthogonality of the array (Phadke 1995). The selected array has eighteen rows, meaning that have to perform eighteen trials, and its one will study a different combination. Table 6.2 illustrates the design of the experiment, by applying the selected levels into the Taguchi's standard orthogonal array L_{18}. On appendix are presented the measured values of each design requirements as obtained from the instrumental measurements.

Table 6.2 Matrix experiment adopting the Taguchi's standard orthogonal array L_{18}

Experiment number	**Control Factors**				
	1	2	3	4	5
	A GG	B PLL	C AL	D LG	E Lub
1	<0.08	0.20	0,1	11.4	none
2	0.08<x<0.15	0.40	0,3	10.55	Middle guide
3	0.15<x<0.25	0.60	0,5	9.7	All guides
4	<0.08	0.20	0,3	10.55	All guides
5	0.08<x<0.15	0.40	0,5	9.7	none
6	0.15<x<0.25	0.60	0,1	11.4	Middle guide
7	<0.08	0.40	0,1	9.7	Middle guide
8	0.08<x<0.15	0.60	0,3	11.4	All guides
9	0.15<x<0.25	0.20	0,5	10.55	none
10	<0.08	0.60	0,5	10.55	Middle guide
11	0.08<x<0.15	0.20	0,1	9.7	All guides
12	0.15<x<0.25	0.40	0,3	11.4	none
13	<0.08	0.40	0,5	11.4	All guides
14	0.08<x<0.15	0.60	0,1	10.55	none
15	0.15<x<0.25	0.20	0,3	9.7	Middle guide
16	<0.08	0.60	0,3	9.7	none
17	0.08<x<0.15	0.20	0,5	11.4	Middle guide
18	0.15<x<0.25	0.40	0,1	10.55	All guides

6.1.6 Conducting phase

This is the phase in which the planned experiment is carried out by building the prototypes according to the matrix experiment design (Table 6.2). The production of the prototypes performed in the plant of the research's affiliate company which is responsible for the design and the manufacturing of the ICIs. For the production, specially designed tools were needed for injection molding, with use of several mold's inserts in order to perform the needed alterations over the design parameters.

To fulfill the design matrix, eighteen combinations were produced; ten times each one in order to identify the existence of variability of the manufacturing process.

The selected prototype is a single push button from the AUDI A1 radio bezel, Figure 6-8. Due to cost reasons, only one button was selected to be used as a case study and not the whole bezel, as discussed at the chapter 3. Thus, the eject button of the bezel was 'cut', by keeping the design beneath the button (the supporting mechanism) identical to the real one. Of course, the action of keeping only a single button, it might have impact on the acoustic emission of the button and in sequence its acoustic behavior, as the surroundings of the button are going to be 'missing'. Unfortunately, due to high costs (much bigger mold was needed for the whole radio bezel), this compromise was made. But we have to understand that since the mechanism is the same, the kinesthetic behavior it will be the same. The mechanism is the one that produces the sound and the only thing that changes it will be the propagation of the sound.

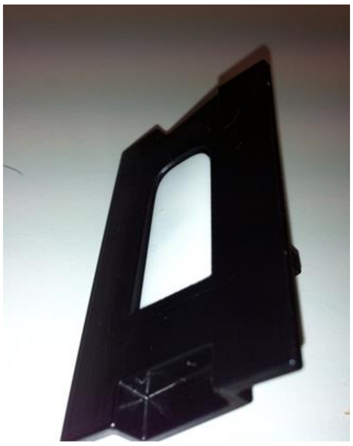

Figure 6-8 Case study ICI push button

In order to keep those design parameters which were excluded from the analysis as constant, a measurement jig. The jig integrates the PCB, the PCB actuator, and the spring (Figure 6-9).

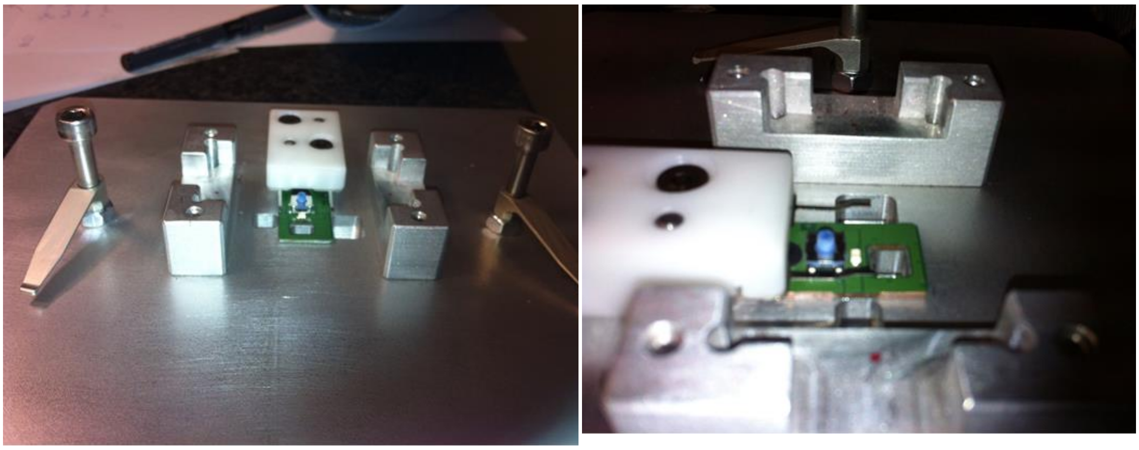

Figure 6-9 Base of the case study which includes the PCB, the spring and the actuator

On the jig, our selected case push button was placed, Figure 6-10, which was produced according to the designed experiment. In this way, the variation from factors which were not included for the presented analysis was kept out.

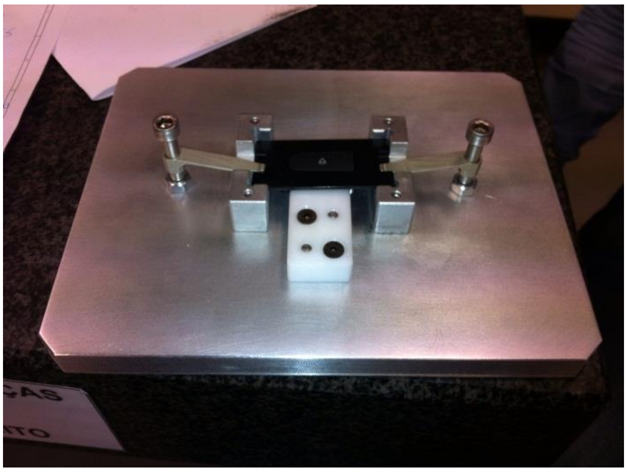

Figure 6-10 Base with the case study push button

Table 6.3 presents the control factors and the assigned component where the modifications were performed. As observed, the control factors GG, LG and Lub were performed on the component trim plate, while the PLL and AL were performed on the component button.

Table 6.3 Control factors and the assigned component

	Control factors	
Trim plate	A	GG
Button	B	PLL
	C	AL
Trim plate	D	LG
Trim plate	E	Lub

For the component trim plate one mold was manufactured with three inserts; one insert for each level of the factor GG. The factor Lub was applied afterwards on the component, and no insert was needed. Primary, the trim plate were produced with the first level of the factor LG, and afterwards, to achieve the two other levels (which are shorter), the part cut in a pneumatic machine that is also developed for the purposes of the presented experiment.

One mold was also manufactured for the production of the component button (Figure 6-11), with two inserts for the two levels of the design parameter PLL and two regarding the LG.

Figure 6-11 The mold of the button

Finally, components were assembled according to the experiment matrix and the acoustic and kinesthetic measurements were performed. From the instrumental measurements the engineering parameters which identified as design requirements were extracted for each combination of the presented experiment in order to be used as objective functions for the analysis.

6.1.7 Results of the analysis

Regarding the kinesthetic related design requirements, FS-PL and DS-DR, as stated at the previous step of the research framework, are design requirements which work at a perceptual level. From the design point of view, the control of those design requirements should be performed through the engineering parameters which affect them, the FS, PL, DS and DR accordingly. For that reason, instead of having as

objective function the design requirements FS-PL and DS-DR, will be used the four corresponding engineering parameters FS, PL, DS and DR.

The statistic software MINITAB was used to perform the analysis of the results.

Engineering parameter PL

The design requirement FS-PL was found to have a negative contribution over the target percept, meaning that the difference between the two forces (FS and PL) has to be minimized. This indicates that the objective parameter PL should increase in order to minimize the parameter FS-PL. Thus the S/N of the PL follows the-higher-the-better. From the instrumental measurements the value of the PL for each experiment recorded and the S/N calculated accordingly. The response table for means of the PL and response graph of the S/N presented in Table 6.4 and Figure 6-12 respectively. The graph illustrates that the PL is only affected by the PLL and on the response table, the effects of each level is presented. A linear relationship could be observed and mainly this phenomenon could be explained due to the constant K of the spring as the only affective factor.

Table 6.4 Response table for means of the PL (N)

Level	**GG**	**PLL**	**AL**	**LG**	**Lub**
1	0,64	0,26	0,60	0,63	0,61
2	0,60	0,56	0,63	0,58	0,58
3	0,59	1,01	0,60	0,62	0,64
Delta	0,05	0,75	0,03	0,05	0,06
Rank	3	1	5	2	4

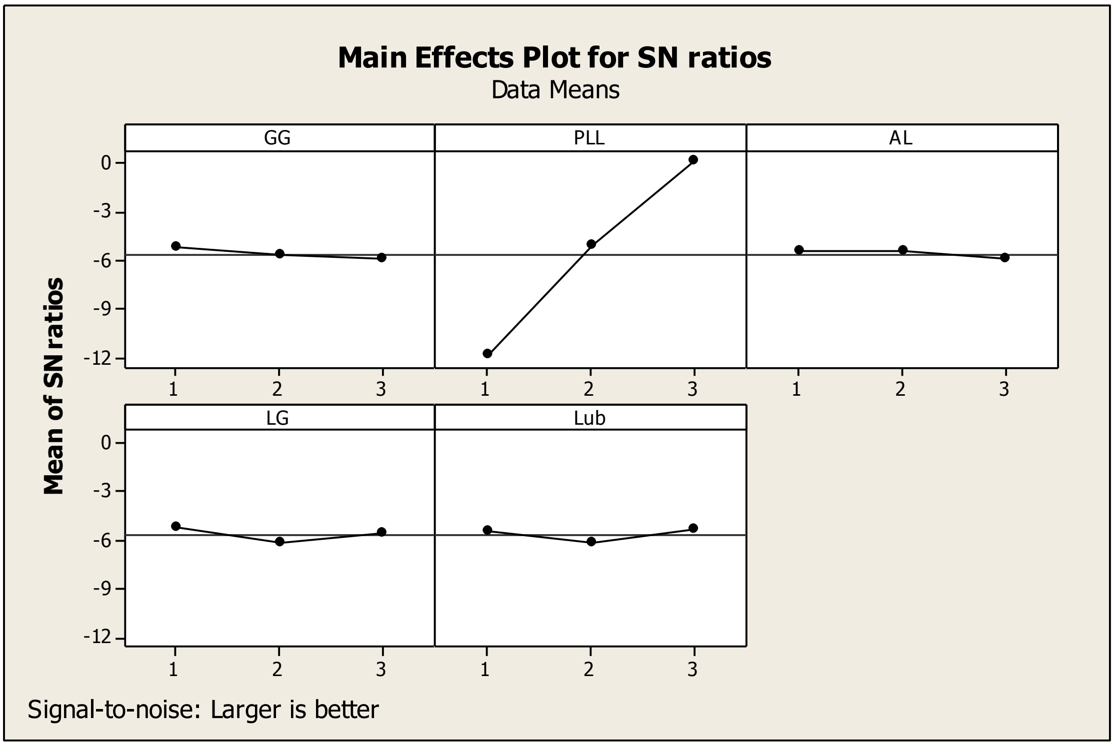

Figure 6-12 S/N graph for PL

To estimate the contribution of each design parameter over the quality characteristic PL, an analysis of variance (ANOVA) performed. Table 6.5 presents the results of the ANOVA and illustrates that the control factor AL is the main affect (98,15% with p-value<0,05) of the engineering parameter Pre-Load as observed at the Plot (Figure 6-12). This is quite reasonable, as the button at its initial position receives only the feedback force from the spring, and the actuator length is the only parameter that is linked with the spring by defining the deformation of the spring at its initial position. As the Pre-load is the needed initial force in order to make the button start moving, the other design parameters do not have any impact, as the button's travel is quite short.

Table 6.5 Analysis of Variance for the PL

Control factor	DOF	Sum of Squares	Means of Square	F	P-value	Contribution
GG	2	2,01	1,00	0,75	0,51	0,46%
PLL	2	427,92	213,96	160,20	0,00	98,15%
AL	2	0,88	0,44	0,33	0,73	0,20%
LG	2	3,03	1,51	1,13	0,38	0,69%
Lub	2	2,16	1,08	0,81	0,48	0,50%
Residual	7	9,35	1,34			
Total	17	445,35				

Engineering parameter FS

Keeping the same line of thinking, as performed with the PL, the FS should be decreased, in order to decrease the FS-PL. Thus it presents a type of problem; the-lower-the-better. Accordingly, the S/N is calculated from the instrumental measurements of the FS for each experiment. Table 6.6 and Figure 6-13 present the response table for means and S/N graph for the FS. As one observes from the graph, the FS is being affected by the design parameters PLL and AL, while the effect of each level of these two design parameters is almost equal, with the PLL to be the primary affective factor. A linear behavior, as observed for the PL, due to the reason that the actuator works also as a spring, of course with a defined constant K.

An interesting point is the fact the engineering parameter PL and the FS which define the engineering requirement FS-PL, both of them are affected by the PLL at the same way. Thus, during the design process when is needed to adjust the engineering parameter PL by increasing the design parameter PLL, this adjustment has an impact over the FS. This type of problem is one of main issue when during the design process is tried to adjust the percept of a push button with the conventional trial-and-error

method. The sensitivity between these two engineering parameters over the same design parameter (PLL) creates an endless process of trial-and-error as one alteration over the design parameter PLL in order to adjust the PL affects the FS and vice versa. Hence, at the design process when it is wanted to achieve a specific value of PL the impact on the FS has to be known.

Table 6.6 Response table for means of the FS (N)

Level	GG	PLL	AL	LG	Lub
1	5,72	5,31	5,31	5,68	5,69
2	5,68	5,66	5,71	5,69	5,67
3	5,67	6,1	6,05	5,7	5,7
Delta	0,05	0,79	0,74	0,02	0,03
Rank	3	1	2	4	5

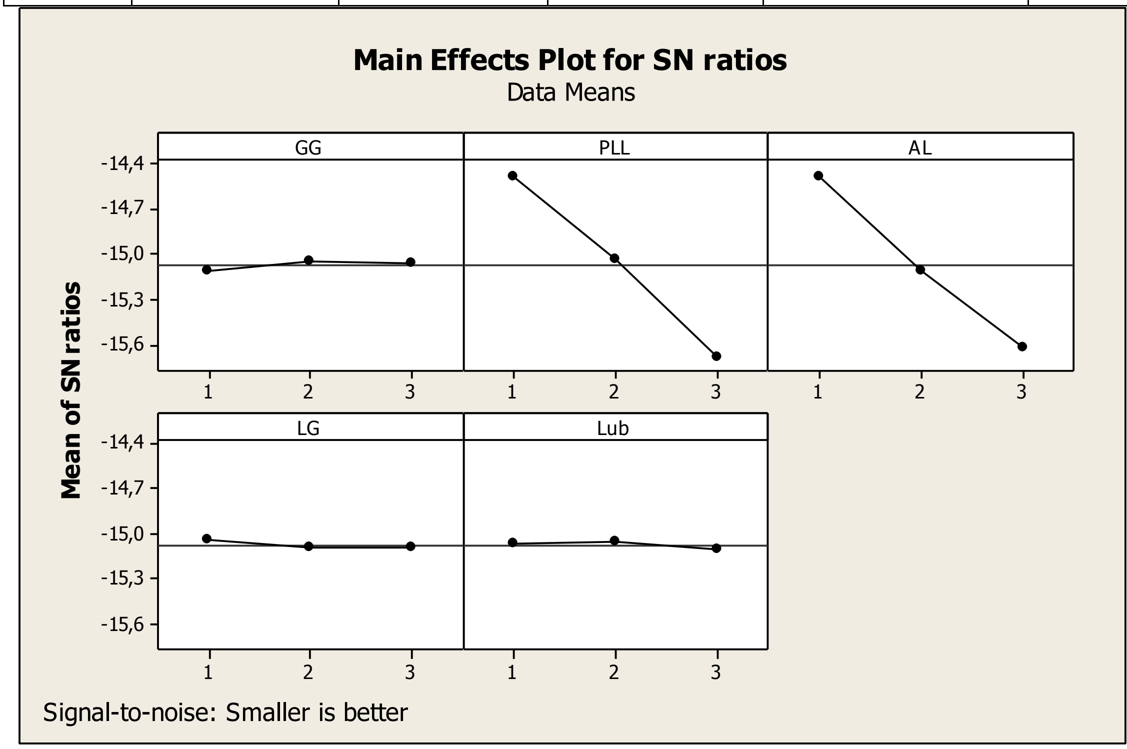

Figure 6-13 S/N graph for FS

The results from the ANOVA for the FS (Table 6.7) that the only contributing factors are the PLL and AL (p-value<0,05) and their effect over the FS is almost equally distributed, with 55,604% and 44,65%, respectively. As was suspected, the feedback force at the activation point is a combination force generated by the spring and the

PCB actuator almost equally, but now the exact contribution of each design parameter revealed and also the fact that the others design parameters do not affect.

Table 6.7 Analysis of Variance for the FS

Control factor	DOF	Sum of Squares	Means of Square	F	P- value	Contribution
GG	2	0,00	0,01	0,90	0,45	0,15%
PLL	2	4,39	2,19	332,44	0,00	55,04%
AL	2	3,92	1,96	269,68	0,00	44,65%
LG	2	0,01	0,00	0,61	0,57	0,10%
Lub	2	0,01	0,00	0,42	0,67	0,07%
Residual	7	0,05	0,01			
Total	17	8,38				

Engineering parameter DS

Following the analysis of the design requirement FS-PL, the design requirement DS-DR will be treated in the same way. As the DS-DR found to effect the target percept negatively, the engineering parameter DS should be decreased, by following the-lower-the-better type of problem. Table 6.8 and Figure 6-14 illustrate the response table for means and the S/N graph for engineering parameter DS, respectively. As one can observe from the graph, the control factor Actuator Length is the only affective factor and on the response table is illustrated the effect of each level over the mean of the DS.

Table 6.8 Response table for means of the DS (dB)

Level	GG	PLL	AL	LG	Lub
1	1,03	1,02	0,86	1,03	1,04
2	1,04	1,04	1,02	1,05	1,03
3	1,04	1,05	1,22	1,03	1,03
Delta	0,01	0,03	0,36	0,02	0,01
Rank	4	2	1	3	5

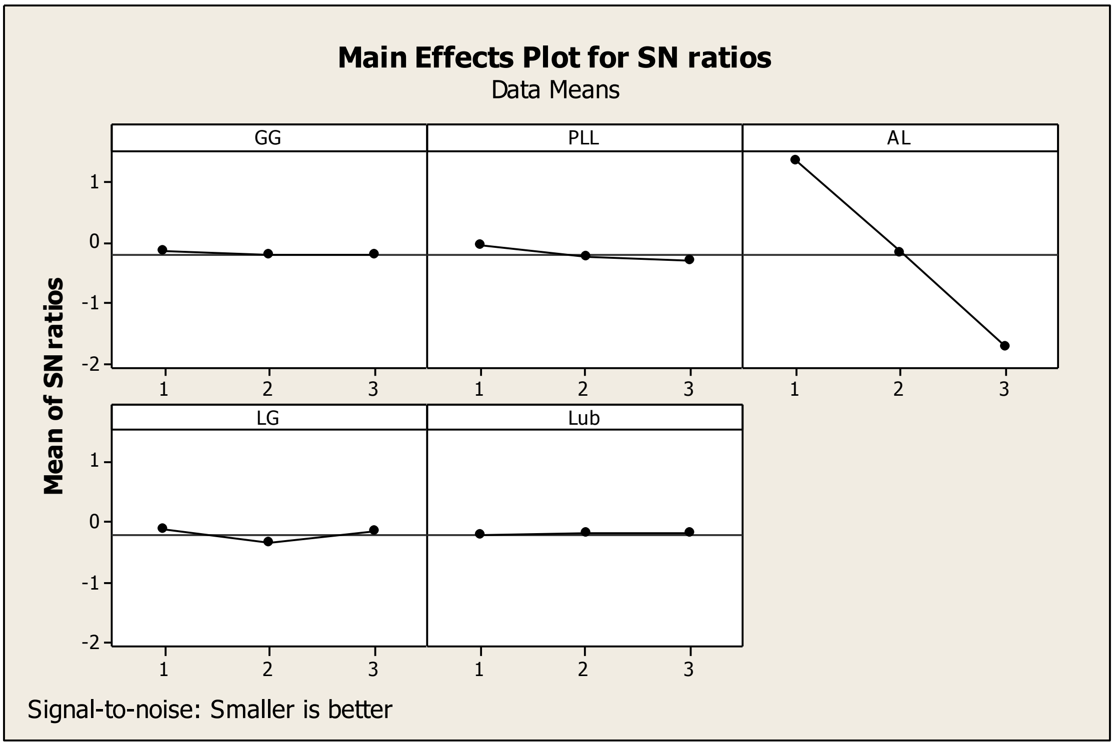

Figure 6-14 S/N graph for DS

The Table 6.9 presents the results from ANOVA of the DS. The 97,60% of the DS is explained by the design parameter Actuator Length, the main and the only affective factor (p-value<0,05). This is reasonable, as the travel of the button till the activation point (DS) is totally dependent on the length of the actuator, as a longer length indicates a shorter travel and the rest of the parameters cannot affect it due to their nature (force related).

Table 6.9 Analysis of Variance for the DS

Control factor	**DOF**	**Sum of Squares**	**Means of Square**	**F**	**P- value**	**Contribution**
GG	2	0,02	0,01	0,16	0,86	0,07%
PLL	2	0,21	0,11	1,68	0,25	0,73%
AL	2	28,36	14,18	226,21	0,00	98,67%
LG	2	0,15	0,07	1,18	0,36	0,51%
Lub	2	0,00	0,00	0,03	0,98	0,01%
Residual	7	0,44	0,06			
Total	17	29,17				

Engineering parameter DR

The engineering parameter DR should be increased in order to minimize the design requirement DS-DR. Thus, we have the lower-the-better type of problem. Observing the response table for means (Table 6.10) and the S/N graph (Figure 6-15) the same behavior as observed with the engineering parameter DS can be noted, since both of them are related to the travel of the button and only affective design parameter found to be the AL.

Table 6.10 Response table for means of the DR (mm)

Level	GG	PLL	AL	LG	Lub
1	0,86	0,85	0,69	0,86	0,87
2	0,87	0,88	0,86	0,88	0,87
3	0,87	0,87	1,05	0,86	0,86
Delta	0,01	0,02	0,36	0,02	0,01
Rank	4	3	1	2	5

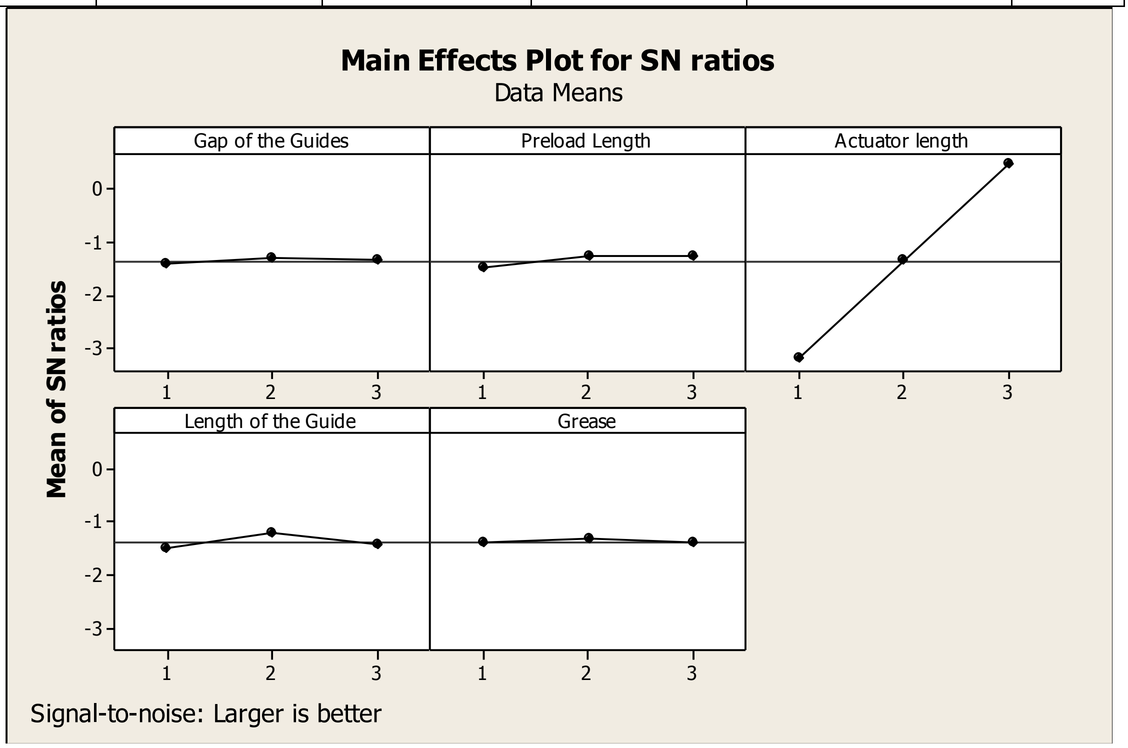

Figure 6-15 S/N graph for DR

By performing the ANOVA for the DR, the results indicate that the 98,12% of the DR could be described by the design parameter AL and is the only contributing factor (p-value<0,05) . The same behavior was noticed for the DS, as both of them have the same nature (distance related engineering parameters).

Table 6.11 Analysis of Variance for the DS

Control factor	DOF	Sum of Squares	Means of Square	F	P- value	Contribution
GG	2	0,05	0,02	0,68	0,54	0,12%
PLL	2	0,19	0,10	2,82	0,13	0,48%
AL	2	39,61	19,80	573,51	0,00	98,12%
LG	2	0,25	0,13	3,68	0,08	0,63%
Lub	2	0,02	0,01	0,33	0,73	0,06%
Residual	7	0,24	0,03			
Total	17	40,37				

Engineering parameter SPLa_press

The first acoustic related design requirement SPLa_press was found to have a negative contribution over the target percept, which indicates the-lower-the-better type of problem. On Figure 6-16, illustrated which design parameters affect the design requirement SPLa_press. One could easily observe that the engineering parameter is being affected almost by all the design parameters. On Table 6.12 the means of the SPLa_press on each level of the design parameters are presented, and it could be observed that the main affective design parameter is the Actuator Length (AL).

Table 6.12 Response table for means of the SPLa_press (dB)

Level	GG	PLL	AL	LG	Lub
1	57,46	56,54	56,48	57.24	56,45
2	57,53	58,11	58,95	56,99	57,55
3	56,63	56,96	56,19	57,39	57,61
Delta	0,9	1,57	2,77	0,4	1,15
Rank	4	2	1	5	3

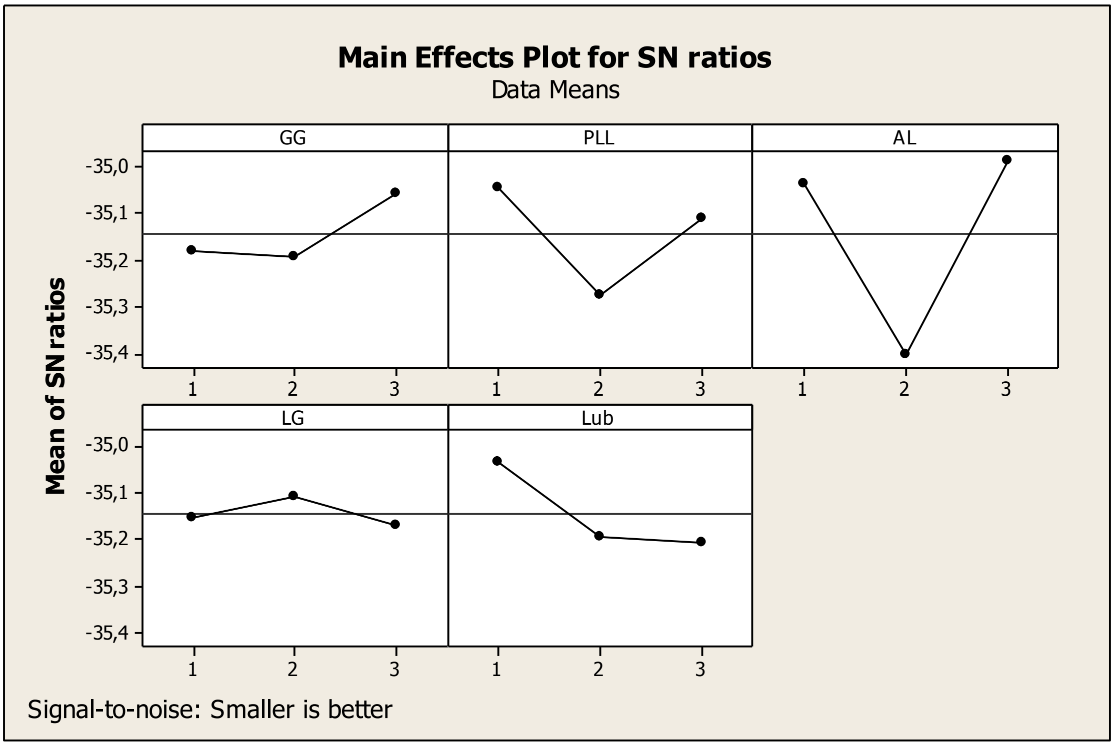

Figure 6-16 S/N graph for SPLa_press

Performing ANOVA for the means of the SPLa_press, results (Table 6.13) indicate that the main affect factor is the Actuator Length, with 63,11%, while the rest design parameters remain on lower levels. Here, it is important to mention the first time of having the Gap of the Guides, Length of the Guides and Grease as affective design parameters. The fact of having the rest factor with lower contribution is reasonable, if one imagines that the main source of the sound is generated by the PCB actuator. The actuator is the one that makes the click, while the other parameters affect the sound that the actuator produces. This is proved by the fact of having the spring (PreLoad Length) as a second affective parameter (17,14%), since it could be considered as the second source of sound within the system. Here it is mentioned that the spring could be considered a source of the sound because it is not exactly producing sound as the actuator, but when it is depressed, it vibrates and produces sound. As third contributing factor is the Lub, which also affect the produced sound as a smoother

movement eliminate the generated sound. The rest of the components of the button also vibrate during the depression phase, but the fact they are made of plastic parts, in comparison with the metallic actuator and the spring, places their contribution on lower levels. Except their lower contribution, all factors found to have statistically significance (p-value <0,05) over the SPLa.

Table 6.13 Analysis of Variance for the SPLa_press

Control factor	DOF	Sum of Squares	Means of Square	F	P- value	Contribution
GG	2	0,07	0,33	0,55	0,05	6,83%
PLL	2	0,17	0,08	1,38	0,03	17,14%
AL	2	0,62	0,31	5,08	0,01	63,11%
LG	2	0,01	0,01	0,11	0,05	1,37%
Lub	2	0,11	0,06	0,93	0,04	11,55%
Residual	7	0,42	0,06			
Total	17	1,40				

Engineering parameter SPLa_release

The design requirement SPLa_release affects the target percept positively, and this implies the-higher-the-better type of problem. As it is observed on the S/N graph for SPLa_release (Figure 6-17), all the engineering parameters affect it, in the same way as observed for the sound pressure level of the pressing phase. On the response table for means (Table 6.14) the effect of each level over the engineering parameter is presented.

Table 6.14 Response table for means of the SPLa_release (dB)

Level	GG	PLL	AL	LG	Lub
1	63,64	63,07	63,76	63,95	63,38
2	64,08	64,3	65,09	63,73	64,2
3	63,26	63,6	62,13	63,3	63,4
Delta	0,83	1,23	2,96	0,64	0,82
Rank	3	2	1	5	4

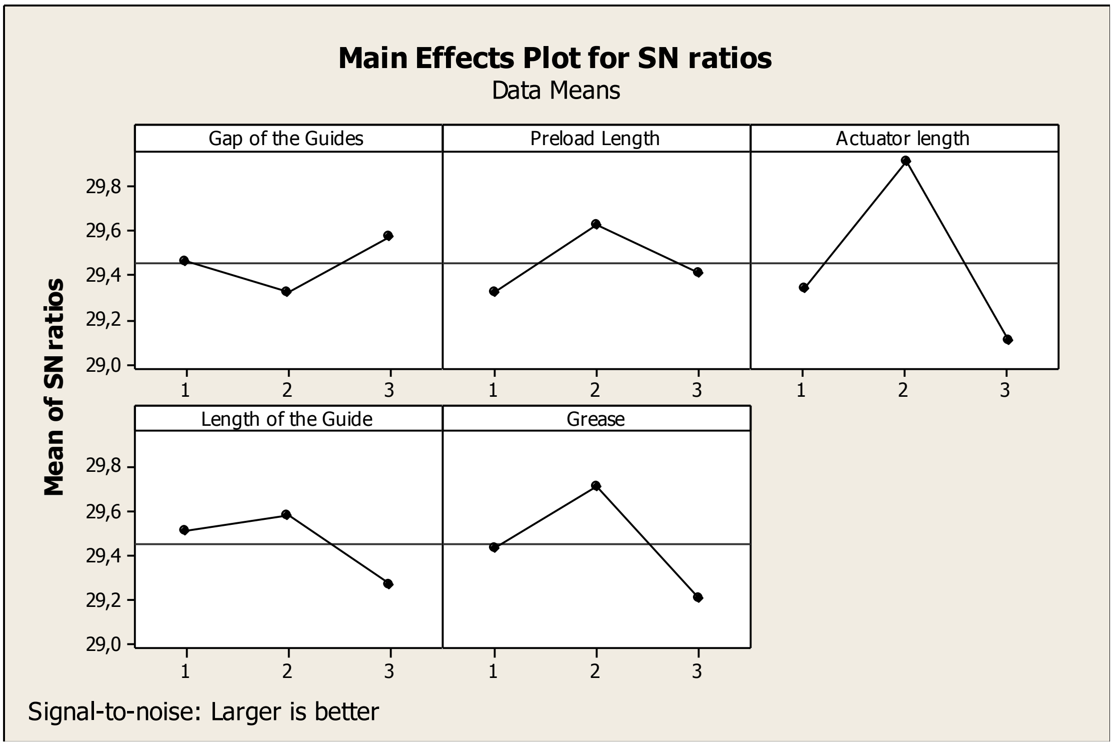

Figure 6-17 S/N graph for SPLa_release

The results of the ANOVA (Table 6.14) present a same behavior as recorded for the pressing phase, with some alterations, mainly due to the difference of the movement. The actuator length remains the first contributor (72,41%) as observed for the pressing phase (63,11%). The second contributor factor remains the PLL (11,11%) . Again all factors appears a statistically significance (p-value<0,05).

Control factor	**DOF**	**Sum of Squares**	**Means of Square**	**F**	**P- value**	**Contribution**
GG	2	0,05	0,02	0,16	0,04	6,13%
PLL	2	0,08	0,04	0,29	0,04	11,11%
AL	2	0,49	0,25	1,89	0,02	72,41%
LG	2	0,02	0,01	0,10	0,05	3,83%
Lub	2	0,04	0,02	0,17	0,04	6,51%
Residual	7	0,92	0,13			
Total	17	1,60				

Table 6-18 Analysis of Variance for the SPLa_release

Engineering parameter SC_release

The last objective function is the acoustic related design requirement, the Spectral Centroid of the release phase. The SC_release affect the target percept negatively, indicating a type of problem the-lower-the-better.

Table 6.15 Response table for means of the SC_release (Hz)

Level	GG	PLL	AL	LG	Lub
1	5956	5926	5930	5918	5885
2	5914	5931	6066	5932	6005
3	5896	5908	5769	5915	5876
Delta	60	23	297	17	129
Rank	3	4	1	5	2

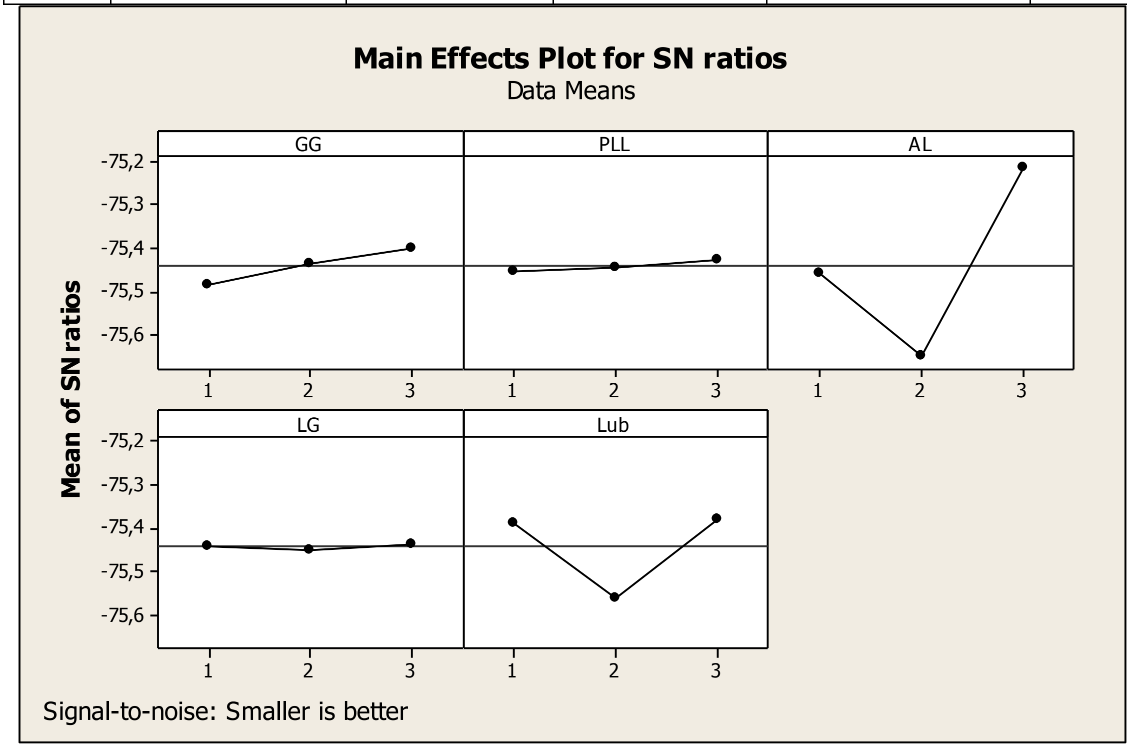

Figure 6-19 S/N graph for N_release

The results of the ANOVA Table 6.16 presents indicate that the main contributor is the AL (77,5%) and follows the Lub(17,5%). The rest factors do not affect (p-value>0,05).

Table 6.16 Analysis of Variance for the SC_release

Design Parameter	DOF	Sum of Squares	Means of Square	F	P- value	Contribution
GG	2	0,022	0,011	0,05	0,05	3,13%
PLL	2	0,002	0,001	0,01	0,12	0,63%
AL	2	0,572	0,286	1,24	0,03	77,50%
LG	2	0,000	0,000	0,02	0,22	1,25%
Lub	2	0,004	0,064	0,28	0,04	17,50%
Residual	7	0,129	0,231			
Total	17	1,622				

6.1.8 Validation

In order to validate the results, the percept of the eighteen experiments evaluated by the AC. Table 6.17 presents the results of a likert scale experiment which performed by the AC.

1=very good, 6=unsatisfactory.

Table 6.17 AC evaluation of the overall percept

Experiment number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	18
Overall impression	2	4	4	6	6	6	6	6	6	4	4	2	6	6	6	6	6

The ranking of the likert scale were used as objective function. On Figure 6-20 is illustrated which design parameters affect the overall impression of the percept. As observed, the main design parameter that affects the percept is the design parameter Gap of the Guides. Table 6.18 presents the responses of the means of the percept of the overall impression on each level of the design parameters. It could be noted that the design parameter Gap of the Guides is the first contributing factor, followed by the Lub, while the rest are placed at the same position as their contribution is equal.

Table 6.18 Response table for means of the overall percept

Level	Gap of the Guides	Preload Length	Actuator length	Length of the Guide	Grease
1	3,33	5,00	5,00	5,00	4,67
2	6,00	5,33	5,00	5,00	5,33
3	6,00	5,00	5,33	5,33	5,33
Delta	2,67	0,33	0,33	0,33	0,67
Rank	1	4	4	4	2

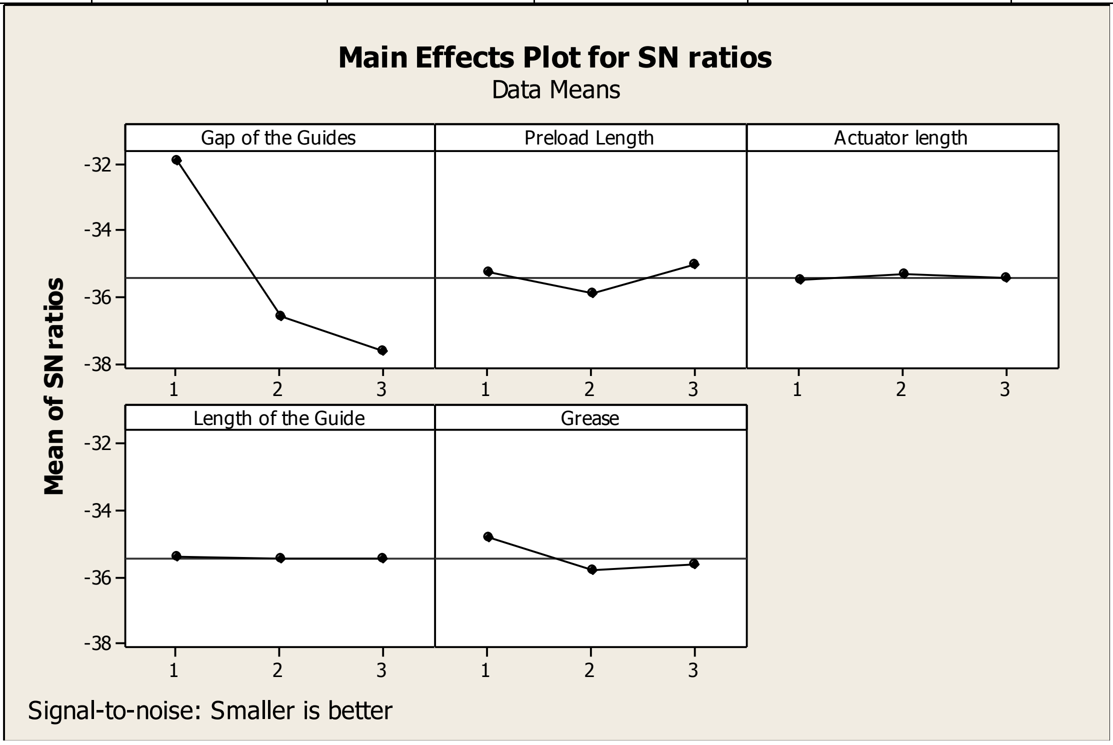

Figure 6-20 S/N graph for the overall percept

The results of the ANOVA (Table 6.19), indicate that the design parameter with the highest contribution can explain the 84,21% of the overall percept, while the second contributor is quite low, 5,26%. The other three parameters were found to have equally a quite low contribution to 1,32%.

The results indicate that the optimum levels regarding the overall percept is Gap of the Guides level 1, Preload Length Level 1 and 3, Actuator Length level 1 and 2, Length of the Guides 1 and 2 and Grease level 1.

Table 6.19 Analysis of Variance for the overall percept

Design Parameter	DOF	Sum of Squares	Means of Square	F	Contribution
GG	2	28,4444	14,2222	44,8	84,21%
PLL	2	0,4444	0,2222	0,7	1,32%
AL	2	0,4444	0,2222	0,7	1,32%
LG	2	0,4444	0,2222	0,7	1,32%
Lub	2	1,7778	0,8889	2,8	5,26%
Residual	7	2,2222	0,3175		
Total	17	33,7778			

6.2 Discussion

The results of the second step of the analysis, many interesting facts revealed regarding the impact of the design over the percept of an ICI push button. As observed some design parameters affect the design requirements in different way, and this highlights the fact of having an endless trial-and-error process. The sensitivity of the system is so high that a single alteration on a design parameter is able to cause unwanted reactions over the rest of the design requirements. Unaware of such dependencies is mainly the main root of the current problematic state.

Another important conclusion is the fact that through the design process were performed modifications on design parameters such as Lub, LG and GG in order to achieve the kinesthetic percept, as requested by the AC. The results indicated that these design parameters mainly effect the acoustic related design requirements which till now were not specified. If one considers that the delivered design requirements were related to the kinesthetic sense, the design process went beyond that and approached design parameters that affect the acoustic sense. This is quite critical because the AC were able to deliver a product that meets the requirements, but they realized that something was missing and approached the problem by altering the design with impact over the acoustic sense. They were aware that these design parameters do not affect those engineering parameters that are delivered, but it was

their only way to achieve the percept and not only to meet the requirements. As mentioned at the previous step, the interaction between acoustic and kinesthetic sense is so high and it is not possible to distinguish the acoustic and kinesthetic related engineering parameters. A possible and reasonable explanation is the fact that the acoustic related parameters could carry kinesthetic information, transmitted through the vibrations from the interaction by the finger.

The design parameter with the highest impact was found to be the actuator length (AL) and it is proposed to be included into the design specifications list. This is reasonable as it is the design parameter which directly affecting the PCB actuator, which can be considered as a button under the button. The PCB actuator creates the main feedback force and is the main source of the sound. In many cases, this parameter was found to have an inverse impact, such as the FS-PL. While the objective is to minimize the difference between the Force to Stroke and the Pre Load, the inverse impact of the actuator length on these two engineering parameters proves the fact that while through the design process it is tried to reduce the FS or increase the PL, by altering the actuator's length level, it returns to the same outcome of not achieving the percept. This is proved from the validation, where the most critical parameter of the overall percept was found to be the Gap of the Guides. Although it was observed that the actuator length has the highest impact, the positive and negative contribution counteracts its impact and that parameter is neutralized. The individual impact on each engineering parameter remains, and from the design process point of view, that type of knowledge is the most valuable in order to control the percept of a ICI.

With the provided results, the supplier company which is responsible for the design and the manufacturing has a better understanding in order to identify the optimum values for each design parameter in a systemic way.

7. GENERAL DISCUSION

The aim to include emotions as design requirements in the design process could be considered as an emerging issue in the automotive industry. If one considers the way of buying a product, especially a car, it could be identified by two main contributing factors: the technical and the emotional part. Although, the significance for both is given, the research related to the emotionally part is still missing. While the first is related with the main function of the product, the latter imparts an added value to the product, which is a hallmark to gain competitive advantage.

The lack of information regarding the perceptual level is obvious from the way of approaching it, by treating it in the same way as they used to deal with a technical function of the product. Based on the fact that AC companies have not yet reached the point of defining a feeling with appropriate design requirements, we are led to the problematic state that we face today, were the produced part is not in a position to achieve the proper percept in order to emote the wanted feeling as the AC wants to deliver to their customers.

Comprehending that the approaching of the emotional part could not be accomplished with the traditional engineering methodologies, in the last decades the research has shifted to the cognitive science in order to design and manufacture products with emotional aspects. The presented research targets to ascribe a predefined feeling to the manufacturing process through the design process.

To approach this issue, the method to define the target percept in engineering terms is first exploited. More specifically, to investigate how an ICI has to perform in order to

achieve the target percept, as defined by the AC. The performance is characterized by a set of design requirements which conveys an appropriate amount of information to define the target percept. To determine the aforementioned set of design requirements, an experiment performed by using existing prototypes (built by trial and error method) which were evaluated by the AC and judged as accepted or rejected regarding their percept. This evaluation was used as an indicator of achieving or not the target percept. Afterwards, these prototypes were instrumentally measured and the acoustic and the kinesthetic behavior recorded. A selection process showed which acoustic and kinesthetic related engineering parameters have physical meaning and could have an impact over the percept. Moreover, statistical analysis was performed between the judgment of the AC and the selected engineering parameters which extracted from the measurements. The results showed which parameters are indeed statistically significant and contribute over the percept and should be included into the delivered set of the design requirements. Besides the selection, the statistical analysis displayed the contribution of each engineering parameter and how they affect the percept.

Until now, ACs have been used to delivering only kinesthetic related design requirements. The results of the study prove that by using only the delivered design requirements it is not possible to define the percept. Instead, the new defined kinesthetic related engineering parameters, the FS-PL and DS-DR, which works at a perceptual level, were found to be statistically significant with impact over the percept. By using these new defined kinesthetic related engineering parameters as design requirements a model with predictive power around 70% was achieved. Moreover, by adding acoustic related engineering parameters into the analysis, the results indicate that there could be reached a predictive power almost equal to 85%.

The fact that acoustic related parameters were found to have impact over the percept, highlights the importance of including acoustic related engineering parameters into the design requirements and the results pointing out that the integration of the acoustic and kinesthetic sense is vital to characterize the percept.

The engineering parameters which were found to have significant contribution over the percept and should be included into the set of the delivered design requirements are the FS-PL, DS-DR, SPLa_press, SPLa_release, and SC_release.

The way that these design requirements affect the percept could be considered as the objective functions of the product. In another sense, as it was found to be, an increase or a decrease of the value of these parameters affects the percept either positively or negatively in term of the wanted target percept. Thus, the second goal of the current study was to investigate how to regulate these parameters through the design process, in order to adjust them into appropriate levels that will offer the wanted target percept. To achieve this goal, the third step of the framework developed, by targeting over the design parameters that affect the performance of an ICI push buttons, i.e. the design requirements which were found to have ca contribution over the percept, in order to be included into the set of the design specifications.

The third step of the research framework aims to identify how the design influences the performance/behavior of and ICI push button in order to control it through the design process. This is a quite critical step, in order to complete the picture of the percept. While the design requirements which affect the percept were recognized, how to control them is still unknown. The nature of the percept, which could be characterized as highly sensitive one, implies to comprehend precisely how the design affects its outcome the performance/behavior of an ICI.

To accomplish this step, a designed experiment was performed, by following the Robust Design methodology. The analysis of the system ICI push button showed which design parameters are critical and could affect its performance. The selected design parameters were assigned into levels and the experiment matrix was developed by using Taguchi's standard orthogonal arrays. New prototypes were built according to the experiment matrix and the acoustic and kinesthetic behavior measured instrumentally. From the measurements the design requirements as defined previously were recorded and were used as objective functions. The result of the analysis showed how each design parameter affects each engineering parameter. As observed, some design parameters affect in different way the design requirements (positive/negative). This indicates a system with high sensitivity and the selection of the proper levels of each design parameter should be performed in a systemic way. This means that we should understand that a single change on a design parameter affects several engineering parameters simultaneously, and should be followed a holistic approach, i.e. the global performance.

The results of this study offers to the design process more inside knowledge, in order to assist to design an ICI push button in such way that it will achieve specific values for the design requirements and consequently to achieve the target percept.

One issue regarding the current research is the applicability on other ICI's elements, which a user interacts with. As the case study was an ICI push button, it should be considered if the same approach could be used for the rest of the elements of an ICI. The presented approach could be considered valid for the other elements, if the analysis will be performed according to the nature of the element under analysis. For instance, an ICI air-vendor, an element which also emits emotions to the user through the interaction with it. The research approach will be the same, in terms of

approaching first the percept by identifying the appropriate design requirements, and then to identify how to control them through the design process. As first step, a selective approach is recommended to be performed and then statistical analysis will show the significance of each engineering parameter, in order to indicate which should be used as design requirement. The statistical analysis could be performed in a different way, depending on the judgment type as well as the prototypes that will be used. For the second step, a designed experiment is needed to explore accurately the effect of the design over the performance, due to the sensitivity of the percept. It could be concluded that the main path of the framework which is based on systemic approach is vital to analyze the percept for any given ICI element.

Finally, It could be mentioned that the current study presents a comprehensive method to analyze the percept of an ICI and indicate that the emotional aspect of an ICI which is reflected through the percept could not been seen as individual function of the product, but as a system, where the senses are integrated and as an outcome emote a feeling.

8. FUTURE WORK

The proposed future work could be grouped into two categories. The first category is related to apply the proposed research by investigating other AC’s target percept, analyzing other type of push buttons with different design architecture and analyzing other ICI elements.

The second category is related to how to optimize the results, meaning to describe the target percept more precisely. The presented framework has as an input a predetermined feeling which is selected by the AC. Though a selection process by interviewing end users of the selected market target, AC choose the feeling that they want to apply into their products. AC experts after the selection process know which percept is the appropriate one and the desired one from the supplier company which is responsible for the design and the manufacturing. This percept is not something that can be translated in engineering terms precisely, as it deals with a quite sensitive issue. It will be quite interesting if a supplier company could enroll into this process, meaning to be involved into the selection process, directly with the end users. Instead of using AC’s judgment as indicator of achieving the target percept, as future work is proposed to bring closer the supplier company with the AC to deal with the issue of delivering a feeling, by having a direct connection with the feeling that they have to produce. To achieve this step a further research is needed over the procedures of choosing the appropriate feeling. The results of this proposal will be closer to eliminate the gaps between the wanted percept and the produced one, as it will bring the feeling into the design level.

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Appendix 1

Table 8.1 Results of the logic test

Participant Number	**PL False Measure**	**DS False Measure**	**FS False Measure**
1	0	8	6
2	0	0	2
3	11	11	6
4	1	2	0
5	0	2	2
6	7	7	1
7	2	0	0
8	0	1	1
9	6	0	0
10	0	1	0
11	11	7	1
12	0	0	0
13	1	1	0
14	2	0	0
15	0	1	0
16	0	2	2
17	0	1	0
18	1	3	5
19	0	0	0
20	0	5	2
21	0	1	5
22	0	2	0
23	0	0	0
24	0	0	0
25	0	0	0
26	0	0	1
27	0	3	2
28	4	1	2
29	0	0	8
30	0	3	2
31	1	5	0
32	0	3	3

Table 8.2 – Difference Δ for each pair of buttons of the measured parameters ΔPLm_{ij}, ΔDSm_{ij} *and* ΔFSm_{ij} *(where j is the second button of each pair).*

pair of buttons i and j	**ΔPLmij (N)**	**ΔDSmij (mm)**	**ΔFSmij (N)**
12	0,664	0,300	-0,013
13	0,090	0,050	-0,191
14	0,868	0,051	-1,340
15	0,544	0,151	-0,370
16	0,947	0,300	-0,159
17	0,312	0,050	0,510
18	0,069	0,101	0,333
19	0,562	0,099	-0,403
23	-0,574	-0,250	-0,178
24	0,204	-0,249	-1,327
25	-0,120	-0,150	-0,358
26	0,283	0,000	-0,147
27	-0,352	-0,250	0,523
28	-0,595	-0,200	0,346
29	-0,102	-0,201	-0,390
34	0,778	0,000	-1,149
35	0,455	0,100	-0,179
36	0,857	0,249	0,031
37	0,222	0,000	0,701
38	-0,020	0,050	0,524
39	0,473	0,049	-0,212
45	-0,324	0,100	0,970
46	0,079	0,249	1,180
47	-0,556	-0,001	1,850
48	-0,798	0,050	1,673
49	-0,305	0,048	0,937
56	0,403	0,149	0,211
57	-0,232	-0,100	0,880
58	-0,475	-0,050	0,703
59	0,018	-0,052	-0,033
67	-0,635	-0,250	0,669
68	-0,878	-0,199	0,493
69	-0,384	-0,201	-0,244
78	-0,243	0,050	-0,177
79	0,251	0,049	-0,913
89	0,493	-0,002	-0,736

Table 8.3 Perceived global valued for the difference δ for the parameter PL was taken as the sum of the 20 matrices, $\sum_{k=1}^{20} \delta PLp_{ij}$, *and named as* ΔPLp_{ij}

pair of buttons i and j	Participant number																				
	1	2	5	8	10	12	15	16	19	20	21	22	23	24	25	26	27	29	30	32	ΔPLp_{ij}
12	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	-6
13	0	0	1	0	1	-1	1	-1	-1	1	1	0	1	0	0	1	-1	0	0	1	-1
14	1	1	1	0	0	1	1	-1	1	0	1	0	0	0	0	1	0	0	-1	1	-2
15	1	-1	0	0	-1	0	1	0	1	0	1	1	1	1	0	0	-1	0	-1	1	-1
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-7
17	0	1	-1	1	1	1	1	0	1	1	1	1	1	1	0	1	0	1	0	1	-2
18	0	1	1	1	1	1	0	-1	1	1	1	1	1	0	0	1	-1	1	-1	1	-5
19	1	1	0	1	1	1	0	0	1	0	1	1	1	1	1	1	0	1	0	1	-5
23	-1	-1	-1	-1	-1	-1	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	2
24	-1	-1	-1	-1	-1	-1	0	0	-1	-1	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	3
25	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	-1	0	-1	0
26	-1	0	0	0	1	1	1	1	0	1	1	1	0	0	0	0	-1	0	-1	-1	-4
27	-1	-1	-1	1	0	0	0	-1	-1	1	-1	1	0	-1	-1	-1	-1	-1	-1	-1	-2
28	-1	-1	-1	1	0	0	0	0	-1	1	-1	0	0	-1	-1	-1	-1	0	-1	-1	-2
29	1	-1	-1	0	0	0	0	0	-1	0	-1	0	0	-1	-1	-1	-1	0	-1	-1	-2
34	1	1	1	0	0	1	0	-1	0	0	1	0	0	0	0	1	-1	-1	-1	1	-3
35	1	1	-1	0	-1	1	0	-1	0	0	1	-1	0	0	0	-1	1	0	1	0	-1
36	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-5
37	1	1	0	1	1	1	1	0	1	1	1	1	1	1	0	1	1	-1	-1	1	-3
38	1	1	-1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	-1	-1	1	-4
39	1	1	0	1	1	1	1	-1	1	1	1	1	1	1	1	1	1	-1	0	1	-1
45	-1	0	-1	0	-1	0	-1	-1	0	0	0	0	0	-1	1	0	1	-1	0	0	6
46	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	1	-3
47	1	1	-1	1	1	1	1	0	1	1	-1	1	1	1	0	1	1	1	-1	1	-2
48	0	1	-1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	-1	1	-2
49	1	-1	-1	1	1	1	1	1	0	1	-1	1	1	1	1	1	1	-1	-1	1	0
56	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	-7
57	1	1	0	1	1	1	1	1	1	1	1	1	1	0	-1	1	1	1	-1	1	-4
58	0	1	-1	1	1	1	1	1	0	1	1	1	1	0	-1	1	1	1	-1	1	-5
59	1	1	1	1	1	1	0	1	1	0	1	0	1	1	0	1	1	0	-1	0	-6
67	-1	-1	-1	0	-1	-1	0	-1	-1	0	0	0	0	-1	-1	0	-1	-1	-1	-1	4
68	-1	-1	-1	0	0	0	0	0	-1	-1	0	0	0	-1	-1	-1	-1	0	-1	-1	2
69	0	-1	-1	-1	0	0	0	-1	-1	-1	-1	-1	-1	-1	0	-1	-1	-1	-1	-1	4
78	-1	-1	0	0	0	1	0	1	0	0	0	0	0	0	0	-1	-1	0	-1	1	-1
79	1	0	0	0	1	1	0	0	1	-1	-1	-1	0	0	1	1	-1	-1	0	0	0
89	1	0	0	0	1	-1	0	-1	1	1	0	-1	0	0	1	0	-1	-1	-1	-1	0

Table 8.4 Perceived global valued for the differences δ for the parameter DS was taken as the sum of the 11 matrices, $\sum_{k=1}^{11} \delta \mathrm{DSp_{ij}}$, and name, d as $\Delta \mathrm{DSp_{ij}}$

pair of buttons i and j	**Participant number**										
	2	7	9	12	14	19	23	24	25	26	29	$\Delta \mathrm{DSp_{ij}}$
12	-1	0	-1	-1	-1	0	-1	1	-1	-1	0	1
13	0	-1	-1	0	1	0	-1	1	0	1	-1	3
14	-1	0	-1	-1	1	0	-1	1	0	1	-1	3
15	0	-1	0	0	0	0	0	0	-1	1	0	1
16	-1	0	-1	-1	0	0	-1	0	-1	-1	-1	0
17	0	0	0	0	0	-1	-1	-1	0	1	0	1
18	0	-1	-1	1	-1	-1	-1	-1	0	0	0	1
19	-1	0	-1	0	0	0	-1	1	-1	-1	-1	1
23	1	0	1	1	0	0	0	0	-1	1	-1	4
24	1	-1	1	0	1	0	1	-1	1	1	-1	6
25	0	-1	0	1	0	0	1	-1	0	1	-1	3
26	-1	-1	-1	0	0	-1	0	0	0	0	0	0
27	1	0	0	1	-1	-1	0	-1	-1	1	-1	3
28	-1	0	0	0	0	0	0	-1	-1	1	0	1
29	0	0	1	0	-1	0	0	-1	0	0	-1	1
34	-1	-1	-1	-1	1	0	0	0	0	1	-1	2
35	-1	-1	0	0	-1	0	1	0	1	1	-1	3
36	-1	0	-1	-1	0	0	0	-1	1	-1	-1	1
37	0	1	-1	0	0	-1	0	-1	0	-1	0	1
38	-1	0	0	0	0	-1	0	-1	0	-1	0	0
39	-1	-1	1	-1	0	0	0	0	1	0	0	2
45	1	0	0	1	0	1	1	0	1	1	0	6
46	-1	1	-1	1	-1	0	-1	0	1	-1	-1	3
47	-1	1	0	1	0	-1	0	0	0	-1	-1	2
48	-1	1	-1	1	-1	1	0	0	0	-1	-1	3
49	-1	1	1	0	0	0	0	0	1	-1	-1	3
56	-1	0	-1	0	-1	0	-1	-1	0	-1	-1	0
57	-1	1	0	0	1	-1	-1	-1	0	-1	-1	2
58	-1	1	0	0	0	-1	-1	-1	-1	-1	0	1
59	-1	0	-1	-1	1	0	-1	-1	0	-1	-1	1
67	1	1	1	1	0	-1	0	0	0	0	1	5
68	1	0	1	0	-1	-1	0	0	0	1	1	4
69	0	0	1	0	1	0	0	0	0	1	1	4
78	0	-1	0	0	0	0	0	0	0	0	0	0
79	-1	-1	1	0	0	1	0	0	1	0	-1	3
89	-1	-1	1	0	0	1	0	0	1	0	-1	3

Table 8.5 Perceived global valued for the differences δ for the parameter FS was taken as the sum of the 15 matrices, $\sum_{k=1}^{15} \delta FSp_{ij}$, *and named as* ΔFSp_{ij}

pair of buttons i and j	Participant number														
	4	7	9	10	12	13	14	15	19	22	23	24	25	31	32	ΔFSp_{ij}
12	1	-1	-1	-1	1	1	-1	-1	0	-1	-1	1	1	-1	1	-2
13	1	-1	-1	-1	1	0	0	0	0	-1	-1	1	0	-1	1	-2
14	1	1	-1	1	1	1	1	1	1	-1	0	1	0	1	1	9
15	-1	1	-1	0	1	0	0	0	-1	0	0	1	1	-1	1	1
16	0	-1	-1	-1	1	1	0	0	0	-1	-1	0	1	0	1	-1
17	-1	-1	0	-1	0	0	0	1	-1	-1	-1	-1	0	-1	0	-7
18	-1	1	-1	0	1	1	0	1	-1	-1	-1	-1	0	-1	-1	-4
19	1	1	-1	1	1	1	0	1	0	-1	-1	-1	1	1	1	5
23	0	0	0	-1	1	1	0	0	0	1	1	0	-1	0	1	3
24	0	1	1	1	1	1	1	1	0	1	1	0	-1	0	1	9
25	-1	0	0	0	0	0	0	1	-1	1	0	0	0	1	0	1
26	0	0	-1	0	-1	0	-1	0	0	1	0	-1	0	1	-1	-3
27	0	1	-1	-1	-1	-1	-1	1	-1	-1	0	-1	1	0	-1	-6
28	0	0	-1	-1	-1	1	-1	0	-1	-1	0	-1	1	1	-1	-5
29	0	1	1	0	1	0	-1	0	0	1	0	-1	0	1	1	4
34	0	1	1	1	1	1	1	1	0	0	-1	0	0	0	1	7
35	0	0	-1	0	0	0	0	1	-1	1	-1	0	1	1	0	1
36	0	0	0	-1	-1	0	-1	0	0	1	1	0	1	0	1	1
37	0	0	-1	-1	-1	-1	0	1	-1	-1	0	-1	0	-1	-1	-8
38	0	1	0	-1	-1	1	0	1	-1	0	0	-1	0	-1	-1	-3
39	0	1	1	0	-1	0	1	0	0	1	0	0	1	1	1	6
45	-1	0	-1	-1	1	-1	-1	-1	0	0	0	0	1	0	-1	-5
46	0	-1	-1	-1	-1	-1	-1	0	0	1	1	0	1	-1	-1	-5
47	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	-1	0	0	-1	-12
48	0	0	-1	-1	-1	0	-1	0	-1	-1	0	-1	0	-1	-1	-9
49	-1	0	0	-1	-1	-1	0	0	0	0	1	-1	1	1	1	-1
56	0	-1	0	0	-1	-1	-1	0	0	1	1	0	0	-1	0	-3
57	-1	-1	-1	-1	-1	0	-1	-1	-1	-1	0	-1	1	-1	-1	-11
58	-1	0	-1	-1	-1	1	0	0	-1	-1	0	-1	1	-1	-1	-7
59	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0	4
67	-1	1	1	-1	1	0	-1	0	-1	-1	-1	-1	0	-1	-1	-6
68	0	1	1	-1	1	1	0	0	-1	-1	0	0	0	1	-1	1
69	0	1	1	1	1	1	0	0	0	0	0	0	0	0	1	6
78	-1	1	-1	0	0	1	0	0	0	0	0	0	0	0	1	1
79	0	0	0	1	1	0	1	0	1	1	1	0	1	1	-1	7
89	0	0	1	1	1	0	1	0	1	1	1	0	1	1	1	10

Appendix 2

Table 8.6 Results of the instrumental measurements of the kinesthetic related engineering parameters and the AC judgment.

Prototype number	AC judgment	PL (N)	FS (N)	DS (mm)	FR (N)	DR (mm)	SA (N)	SI
9_1	1	1,63	5,21	0,65	3,01	0,48	0,31	6,28
9_2	0	0,62	4,13	0,65	2,46	0,50	0,34	6,51
9_3	0	1,10	5,58	0,70	3,09	0,53	0,68	7,34
9_4	1	0,57	4,12	0,75	2,23	0,54	0,19	5,82
9_5	1	3,00	5,95	0,50	3,44	0,34	0,48	7,22
9_6	1	0,68	4,21	0,65	2,81	0,50	0,28	6,26
9_7	0	0,74	5,70	0,85	3,78	0,69	0,44	6,50
9_8	1	0,43	4,70	0,70	3,14	0,58	0,50	6,79
9_9	0	2,05	6,49	0,70	4,68	0,55	0,52	6,93
9_10	1	1,44	4,85	0,60	2,96	0,44	0,35	6,82
9_11	1	0,81	5,83	0,80	3,94	0,67	0,52	6,82
9_12	1	1,64	4,66	0,55	3,17	0,43	0,47	6,86
9_13	1	3,40	5,04	0,35	3,05	0,18	0,30	4,15
9_14	1	2,00	5,05	0,60	3,34	0,42	0,44	6,01
9_15	1	3,06	5,26	0,45	3,74	0,32	0,58	6,18
9_16	0	0,44	5,14	0,85	3,21	0,71	0,30	6,45
8_1	1	0,60	5,15	0,80	3,42	0,64	0,32	6,55
8_2	1	0,68	4,35	0,65	2,92	0,54	0,37	6,66
8_3	0	1,73	6,16	0,75	3,15	0,56	0,15	6,71
8_4	1	0,63	4,15	0,75	2,27	0,56	0,26	5,60
8_5	0	2,90	6,63	0,60	3,61	0,42	0,21	6,65
8_6	1	0,79	4,34	0,65	2,92	0,52	0,43	6,24
8_7	0	0,65	5,48	0,95	4,14	0,82	0,53	6,39
8_8	1	0,77	5,53	0,80	3,07	0,65	0,26	6,87
8_9	0	1,65	6,45	0,85	4,87	0,70	0,42	6,69
8_10	1	0,57	4,93	0,70	3,59	0,59	0,52	7,14
8_11	1	1,17	5,90	0,85	3,84	0,71	0,42	6,62
8_12	1	1,31	5,21	0,65	2,86	0,49	0,46	7,04
8_13	1	2,56	4,69	0,45	3,04	0,30	0,56	5,93
8_14	1	2,10	5,07	0,60	3,29	0,39	0,28	5,85
8_15	1	2,76	5,17	0,50	3,77	0,36	0,49	6,09
8_16	1	0,44	5,30	1,00	3,46	0,84	0,24	6,26
7_1	1	0,51	5,22	0,85	3,35	0,67	0,29	6,67
7_2	1	0,68	4,41	0,65	2,89	0,52	0,38	6,68
7_3	1	1,46	5,79	0,70	3,52	0,55	0,40	7,19
7_4	1	0,61	4,24	0,75	2,76	0,59	0,25	5,80

7_5	0	2,91	5,92	0,55	2,42	0,35	0,43	6,96
7_6	1	0,84	4,44	0,65	2,89	0,49	0,33	6,32
7_7	0	0,86	5,87	0,85	4,14	0,67	0,35	6,47
7_8	1	0,76	5,34	0,75	3,29	0,63	0,55	6,91
7_9	1	1,72	6,73	0,85	4,70	0,66	0,40	6,92
7_10	0	0,44	5,18	0,80	3,63	0,65	0,20	6,75
7_11	1	0,94	5,91	0,85	3,87	0,71	0,45	6,67
7_12	1	1,02	5,27	0,70	3,15	0,54	0,54	6,99
7_13	1	2,52	4,99	0,50	3,11	0,32	0,40	5,86
7_14	1	1,60	4,95	0,65	3,28	0,48	0,38	5,91
7_15	1	2,01	4,47	0,50	2,53	0,44	0,61	6,01
7_16	1	1,08	5,05	0,70	2,99	0,56	0,32	6,46
6_1	1	0,63	5,46	0,95	3,88	0,82	0,48	6,69
6_2	1	0,46	5,58	1,00	3,64	0,84	0,31	6,72
6_3	1	0,56	5,97	0,90	3,45	0,75	0,45	7,56
6_4	1	0,45	5,08	0,90	3,41	0,72	0,43	5,96
6_5	1	2,08	5,89	0,60	2,62	0,44	0,38	7,69
6_6	1	1,08	4,65	0,60	2,80	0,48	0,48	7,02
6_7	0	0,85	5,36	0,80	3,93	0,68	0,48	6,67
6_8	1	1,13	5,31	0,70	3,22	0,57	0,27	6,62
6_9	0	0,99	6,02	0,85	4,11	0,71	0,51	7,26
6_10	1	0,70	4,45	0,65	3,27	0,56	0,67	6,62
6_11	0	0,51	5,84	1,00	3,48	0,84	0,43	6,84
6_12	0	0,32	4,87	0,85	3,31	0,72	0,47	6,48
6_13	1	1,79	4,66	0,55	3,15	0,40	0,47	6,29
6_14	1	1,41	5,07	0,70	3,14	0,50	0,37	5,99
6_15	1	0,77	5,18	0,80	3,56	0,65	0,30	6,32
6_16	1	0,86	4,35	0,65	2,51	0,52	0,41	6,42
5_1	0	0,88	5,44	0,85	3,72	0,71	0,39	6,50
5_2	0	0,33	5,10	0,90	3,61	0,75	0,16	6,69
5_3	0	0,95	6,13	0,85	3,56	0,69	0,47	7,37
5_4	0	0,72	5,18	0,85	3,04	0,61	0,50	5,68
5_5	0	1,97	6,75	0,65	2,52	0,46	0,29	6,86
5_6	0	1,17	5,01	0,65	2,69	0,45	0,26	6,89
5_7	0	0,82	5,52	0,80	3,87	0,64	0,30	6,69
5_8	1	1,18	5,38	0,70	3,05	0,58	0,58	6,83
5_9	0	1,25	6,58	0,90	4,14	0,71	0,16	7,19
5_10	0	0,73	4,94	0,70	3,40	0,60	0,51	6,81
5_11	0	0,95	5,89	0,85	3,56	0,71	0,69	7,06
5_12	0	1,09	4,96	0,65	3,23	0,50	0,52	6,88
5_13	0	2,92	4,85	0,40	3,06	0,24	0,53	6,17
5_14	0	1,88	5,16	0,65	3,22	0,45	0,33	5,83
5_15	1	2,19	5,27	0,60	3,30	0,43	0,23	5,90

5_16	0	0,84	4,53	0,70	2,60	0,53	0,17	5,87
4_1	0	0,43	5,16	0,85	2,93	0,69	0,26	6,29
4_2	0	0,68	5,60	0,85	3,89	0,72	0,31	7,19
4_3	0	0,58	5,34	0,75	3,25	0,60	0,54	7,32
4_4	0	0,90	5,63	0,90	3,51	0,70	0,39	5,81
4_5	0	2,26	6,10	0,65	2,89	0,48	0,42	6,97
4_6	1	1,43	5,13	0,65	3,32	0,50	0,49	6,65
4_7	0	1,21	5,17	0,70	3,35	0,54	0,45	6,50
4_8	0	1,37	5,82	0,75	2,84	0,57	0,16	6,42
4_9	0	0,96	5,73	0,80	4,30	0,69	0,58	6,93
4_10	0	0,62	5,33	0,80	3,50	0,66	0,44	6,87
4_11	0	1,01	6,16	0,95	3,27	0,77	0,27	6,62
4_12	0	0,85	5,61	0,80	3,40	0,63	0,39	6,97
4_13	0	2,63	5,63	0,60	3,05	0,40	0,35	5,76
4_14	0	2,63	5,63	0,60	3,05	0,40	0,35	5,76
4_15	0	1,46	4,89	0,65	3,22	0,48	0,33	6,06
4_16	0	0,79	4,85	0,70	3,17	0,58	0,49	6,65
3_1	0	0,41	5,00	0,85	3,38	0,71	0,35	6,34
3_2	0	0,30	5,32	0,90	3,53	0,74	0,26	6,81
3_3	0	0,64	5,68	0,85	3,91	0,70	0,26	7,04
3_4	0	0,57	5,23	0,90	3,48	0,75	0,58	6,37
3_5	0	2,19	6,52	0,70	2,24	0,48	0,27	7,03
3_6	0	1,08	5,37	0,70	2,67	0,53	0,49	6,91
3_7	0	0,70	5,28	0,80	3,19	0,64	0,68	6,73
3_8	0	1,51	5,73	0,70	2,62	0,56	0,62	6,73
3_9	0	0,86	6,03	0,90	3,79	0,71	0,31	7,11
3_10	0	0,45	5,11	0,85	3,14	0,68	0,39	6,58
3_11	0	0,45	5,73	1,05	3,98	0,93	0,50	6,74
3_12	0	0,43	4,85	0,80	3,37	0,65	0,35	6,38
3_13	0	1,55	4,32	0,55	2,62	0,41	0,66	5,96
3_14	0	2,02	5,49	0,65	2,89	0,45	0,31	6,22
3_15	0	1,22	5,00	0,70	3,35	0,55	0,59	6,24
3_16	0	0,83	5,64	0,85	3,81	0,70	0,42	6,97
2_1	0	0,36	5,21	0,90	3,32	0,75	0,40	6,61
2_2	0	0,25	5,11	0,85	3,20	0,67	0,22	6,70
2_3	0	0,31	5,53	0,95	3,51	0,80	0,38	6,87
2_4	0	0,49	5,18	0,85	3,60	0,71	0,48	6,55
2_5	0	0,60	4,89	0,70	3,16	0,55	0,56	6,94
2_6	0	0,77	4,62	0,65	2,89	0,49	0,50	6,77
2_7	0	0,70	4,99	0,75	3,54	0,63	0,49	6,47
2_8	0	0,25	4,78	0,80	3,53	0,68	0,30	6,37
2_9	0	0,76	6,02	0,85	3,70	0,68	0,41	7,43
2_10	0	0,55	5,07	0,90	3,37	0,69	0,32	5,89

2_11	0	0,26	5,68	1,00	3,85	0,87	0,46	7,02
2_12	0	0,47	4,94	0,85	3,17	0,66	0,37	6,27
2_13	0	1,61	4,26	0,55	2,72	0,38	0,31	5,57
2_14	0	0,73	4,40	0,75	2,56	0,52	0,19	5,64
2_15	0	0,68	4,64	0,75	3,39	0,62	0,34	5,89
2_16	0	0,72	4,55	0,70	2,71	0,54	0,27	6,19
1_1	0	0,54	5,06	0,85	3,28	0,67	0,37	6,24
1_2	0	0,58	5,38	0,85	3,72	0,70	0,31	6,99
1_3	0	0,60	5,49	0,85	3,04	0,63	0,20	6,48
1_4	0	0,81	5,23	0,85	3,74	0,75	0,52	5,82
1_5	0	1,38	5,13	0,65	3,28	0,49	0,49	6,78
1_6	0	0,66	4,95	0,80	3,69	0,65	0,22	6,10
1_7	0	0,60	5,22	0,85	3,71	0,70	0,44	6,16
1_8	0	0,38	5,02	0,95	2,97	0,84	0,37	6,12
1_9	0	0,89	5,80	0,90	3,73	0,72	0,33	6,27
1_10	0	0,53	4,96	0,85	3,44	0,67	0,31	5,93
1_11	0	0,22	5,68	1,10	3,24	0,91	0,29	6,25
1_12	0	0,71	4,95	0,80	3,29	0,62	0,24	5,79
1_13	0	1,28	4,54	0,65	3,06	0,49	0,22	5,69
1_14	0	1,18	5,42	0,75	3,27	0,53	0,30	6,36
1_15	0	1,33	4,59	0,65	2,99	0,48	0,42	5,78
1_16	0	0,47	4,47	0,75	2,77	0,57	0,24	6,03

Table 8.7 Results of the instrumental measurements of the acoustic related engineering parameters.

Prototype number_ button number	AC judgement	FS-PL(N)	DS-DR(mm)	SPLa_press (dB)	SC_press	Ton_press	SPLa_release	SC_release	Ton_release	N_press	N_releae
prototype 9-1	1	3,57	0,17	52,85	6695,89	0,00889	59,52	6573,31	0,01787	7,06	8,66
prototype 9-2	0	3,5	0,15	52,9	6097,92	0,00873	57,81	6317,59	0,01646	6,98	8,55
prototype 9-3	0	4,49	0,17	51,69	5851,67	0,0076	57,96	6187,08	0,01676	6,83	7,69
prototype 9-4	1	3,55	0,21	54,5	5666,77	0,01074	59,65	6100,25	0,01813	7,71	9,16
prototype 9-5	1	2,95	0,16	52,48	6004,65	0,00851	60,44	6370,99	0,01985	7,19	7,74
prototype 9-6	1	3,54	0,15	57,13	5352,14	0,01455	62,55	6375,39	0,02532	8,77	8,35
prototype 9-7	0	4,96	0,16	54,21	5130,33	0,01015	60,48	5752,15	0,02238	8,3	9,04
prototype 9-8	1	4,27	0,12	54,68	5406,93	0,01096	61,05	5926,15	0,0213	8,13	8,35
prototype 9-9	0	4,44	0,15	55,41	6558,47	0,01165	61,72	7196,55	0,02581	8,08	8,22
prototype 9-10	1	3,4	0,16	55,64	6558,02	0,01224	62,2	6851,57	0,02431	7,8	10,03
prototype 9-11	1	5,02	0,13	54,86	5057,03	0,01119	60,35	5471,32	0,01966	8,49	10,18
prototype 9-12	1	3,03	0,12	55,81	5708,45	0,01249	61,82	6506,89	0,02327	8,61	9,39
prototype 9-13	1	1,64	0,17	54,94	4998,32	0,01129	59,29	5226,67	0,0174	8,44	9,04
prototype 9-14	1	3,05	0,18	56,14	4877,37	0,01298	62,05	5915,68	0,02392	9,15	11,2
prototype 9-15	1	2,2	0,13	53,47	5256,39	0,00954	58,73	5666,25	0,01631	8,05	9,16
prototype 9-16	0	4,7	0,14	52,77	5677,52	0,0086	59,14	6118,1	0,01918	7,62	9,59
prototype 8-1	1	4,54	0,16	52,93	6638,79	0,00897	58,38	6118,68	0,01568	6,63	7,6
prototype 8-2	1	3,67	0,11	52,98	5841,87	0,00902	57,62	5622,96	0,01435	7,22	8,48
prototype 8-3	0	4,43	0,19	52,36	6162,6	0,0082	57,61	6313,64	0,0161	6,03	7,48
prototype 8-4	1	3,53	0,19	53,73	5690,91	0,00983	62,86	6516,87	0,02623	6,47	9,78
prototype 8-5	0	3,73	0,18	54,36	5762,91	0,01033	60,2	6555,71	0,02168	7,62	9,62
prototype 8-6	1	3,55	0,13	56,72	5838,16	0,01387	61,88	6581,19	0,02345	8,22	9,97
prototype 8-7	0	4,83	0,13	55,83	5087,11	0,01223	60,03	5789,45	0,02125	8,56	9,34
prototype 8-8	1	4,75	0,14	54,63	5346,23	0,01091	60,96	5940,59	0,0211	7,58	9,5
prototype 8-9	0	4,81	0,15	55,93	6802,18	0,01238	62,72	7475,8	0,02898	7,78	7,76
prototype 8-10	1	4,36	0,11	54,26	6230,27	0,01045	61,54	6900,63	0,02253	7,26	8,99
prototype 8-11	1	4,73	0,14	54,34	5080,77	0,01054	60,02	5333,91	0,01893	7,65	8,16

Prototype number_ button number	AC judgement	FS-PL(N)	DS-DR(mm)	SPLa_press (dB)	SC_press	Ton_press	SPLa_release	SC_release	Ton_release	N_press	N_releae
prototype 8-12	1	3,9	0,16	54,36	5774,05	0,01058	60,67	6409,46	0,02039	7,35	8,25
prototype 8-13	1	2,14	0,15	55,58	5257,35	0,01217	59,4	5485,15	0,01762	7,78	9,1
prototype 8-14	1	2,97	0,21	53,81	5689,74	0,00993	62,06	6637,72	0,02395	8,05	9,32
prototype 8-15	1	2,41	0,14	54,43	5467,59	0,01066	59,81	5998,53	0,01847	8,11	9,54
prototype 8-16	1	4,86	0,16	53,65	5742,05	0,00974	59,75	5822,07	0,01835	6,99	8,05
prototype 7-1	1	4,72	0,18	51,37	6209,52	0,00749	56,9	6020,56	0,01321	6,57	7,4
prototype 7-2	1	3,73	0,13	53,42	5093,09	0,00949	56,24	5451,47	0,01225	7,2	8,04
prototype 7-3	1	4,33	0,15	52,45	5859,54	0,00848	59,98	6431,88	0,01885	7,05	8,6
prototype 7-4	1	3,63	0,16	53,7	5379,97	0,0098	59,43	6044,17	0,01768	8,5	9,06
prototype 7-5	0	3,02	0,19	52,95	5967,64	0,00878	59,05	6755,57	0,01899	8,06	8,36
prototype 7-6	1	3,6	0,16	56,49	6356,75	0,0135	62,7	7066,81	0,02576	8,14	9,76
prototype 7-7	0	5,01	0,18	54,27	5375,29	0,0102	58,56	5882,78	0,01795	7,54	8,8
prototype 7-8	1	4,57	0,12	54,41	5756,31	0,0106	60,69	6096,26	0,02044	7,74	9,21
prototype 7-9	1	5,01	0,19	54,26	6458,33	0,0104	62,27	7348,14	0,02452	7,4	7,58
prototype 7-10	0	4,74	0,15	55,21	6120,07	0,0114	59,8	6704,71	0,02069	8,02	8,98
prototype 7-11	1	4,98	0,14	55,55	5485,35	0,01212	61,21	5806,09	0,02171	7,85	9,14
prototype 7-12	1	4,25	0,16	55,36	5471,9	0,01186	61,27	6147,55	0,02184	8,04	9,5
prototype 7-13	1	2,47	0,18	55,72	4974,89	0,01236	59,71	5366,6	0,01826	8,99	10,29
prototype 7-14	1	3,35	0,17	56,34	5142,3	0,01328	62,25	6261,5	0,02447	8,46	11,07
prototype 7-15	1	2,46	0,06	53,48	4782,57	0,00955	58,37	5392,45	0,01566	7,98	9,76
prototype 7-16	1	3,97	0,14	50,74	5868,65	0,00697	59,31	6150,23	0,01743	5,89	8,37
prototype 6-1	1	4,83	0,13	51,48	6217,73	0,00759	56,73	5839,19	0,01295	6,96	8,47
prototype 6-2	1	5,12	0,16	51,84	5702,52	0,00791	57,36	5707,23	0,01394	6,63	8,27
prototype 6-3	1	5,42	0,15	51,59	6260,93	0,00769	58,15	6626,39	0,01525	6,53	7,38
prototype 6-4	1	4,63	0,18	52,56	6068,22	0,00859	59,59	6612,71	0,018	6,76	8,59
prototype 6-5	1	3,81	0,16	52,32	6644,16	0,00836	60,6	7129,72	0,02024	5,89	7,89
prototype 6-6	1	3,57	0,12	54,11	6113,85	0,01027	62,17	6815,24	0,02425	7,32	8,48
prototype 6-7	0	4,51	0,12	53,49	5676,64	0,00935	60,39	6506,39	0,02215	7,82	9,14
prototype 6-8	1	4,17	0,13	53,37	6050,71	0,00943	59,86	6298,72	0,01858	7,52	9,01
prototype 6-9	0	5,03	0,14	53,59	6996,27	0,00945	60,43	7504,16	0,02226	6,21	7,7

Prototype number_ button number	AC judgement	FS-PL(N)	DS-DR(mm)	SPLa_press (dB)	SC_press	Ton_press	SPLa_release	SC_release	Ton_release	N_press	N_releae
prototype 6-10	1	3,75	0,09	53,69	6325,8	0,00978	60,43	6774,18	0,01983	6,4	8,28
prototype 6-11	0	5,33	0,16	53,73	5621,08	0,00961	57,91	6163,47	0,01665	7,44	9,13
prototype 6-12	0	4,54	0,13	53,92	5821,02	0,00982	58,62	6382,31	0,01807	7,39	8,48
prototype 6-13	1	2,88	0,15	53,47	5534,44	0,00954	58,5	5837,26	0,01589	7,57	8,69
prototype 6-14	1	3,66	0,2	53,45	5914,35	0,00952	61,49	6799,24	0,02242	7,18	9,77
prototype 6-15	1	4,41	0,15	54,61	5574,82	0,01087	58,7	6307,08	0,01626	6,88	8,83
prototype 6-16	1	3,49	0,13	51,37	5828,8	0,00749	58,51	6314,74	0,01591	7,27	9,19
prototype 5-1	0	4,55	0,14	51,94	6251,44	0,00782	55,51	5987,46	0,01263	6,23	7,71
prototype 5-2	0	4,77	0,15	51,29	5234,49	0,00725	51,58	5302,42	0,00804	6,56	6,88
prototype 5-3	0	5,18	0,16	51,91	6531,19	0,00779	56,35	6397,7	0,01392	5,87	7,44
prototype 5-4	0	4,47	0,24	51,72	5873,93	0,00762	57,16	6162,35	0,01528	6,6	7,87
prototype 5-5	0	4,78	0,19	53,41	6256,25	0,00926	58,82	6601,89	0,01848	6,63	8,48
prototype 5-6	0	3,84	0,2	52,29	5477,52	0,00814	57,46	6280,6	0,01581	7,06	8,82
prototype 5-7	0	4,7	0,16	52,92	4892,72	0,00875	58,54	6254,44	0,01791	7,49	8,31
prototype 5-8	1	4,2	0,12	54,23	5609,32	0,01042	60,03	6227,96	0,01894	7,26	8,52
prototype 5-9	0	5,33	0,19	53,23	6841,15	0,00907	59,17	7445,91	0,01925	6,44	7,68
prototype 5-10	0	4,21	0,1	53,61	6203,93	0,00947	58,81	7026,56	0,01847	7,18	8,04
prototype 5-11	0	4,94	0,14	52,99	5975,27	0,00882	57,38	6560,1	0,01566	6,47	8,13
prototype 5-12	0	3,87	0,15	54,45	5194,46	0,01044	57,63	6247,64	0,01612	8,27	8,34
prototype 5-13	0	1,93	0,16	55,05	5185,2	0,01119	58,18	5436,03	0,01718	8,52	9,68
prototype 5-14	0	3,28	0,2	54,33	5729,38	0,01029	60,64	6933,61	0,0228	8,68	9,92
prototype 5-15	1	3,09	0,17	52,86	5683,21	0,0089	58,1	6201,6	0,01518	6,74	8,27
prototype 5-16	0	3,69	0,17	52,98	6368,1	0,00882	58,84	6708,97	0,01853	6,57	8,26
prototype 4-1	0	4,73	0,16	52,41	5965,82	0,00826	56,31	6010,37	0,01385	6,53	8,14
prototype 4-2	0	4,91	0,13	51,18	5147,25	0,00716	56,61	5310,08	0,01433	7,12	8,48
prototype 4-3	0	4,76	0,15	52,43	6385,18	0,00827	56,83	6523,19	0,01471	6,55	8,59
prototype 4-4	0	4,73	0,2	52,25	5975	0,0081	57,64	5900,1	0,01614	7,49	7,91
prototype 4-5	0	3,84	0,17	53,18	5930,39	0,00902	58,84	6178,32	0,01854	7,67	9,7
prototype 4-6	1	3,7	0,15	56,15	5926,48	0,01298	62,16	6800,96	0,0242	8,23	10,02
prototype 4-7	0	3,96	0,16	54,06	4565,59	0,00998	59,05	5815,91	0,01899	7,79	9,29
prototype 4-8	0	4,45	0,18	56,35	5795,08	0,01298	59,74	6161,88	0,02055	8,23	9,99

Prototype number_ button number	AC judgement	FS-PL(N)	DS-DR(mm)	SPLa_press (dB)	SC_press	Ton_press	SPLa_release	SC_release	Ton_release	N_press	N_releae
prototype 4-9	0	4,77	0,11	55,25	6723,45	0,01144	62,39	7503,85	0,02789	7,53	9,3
prototype 4-10	0	4,71	0,14	53,41	5999,28	0,00926	58,71	6508,57	0,01827	7,09	8,77
prototype 4-11	0	5,15	0,18	54,11	5054,03	0,01004	58,38	6117,42	0,01758	7,77	9,54
prototype 4-12	0	4,76	0,17	54,99	5294,72	0,01111	59,23	6173,82	0,01939	7,85	9,3
prototype 4-13	0	3	0,2	56,14	5118,74	0,01268	58,96	5457,39	0,0188	8,18	10,15
prototype 4-14	0	3	0,2	56,41	5574,07	0,01307	62,59	6501,7	0,02853	8,18	10,18
prototype 4-15	0	3,42	0,17	53,01	5369,53	0,00884	57,69	5742,16	0,01624	7,5	9,48
prototype 4-16	0	4,06	0,12	53,09	5766,55	0,00893	58,34	6103,1	0,01751	6,96	8,55
prototype 3-1	0	4,59	0,14	54,29	6298,44	0,01024	57,63	5924,29	0,01613	6,73	8,89
prototype 3-2	0	5,02	0,16	51,93	5677,31	0,00781	51,34	5429,5	0,00781	7,45	7,75
prototype 3-3	0	5,04	0,15	53,17	5926,16	0,009	58,42	6359,42	0,01766	7,01	8,84
prototype 3-4	0	4,67	0,15	54,01	6124,24	0,00992	59,02	6347,63	0,01893	7,36	9,28
prototype 3-5	0	4,33	0,22	53,5	5464,39	0,00935	59,56	6068,64	0,02013	7,36	9,18
prototype 3-6	0	4,28	0,17	54,76	6086,51	0,01082	59,51	6667,22	0,02002	8,45	9,4
prototype 3-7	0	4,58	0,16	53,48	5017,83	0,00933	59,42	5776,84	0,01981	8,32	9,93
prototype 3-8	0	4,22	0,14	54,76	5919,07	0,01082	59,6	6023,44	0,02023	7,59	8,8
prototype 3-9	0	5,17	0,19	54,16	5869,33	0,01009	60,66	6748,77	0,02285	7,84	8,66
prototype 3-10	0	4,66	0,17	54,98	6128,34	0,01109	59,5	6567,96	0,02001	7,34	8,98
prototype 3-11	0	5,28	0,12	54,07	5633,4	0,00999	58,95	6346,58	0,01877	7,46	9,27
prototype 3-12	0	4,41	0,15	54,22	5748,37	0,01016	59,04	6440,04	0,01897	7,92	9,31
prototype 3-13	0	2,77	0,14	54,74	5807,01	0,01079	58,37	5875,19	0,01755	8,27	9,4
prototype 3-14	0	3,47	0,2	56,18	6121,58	0,01274	61,58	6684,91	0,02543	7,43	10,69
prototype 3-15	0	3,78	0,15	51,99	4912,48	0,00786	57,05	5738,94	0,01509	7,27	9,28
prototype 3-16	0	4,81	0,15	52,34	6026,23	0,00818	58,24	6386,31	0,01729	7,13	8,27
prototype 2-1	0	4,85	0,15	54,4	5401,12	0,01038	58	5269,2	0,01683	7,01	8,55
prototype 2-2	0	4,86	0,18	52,64	5465,24	0,00847	58,82	5789,12	0,01849	6,48	9,1
prototype 2-3	0	5,23	0,15	54,88	6531,81	0,01097	60,58	7118,08	0,02266	6,78	8,52
prototype 2-4	0	4,69	0,15	55,21	6355,46	0,01139	59,2	6471,76	0,01933	7,09	8,12
prototype 2-5	0	4,29	0,15	54,68	6224,17	0,01071	60,83	6538,14	0,02331	6,67	8,06
prototype 2-6	0	3,84	0,16	53,87	6099,71	0,00976	60,59	6447,61	0,02269	7,45	9,28
prototype 2-7	0	4,29	0,12	53,88	5371,35	0,00978	59,86	6200,45	0,02086	7,14	7,38

Prototype number_ button number	AC judgement	FS-PL(N)	DS-DR(mm)	SPLa_press (dB)	SC_press	Ton_press	SPLa_release	SC_release	Ton_release	N_press	N_releae
prototype 2-8	0	4,53	0,12	54,73	6140,68	0,01078	59,28	6242,31	0,0195	8,13	9,04
prototype 2-9	0	5,26	0,17	53,3	6030,88	0,00915	56,32	6571,01	0,01386	7,17	7,91
prototype 2-10	0	4,52	0,21	53,52	5883,16	0,00938	56,6	5940,43	0,01432	7,4	8,57
prototype 2-11	0	5,42	0,13	54,94	4885,71	0,01104	57,87	6366,75	0,01657	7,64	8,56
prototype 2-12	0	4,48	0,19	53,54	5351,63	0,0094	57,33	5872,46	0,01557	7,42	8,9
prototype 2-13	0	2,65	0,17	53,49	5292,05	0,00934	57,67	6633,32	0,01619	7,38	8,55
prototype 2-14	0	3,67	0,23	54,34	5841,56	0,0103	59,98	5715,31	0,02114	7,53	9,23
prototype 2-15	0	3,96	0,13	44,09	5572,35	0,00316	55,77	6744,17	0,01302	5,16	7,7
prototype 2-16	0	3,83	0,16	52,33	6778,55	0,00818	57,79	6330,83	0,01642	6,3	7,93
prototype 1-1	0	4,52	0,18	51,59	5495,33	0,00751	56,38	5926,96	0,01397	6,08	7,66
prototype 1-2	0	4,8	0,15	49,51	4944,34	0,00591	55,3	5531,13	0,01233	6,35	8,77
prototype 1-3	0	4,89	0,22	53,53	6532,31	0,00939	59,73	6980,23	0,02053	6,83	7,68
prototype 1-4	0	4,42	0,1	53,52	5617,68	0,00937	57,36	5874,74	0,01563	6,94	8,33
prototype 1-5	0	3,75	0,16	50,77	5276,38	0,00683	58,53	6139,02	0,01789	6,64	8,68
prototype 1-6	0	4,29	0,15	53,76	5653,53	0,00964	58,99	6374,32	0,01887	6,78	8,66
prototype 1-7	0	4,63	0,15	52,73	5199,95	0,00856	55,93	5937,71	0,01326	6,85	8,08
prototype 1-8	0	4,64	0,11	51,94	5636,14	0,00781	56,57	5877,92	0,01428	7,33	7,47
prototype 1-9	0	4,91	0,18	51,8	5963,09	0,00769	58,28	6764,26	0,01738	6,9	8,17
prototype 1-10	0	4,43	0,18	53	6184,31	0,00883	56,75	6396,04	0,01458	5,88	8,3
prototype 1-11	0	5,45	0,19	54,8	5517,89	0,01086	60,21	5680,65	0,02171	7,74	9,99
prototype 1-12	0	4,24	0,18	54,07	5307,12	0,00999	60,19	5761,65	0,02165	7,38	9,14
prototype 1-13	0	3,27	0,16	53,41	5852,96	0,00926	55,71	5988,43	0,01293	7,54	7,91
prototype 1-14	0	4,23	0,22	54,61	5975,92	0,01064	61,21	6737,37	0,02435	6,78	9,6
prototype 1-15	0	3,26	0,17	50,42	5312,3	0,00656	56,44	6187,31	0,01406	6,58	8,17
prototype 1-16	0	3,99	0,18	55,17	6347,85	0,01134	61,75	6619,6	0,02591	6,96	7,96

Appendix 3

```
function [Loudness, LoudnessLevel] = Loudness_LMIS(signal, FS, type, show)

%%%%%%%%%%%%
% FUNCTION:
%   Calculation of loudness of impulsive sounds acording to Boullet's model
%   LMIS: Loudness Model for Impulsive Sounds
%
% USE:
%   [Loudness LoudnessLevel] = Loudness_LMIS(signal, FS, type, show)
%
% INPUT:
%   signal : acoustic signal, monophonic (Pa)
%   FS     : sampling frequency (Hz)
%   type   : (optional parameter) 'mic' (default value) for omnidirectional sound
%            recording, 'head' for dummy head measurement
%   show   : optional parameter for some figures display.
%            May be false (disable, default value) or true (enable).
%
% OUTPUT:
%   Loudness      : overall loudness (sone)
%   LoudnessLevel : overall loudness level (phon)
%
% REFERENCES:
% Boullet - "La sonie des sons impulsionnels: perception, mesures et modθles"
% Ph.D thesis - LMA-CNRS, Marseille - 2005
%
% Boullet et al - "Un estimateur de sonie d'impulsion: ιlaboration et
% validation" - Proc. Acoustics French Congress CFA'06 - Tours - 2006
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% GENESIS S.A. - 2009 - www.genesis.fr
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%% Pre-processing

if nargin < 2,
   help LMIS;
   error('Not enough arguments');
end;

if nargin < 3,  % default type is microphone
   type = 'mic';
end;

if nargin < 4,  % default display is disabled
   show = false;
end;



%% recording type processing
```

```
switch type,
   case 'mic',  % MICROPHONE: nothing to do, standard case for LMIS algorithm
      sig = signal(:);

   case 'head', % Dummy head: outer ear effect must be corrected

      sig = signal(:);

      % Frequency vector for filter
      freq_earFRF = 0:FS/2; % (1 to FS Hz by 1 Hz steps)
      normalized_freq = linspace(0, 1, FS/2+1);

      % Outer ear effect is inverted
      WdB_cor = -Transfer_function_to_eardrum(freq_earFRF);

      % FIR filter design

      % Filter order
      FIRorder = 4096;

      % Zero padding
      sig((end + 1) : (end + FIRorder)) = 0;

      % Filter design
      outEarFIR = fir2(FIRorder, normalized_freq, 10.^(WdB_cor./20));

      % Filtering step
      sigFilt = filter(outEarFIR, 1, sig);

      % Zero padding
      sigFilt((end + 1) : (end + 0.1 * FS)) = 0;

      % sig will be used in what follows
      sig = sigFilt;

   otherwise,
      error('Wrong parameter type : "mic" or "head"')

end;



if show == true,
   disp('---------------------------------------------------------------')
   disp('Calculation of critical bands energy...')
end


%% Decay time (-60 dB) within each critical band

% dyn: dyn parameter for RT60 calculation (20 or 30 dB)

dyn = 20; % dB

sigFilt = gene_filtersBC(sig, FS);
```

```
 I0 = 1e-12;
 pc = 415;

%% Energy level into the 24 critical bands
Eband = (mean(sigFilt.^2)./pc)* length(sig)/FS;

Nband = 10*log10( Eband / I0 );

Tnoise = 0.05;
Td = zeros(1,24);

for i = 1:24,

    [Td(i), sig2noise] = gene_RTx(sigFilt(:,i), FS, dyn, Tnoise, 'off');

    if (sig2noise) && (show == true),
       disp(['SNR in band n. ' int2str(i)]);
       disp('-----------------------------------');
    end;

end;


%% Optional display

if (show == true),
    figure;
    subplot(211);
    bar(1000 * Td);
    ax = axis; ax(3) = 0; ax(4) = 300; axis(ax);
    title(['Temps de descente dans chaque bande critique: RT' num2str(dyn)]);
    ylabel('Temps en millisecondes');
    grid on;
    subplot(212);
    stairs(0.5:1:24.5, Eband(1):Eband(end));
    grid on;
    legend('Energie');
    title('Energie et ιnergie pondιrιe ao dans chaque bande critique');
    ylabel('Energie en Joules / Bark');
    xlabel('Bandes critiques');
    grid on;

end


%% Main loudness

% Steepness of loudness functions
alpha = [0.42 0.42 0.42 0.4225 0.425 0.3825 0.34 0.365 0.39 0.40...
         0.41 0.395 0.38 0.405 0.43 0.425 0.42 0.415 0.41 0.415...
         0.42 0.405 0.39 0.39];

% Constants for critical bands corrections
K = [15.254 15.254 15.254 16.36 17.604 14.63 12.155 12.24 12.845 13.831...
     15.081 14.989 14.94 17.153 19.005 20.16 21.335 18.104 15.094 14.024...
     13.044 9.4124 6.1607 6.1607];

beta = 0.1;
```

```
krn = zeros(1,24);
for i = 1:24,
   if Td(i) ~= 0,
       krn(i) = K(i) * Eband(i).^(alpha(i)/2) .* (1000.*Td(i)).^beta;
   else
       krn(i) = K(i) * Eband(i).^(alpha(i)/2);
   end;
end;


%% Specific loudness

if show == true,
    disp('-------------------------------------------------------------')
    disp('Calculation of specific loudness...')
end;

% Number of calculation steps per critical band
Nbc = 20;
if (show == true),
    l_show = 'on';
else
    l_show = 'off';

end;

% Specific loudness calculation
SpecificLoudness = gene_mainLoudness2density(krn, Nbc, l_show);

% Integration
Loudness = sum(SpecificLoudness) / Nbc;

% Conversion
LoudnessLevel = gene_sone2phon_ISO532B(Loudness);
```

Appendix 4

Experiment number	Objective functions - Design Requirements						
	1	2	3	4	5	6	7
	Pre load (N)	Force to stroke (N)	Displacement to stroke (mm)	Displacement to release (mm)	SPLa_Press (dB)	SPLa_release (dB)	SC_press (Hz)
1	0,3588	4,9958	0,8104	0,6521	56,85	64,42	5841,42
2	0,5097	5,6721	1,0550	0,8891	62,18	69,08	6226,13
3	1,1412	6,5589	1,2102	1,0336	56,81	63,11	5562,44
4	0,2341	4,9191	0,8403	0,6961	55,50	64,10	5904,76
5	0,6695	5,7038	0,9901	0,8439	61,48	65,02	5871,78
6	0,9526	6,3913	1,2402	1,0664	56,69	63,51	5466,43
7	0,2461	5,3073	1,0202	0,8421	57,84	64,39	5631,99
8	0,5261	5,9979	1,2248	1,0565	54,18	59,12	5538,82
9	0,9134	5,6392	0,8698	0,7022	55,88	62,24	5704,48
10	0,2317	5,6836	1,1953	1,0330	55,91	59,94	5849,52
11	0,5818	5,2350	0,8549	0,6849	56,22	61,55	5604,61
12	0,9885	6,1622	1,0551	0,8831	56,76	63,73	6079,27
13	0,2470	5,2832	1,0207	0,8474	56,99	63,21	5741,62
14	0,5270	6,0105	1,2398	1,0711	57,36	64,73	5689,89
15	0,9690	5,7417	0,8954	0,7180	57,15	63,94	5793,89
16	0,2347	5,6641	1,2250	1,0547	56,16	62,38	5829,35
17	0,5301	5,3119	0,8802	0,7046	57,26	66,31	6015,49
18	1,0915	6,1088	1,0003	0,8398	58,48	65,09	5746,92