CHALMERS
UNIVERSITY OF TECHNOLOGY

Development of Capacitive and Conductive Test Dummy

Supporting Development of Seats with Capacitive Occupant Sensors

Master's thesis in Product Development

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Department of Product and Production Development
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Gothenburg, Sweden 2017

MASTER'S THESIS 2017

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Cover: The developed Capacitive and Conductive Test Dummy Kim.

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This thesis, comprising 30 HE credits, is the final part of our master in Product Development at Chalmers University of Technology. The thesis was performed at Volvo Car Corporation in Gothenburg during the spring semester of 2017. The work has been equally distributed between us throughout the entire process.

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Gothenburg, June 2017

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Abstract

Within the automotive industry, safety is an important topic, and vehicles are constantly improved to minimize fatalities in traffic. A Capacitive Occupant Sensor system in the passenger front seat can detect and classify passengers. The classification is communicated to the airbag suppression system, which enables or suppresses the airbag accordingly.

The purpose of this master thesis is to explore the possibility of developing a Capacitive and Conductive Test Dummy to facilitate testing of the Capacitive Occupant Sensor system and support future development of seats. The objective is to develop a Capacitive and Conductive Test Dummy with admittance characteristics, correlating to a user group of up to one-year-old children.

The project is divided into two blocks, where the main block constituted an empirical study, focusing on Concept Development and Product Testing. The final result was achieved through idea generations and the completion of six experiments. The findings indicate that children within the one-year-old group give small variations in admittance value. It is therefore possible to establish an admittance value for a Capacitive and Conductive Test Dummy, to correspond to the majority in the group. Different mixtures of water were found to be the best material for mimicking the admittance characteristics of the 1yo group.

Through the output from the experiments, the project arrived at a dummy, named Kim. Kim has a textile body cover and an internal body made of plastic bags filled with a mixture of water and Super Absorbent Polymer. The dummy resembles the shape of a one-year-old child and has the same admittance characteristics as the representative for the one-year-old group. This support the use of the Capacitive and Conductive Test Dummy Kim for seat development.

KEYWORDS: Capacitive Occupant Sensor, Occupant Sensing, Capacitance, Admittance, Dummy, Child Dummy, Capacitive and Conductive Test Dummy, Product Development, Empirical Study, Experiments.

Table of Contents

Abbreviations

1yo Group	One-year-old user group*
COS	Capacitive Occupant Sensor
CRS	Child Restraint System
CCTD	Capacitive and Conductive Test Dummy*
DOE	Design of Experiment(s)
FMVSS	Federal Motor Vehicle Safety Standards
HTS	Human Test Subject(s)*
NHTSA	National Highway Traffic Safety Administration
SAP	Super Absorbent Polymer
US	United States
VCC	Volvo Car Corporation

* The abbreviation is defined specifically for this project.

1 Introduction

This master thesis report describes the development of a Capacitive and Conductive Test Dummy, with properties similar to a representative for a pre-defined user group, to be used by Volvo Car Corporation for internal development of seats with Capacitive Occupant Sensors.

1.1 Company Description

Volvo Car Corporation (VCC) is a Scandinavian car developer and manufacturer that aims to be a leader in developing innovative human-centric technology for the next generation of intelligent, safe, and sustainable premium cars *(Volvo Car Corporation, 2017)*.

VCC was founded in 1927 and was a part of Volvo Group until 1999 when the company was sold to Ford Motor Company. In 2010 VCC was bought by its present owner Zhejiang Geely Holding of China. It is a global company with headquarter and product development in Gothenburg, Sweden, and production in Sweden, Belgium, China and Malaysia. By the end of June 2016, the company had more than 29 000 employees *(Volvo Car Corporation, 2017)*.

1.2 Background

Within the automotive industry, safety is an important topic, and vehicles are constantly improved to minimize fatalities in traffic. In the past 40 years, several safety features have been developed, which have led to a large reduction of fatal accidents *(Christensen and Bastien, 2016)*. The airbag was introduced in the 1960s as a passive safety system to protect occupants in crashes *(Christensen and Bastien, 2016)* and since its introduction, the overall number of fatal accidents have significantly decreased *(Shaout and Mallon, 2000)*. The frontal airbags are estimated to have saved more than 40 000 lives since 1987 *(National Highway Traffic Safety Administration$_2$, 2017)*. However, if the occupant is improperly positioned or if the airbag is unsuitably deployed, it can give other undesirable effects on the occupant *(Huang et al., 2009)* and the risks of injuries, induced by the airbag, increases *(Braver et al., 1997)*.

In the United States (US) the federal agency National Highway Traffic Safety Administration (NHTSA) regulates the safety of motor vehicles by enforcing vehicle performance standards *(National Highway Traffic Safety Administration$_1$, 2017)*. The main rule collection is the Federal Motor Vehicle Safety Standards (FMVSS) where one of the rules, FMVSS no. 208 - Occupant Crash Protection, is a collection of several standards and requirements with the purpose of improving the occupant protection in crashes. This rule includes e.g. requirements for seatbelts and airbags, and applies for all passenger cars, multipurpose passenger vehicles, trucks, and buses that are to be used in the US *(National Highway Traffic Safety Administration, 2016)*. In 2004, the existing FMVSS no. 208 were amended with focus on minimising the risk of injuries caused by the airbag. Among the changes, the concepts of low risk deployment airbag and automatic airbag suppression were introduced, which affects the configuration of the airbag system *(National Highway Traffic Safety Administration, 2016)*.

As VCC acts on the US market *(Volvo Car Corporation, 2017)*, they must comply with the FMVSS. One alternative for complying with the updated safety regulation FMVSS no. 208 is to use a Capacitive Occupant Sensor (COS) system in the passenger front seat to detect and classify passengers, as a part of the airbag suppression system. The sensor distinguishes an adult from a child in a Child Restraint System (CRS), shown in figure 1.1. The occupant classification is communicated to the airbag suppression system, which enables or suppresses the airbag accordingly.

The COS system is new for VCC. To understand the system boundaries, the capacitance characteristics of a human, in different conditions and scenarios, needs to be understood. Instead of doing tests with Human Test Subjects (HTS), the testing of the COS system could benefit from the development of a Capacitive and Conductive Test Dummy (CCTD).

Figure 1.1. Rearward facing Child Restraint System. Photo credit: Volvo Car Corporation, the copyright owner.

1.3 Purpose and Objective

The purpose of this master thesis is to explore the possibility of developing a CCTD. The CCTD should facilitate testing of the COS system as well as support future development of seats with integrated COS.

The objective is to develop a CCTD with capacitive and conductive characteristics, correlating to a specific user group representative. The focus for this project is the youngest user group: children up to one-year-old. The group, referred to as "1yo group", is for this project defined according to table 1.1.

Table 1.1. Definition of the 1yo group.

	1yo group
Age	≤ 1 year
Length	≤ 84 cm
Weight	≤ 14.5 kg

1.4 Research Questions

The functioning principles of the COS system and the way the human body affects the electric field created by the COS, needs to be investigated to understand the characteristics of the user group.

To achieve the purpose, the problem is divided into the following three research questions that are to be answered during the project:

1. How does the admittance vary for different users, within the 1yo group?
2. What physical variables, of the object occupying the seat, have the greatest effect on the COS system output?
3. What properties are necessary for the CCTD to possess, to correspond to a 1yo group representative's measured admittance?

1.5 Boundaries

This project is carried out as a master thesis work with a budget of 1000 SEK, for external expenses. The following boundaries have constrained the project:

- The COS system's function will only be tested to understand how the system works in relation to a human, apart from that aspect, the system itself will not be investigated.
- The investigation of capacitive and conductive properties will only consider the 1yo group.
- The CCTD is restrained to have weight and coarse dimensions similar to a 1yo group representative, to demonstrate a more realistic scenario with respect to position and behaviour. The CCTD is however, not intended to represent the complete anthropometry for a 1yo group representative.
- The system is developed to be used in the US market, and the definition for the 1yo group is therefore based on growth statistics for US children. Since the project is carried out in Sweden the experiments are limited to Swedish HTSs.
- A physical representation of the CCTD will be created but may differ from the final specification.

1.6 Report Outline

The first chapter act as an introduction of the thesis project. It describes the background to the problem, states the purpose and objective of the project, defines the guiding research questions, and establishes the boundaries of the work.

Chapter 2 Theoretical Framework provides a background to the different topics treated in the thesis work.

Chapter 3 Approach and Methods presents the product development approach used in the project. The two main blocks of Pre-Study and Empirical Study, constituting the approach, are described with related methods.

Chapter 4 Result and Analysis presents the outcome, with related analyses, of the Empirical Study in three parts: Concept Development, Product Testing, and Product Engineering.

Chapter 5 Discussion presents a discussion and reflection regarding the project outcome, project execution, and the ethical considerations related to the work.

Chapter 6 Conclusion concludes the thesis work and proposes future research and development possibilities.

2 Theoretical Framework

This chapter provides a background to the different topics involved in the thesis, and aims to create understanding for clear analysis and discussion. The chapter include: injury mitigation systems, occupant detection systems, human simulation dummies, electrical properties, and anthropometric data for children.

2.1 Injury Mitigation Systems

There are several safety systems in the vehicle, called injury mitigation systems, that protect the occupants during and after a crash. The safety systems are often divided into two categories: active and passive (see figure 2.1). Sensors and radars, used to prevent accidents, are considered active, while seatbelts and airbags, used to mitigate damage to the occupant when an accident happens, are considered passive *(Seiffert and Wech, 2007)*.

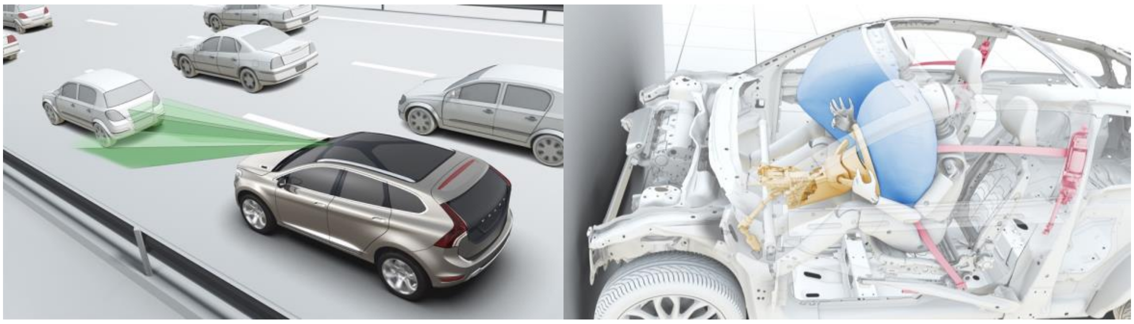


Figure 2.1. Active and passive safety systems. Photo credit: Volvo Car Corporation, the copyright owner.

The seatbelt was developed during the mid-19th century, as a two-point belt *(Center for Autosafety, 2017)*. In 1958, the three-point seatbelt was developed by Nils Bohlin at Volvo Car Corporation (VCC) *(Center for Autosafety, 2017)* and is now the standard seatbelt for vehicles. In a crash, the seatbelt restrains the occupant to the seat to minimize impact and loads on the body.

The airbag was first introduced in the end of 1960's *(Seiffert and Wech, 2007)*. The modern vehicles have several airbags integrated to comprehensively protect all occupants in the vehicle. The frontal airbags reduce the risk of injuries during crashes, through a quick deployment of the bag into the space between the occupant and the dashboard *(Song et al., 2007)*. The airbag absorbs the occupant's kinetic energy and protects the body from impact with the interior.

There are several laws and standards in the United States (US) that control the performance and test procedures for the passive and active vehicle safety systems.

Within the Federal Motor Vehicle Safety Standards (FMVSS) no. 208, there are requirements for the passive safety features of seat belts and airbags *(National Highway Traffic Safety Administration, 2014)*, e.g. requirements making it mandatory for cars to have three-point seat belts *(National Highway Traffic Safety Administration, 2014)* and automatic airbag suppression for the right front passenger airbag *(National Highway Traffic Safety Administration, 2014)*. Even though there are standards, declaring mandatory features to integrate in a car, each state in the US defines its own laws for which safety features that are mandatory to use *(Governors Highway Safety Association, 2017)*. The majority of the states have made it mandatory for passengers to use seat belts, but there are states in which it is not.

When only using the front airbag in a frontal collision, the airbag itself must absorb the occupant's whole body mass and kinetic energy. This means that the airbag pressure needs to be higher compared to when the seat belts are used; more than five times higher according to Seiffert and Wech when comparing a 50 percentile male's reduced head mass of 6.8 kg to the reduced body mass of 36 kg. Increasing the airbag pressure to maintain the absorbing effect can in turn lead to severe injuries on the occupant *(Seiffert and Wech, 2007)*.

In a frontal collision, the best safety effect is reached when using the three-point seat belt and airbag in combination. The occupant will be restrained to the seat by the seat belt and the critical head rotation will be significantly reduced by the airbag. The needed airbag pressure is also less which has a positive effect on the injury rate *(Seiffert and Wech, 2007)*.

To reach best possible safety in crash, it is therefore important that the airbag and seatbelt cooperate. This can be achieved through the use of various sensors, which make the passive safety systems become progressively active *(Seiffert and Wech, 2007)*. The cooperation between airbag and seatbelt is further improved by the development of occupant detection systems, which are described in the next section.

2.2 Occupant Detection Systems

Since FMVSS no. 208 requires vehicles used in the US to have automatic airbag suppression, occupant detection systems are used to support an effective decision-making process for the airbag control unit. The main function of the occupant detection system is to determine if an occupant is sitting in the seat. It also determines the size of the occupant.

Currently, different technologies for detecting occupants are used. Amongst the car manufacturers with vehicle sales in the US, two common variants of occupant detection systems are used: weight-sensing systems and capacitance-sensing systems. A general description of occupant weight-sensing systems are described in 2.2.1, while a specific capacitive occupant sensing system is described in section 2.2.2.

2.2.1 Description of Occupant Weight Sensing

Occupant detection, based on weight sensing technologies, allows detection of occupants by sensing the weight on the seat. When the seat is occupied, the occupant's weight creates forces on the seat cushion. One way of detecting the occupant's weight is by placing a fluid-filled bladder, e.g. filled with silicone, in the seat cushion. The force from the occupant will cause the fluid pressure to increase and the pressure can then be measured by a pressure sensor *(Hollembeak, 2007), see figure 2.2*. Another alternative of weight-based occupant detection is to use a sensor, consisting of a strain gauge and Wheatstone bridge circuit system, in the seat to measure the force of the occupant *(Sakai et al., 2004)*. Based on the pressure/weight level detected by the sensor, an electronic control unit classifies the occupant and communicates to the air bag suppression system if the airbag should be enabled or not *(Hollembeak, 2007) (Sakai et al., 2004)*.

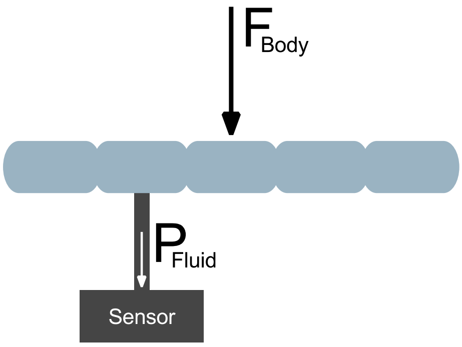


Figure 2.2. Illustration of occupant weight sensor system. F_{body} is the force created by the occupant and P_{fluid} is the pressure (from the fluid) on the sensor.

2.2.2 Description of a Capacitive Occupant Sensing System

An occupant sensing system based on capacitive technologies allows detection of changes in admittance in vicinity to the sensor, i.e. the changes imposed by the conductivity and resistivity of a human body. A Capacitive Occupant Sensor (COS) integrated in the seat creates a circuit, according to figure 2.3. The seat and car frame has characteristics equal to a capacitor, where the seat and car frame act as the conductive surfaces and the air between them is the dielectric. To detect an occupant placed in a car seat, the COS measures the current in the circuit and based on that, the total admittance is calculated to determine if the value correspond to an occupant or not. When the seat is empty, the distance between the sensor and car frame is large, which gives a low admittance. When an occupant is placed in the seat, the surface of the human body creates a conductive path from the sensor to the body and from the body to the car frame (ground), which increases the admittance.

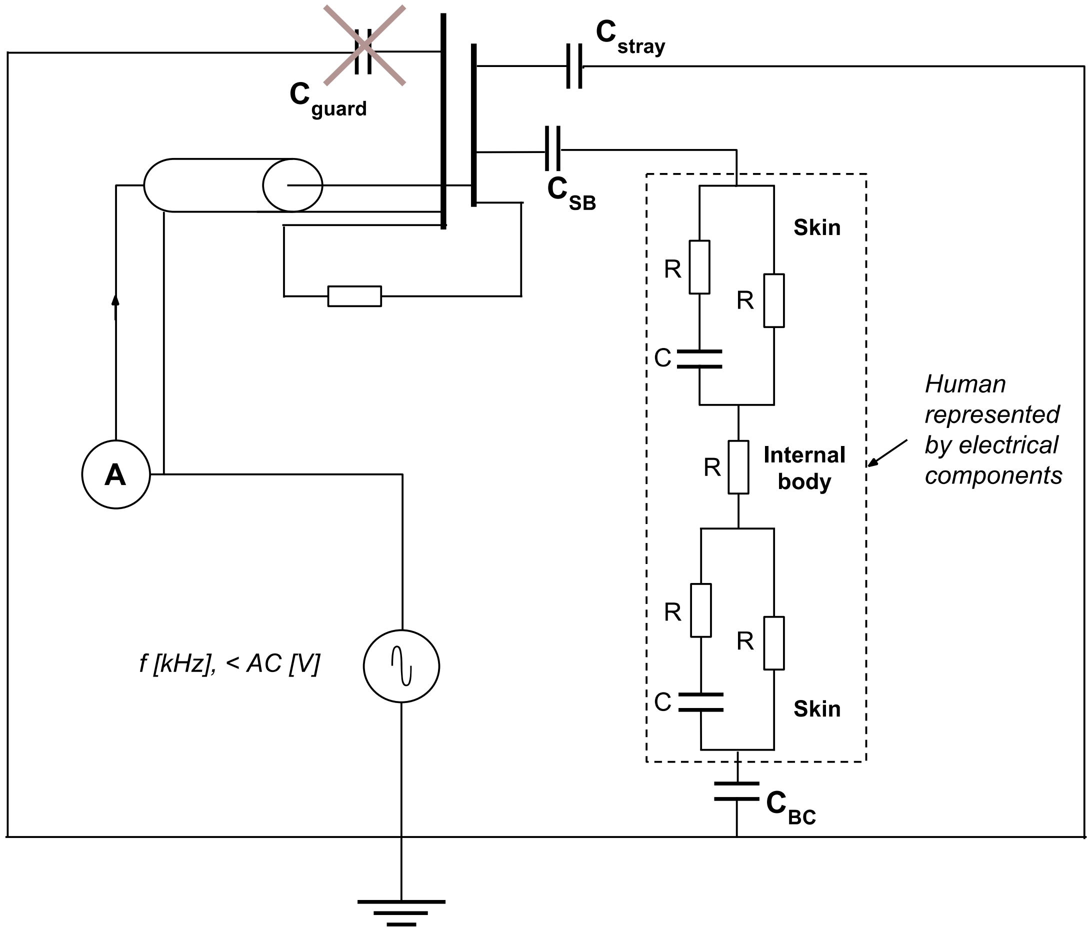


Figure 2.3. Capacitive Occupant Sensor system. C_{SB} is the capacitance between sensor and occupant body and C_{BC} is the capacitance between occupant body and car. C_{stray} is a stray capacitance.

2.3 Human Simulation Dummies

To not harm or risk the well-being of living humans, there are verification and educational situations that require the use of human simulation dummies. Human simulation dummies can be found in a variety of shapes and sizes, developed for different needs.

2.3.1 Crash Test Dummies

Within the automotive industry, there are several technologies for prevention of crash injuries that need to be tested with the help of test dummies. Child simulation dummies for crash testing have been developed since the 1970s and were introduced to the Code of Federal Regulations in the US, in 1979 *(Humaneticsatd.com, 2017)*.

In the US, the FMVSS no. 208 propose a variety of test dummies for crash protection testing, depending on the size of the human that should be simulated. To represent small children in tests treating airbag suppression systems, CRABI dummies are recommended to be used *(National Highway Traffic Safety Administration, 2014)*. The dummies can be found in the size of a six-month-old, a one-year-old (figure 2.4), and a one-and-a-half-year-old. The CRABI dummies aim to support evaluation of child restraint systems (CRS) in automotive crash environments *(de Jager et al., 2005)*, and each dummy is meant to have the basic anthropometry of a child of the corresponding age *(Weber, Lehman and Schneider, 1985)*. The anthropometrical data used in the development of the CRABI dummies have been derived from children measured in the US in 1975, 1977, and 1984 *(Weber, Lehman and Schneider, 1985)*.

Figure 2.4. CRABI twelve-month-old. Photo credit: Humanetics Innovative Solutions Inc., the copyright owner.

In 1981, the first European crash test child dummies to become official, through the ECE-R44 regulation, were the P-series dummies *(Humanetics Innovative Solutions, 2017)*. The P-series consist of dummies simulating children in the age of six weeks, nine months, three years, six years, and ten years. Over time, the need of a new child dummy series increased due to the limited testing capabilities of the P-series dummies, and in 1993, the international Child Dummy Working Group was formed with the aim to develop a new child dummy series *(Wismans et al., 2008)*. The new dummy series, called Q-series, was made as a more advanced variant of the P-series, with anatomical representation of body regions, use of advanced materials, and multi-directional testing possibilities *(Wismans et al., 2008)*. The children simulated by the Q-series dummies are new-borns, one-year-olds (figure 2.5), one-and-a-half-year-olds, three-year-olds, and six-year-olds. For the development of the Q-series the, at that time, latest collection of anthropometry data (based on children originating from US, Europe, and Japan) was used *(Wismans et al., 2008)*.

Figure 2.5. Q1 dummy. Photo credit: Volvo Car Corporation, the copyright owner.

A specification for the CRABI one-year-old representative (CRABI 12-month) and the Q-series one-year-old representative (Q1) *(Carlson et al., 2007)* is presented in table 2.1.

Table 2.1. Specification for CRABI and Q1 dummies.

	CRABI 12-month	*Q1*
Standing height	74 cm	74 cm
Weight [kg]	10 kg	9.6 kg
Materials used	Fiberglass Steel Aluminium Polyurethane Foam Rubber	Polyvinyl chloride Steel Aluminium Polyurethane Foam Rubber

2.3.2 Miscellaneous Dummies

Except for crash dummies, there are also dummies developed for other types of usage. Amongst the human simulation dummies, there are medical manikins used by e.g. medical employees under training *(Medicalexpo.com, 2017)*, rescue manikins used by e.g. emergency personnel or lifeguards under training *(Lifemedicalsupplier.com, 2017)*, and parenting manikins used by e.g. students and expectant parents *(Firstaid-supply.com, 2017)*.

2.4 Electrical Properties

In this section, the basic electrical properties and concepts are first described, to later clarify the electrical properties of materials and the human body.

The main electrical concepts are current (I), measured in ampere [A], voltage (U), measured in volt [V], and resistance (R), measured in ohm [Ω]. Current is formed by electrical charges (Q), either electrons or ions, in motion *(Eriksson, 2017).* The charges move to decrease their electrostatic potential (a difference in electrical potential between two points in a conductor) called voltage. The movement is slowed down by the electrical opposition, called resistance.

In an electric circuit, with alternating current and voltage applied, the electrical opposition is instead called impedance (Z), measured in Ohm [Ω] *(Nationalencyklopedin$_1$, 2017)*. The impedance is defined as a ratio between voltage and current (1) and is represented by a complex number (2). The real part is the circuit's resistance, and the imaginary part is called reactance.

$$Z = \frac{U}{I} \qquad (1)$$

$$Z = R + \frac{j}{\omega C} \qquad (2)$$

The reactance depends on the capacitance in the circuit. Capacitance (C) is a measure of the amount of electric charge that can be stored on a conductor surface and is measured in farad [F] *(Nationalencyklopedin$_2$, 2017)*. The unit farad is large, thus the capacitance in a circuit is usually expressed in the units nanofarad [nF].

An electrical component that can store electric charge is called a conductor (*Nationalencyklopedin$_3$, 2017).* A conductor consists of two conductive surfaces separated by an isolator, also called dielectric. The capacitance of the capacitor is estimated by equation (3) and depends on: the capacitor's geometry, i.e. the area of surfaces (A) and the distance between them (d), and the electrical property of the dielectric, i.e. its relative static permittivity (ε_r) multiplied with the vacuum permittivity (ε_0). The permittivity is a measure of a matter’s ability to polarise when exposed to an electrical field (*Nationalencyklopedin$_4$, 2017).*

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \qquad (3)$$

In contrast to impedance, admittance (Y) is the electrical conductance in a circuit, measured in Siemens [S]. The admittance is expressed as the inverse of impedance (4). In a circuit where the components are connected in parallel, the total admittance is the sum of the components admittances (5).

$$Y = \frac{1}{Z} \qquad (4)$$

$$Y_{tot} = \frac{1}{Z_1} + \frac{1}{Z_2} + \cdots + \frac{1}{Z_n} \rightarrow \frac{1}{R} + j\omega C \qquad (5)$$

As previously mentioned, the total impedance of an object or circuit depends on geometry and size. However, the electrical properties of the material in the object or circuit also affect the impedance.

2.4.1 Materials' Electrical Properties

Materials' main electrical characteristic is their ability or inability to conduct current. The electrical properties are characterised by the electrons *(Hummel, 1998)*. Electrons are a part of the atom and cycle around the atomic core in different orbits. The electrons in the outer orbit, called valence electrons, are the once affecting the electrical properties the most. A material with a large number of free valence electrons, also has a high conductivity. Based on this, materials can be divided into three classes; conductors (e.g. metals), semiconductors (e.g. silicon) and insulators (e.g. polymers).

In conductors, the electrons are loosely bound to the atomic core and can therefore move rather free through the conductor. However, at higher temperatures the resistivity in the material increase; the oscillating movements increase which enhance the probability of collision between electrons and lattice atoms. When the electrons collide the movement is detained, which in turn increases the resistivity *(Hummel, 1998)*. A semiconductor has fewer free electrons, which leads to lower conductivity than conductors. On the other hand, the conduction for a semiconductor increases with increasing temperature. In insulators, the electrons have a stronger bond to the core and therefore have lower conductivity than the previously mentioned material classes.

When insulators are exposed to an external electric force the electrons can oscillate around the atomic core, where the negative and positive charges become separated, creating a dipole *(Hummel, 1998)*. This phenomenon is called electronic polarisation and is utilised in capacitors. When the insulator, also referred to as dielectric, is placed between the conductive plates, the material will polarise and create an electric field in the opposite direction of the external field, which in turn reduce the electric field strength and increases the capacitance. A similar phenomenon can occur in ionic materials, called ionic polarisation. Moreover, there are materials, such as water and oils, which possess permanent dipoles, called molecular polarisation.

In an alternating electric circuit, the material needs to reorient the dipoles quickly. Depending on the frequency in the circuit, the three types of polarisation processes' suitability differs. Molecular polarisation is the slowest while the electronic polarisation is the fastest *(Hummel, 1998)*. If materials are used at frequencies not suitable for its polarisation process, part of the energy will instead be absorbed and turned into heat.

2.4.2 The Human Body and Tissue

Documentation regarding bioelectricity is traced back to 17th century, and investigations and measurements of the body's intrinsic properties have been performed since the middle of 19th century *(Malmivuo and Plonsey, 1995)*. The knowledge is today widely used in several applications, e.g. in medical technology *(Yang and Dong, 2016)*, information technology *(Johnson et al., 2017)* and automotive industry *(Satz, Hammerschmidt and Tumpold, 2009).*

The human body can be seen as a conductor; the electrical properties are given by the movement of ions, which makes it possible for a current to flow through physiologic fluids in the body. The movement of ions is countered by for instance the body's viscosity, which can be modelled as electrical resistance. On the other hand, the current will charge cell membranes and other interfaces in the body which then acts as capacitors *(Foster and Lukaski, 1996)*. This gives the electrical representation of the human body, consisting of both resistance and capacitance, presented in figure 2.6.

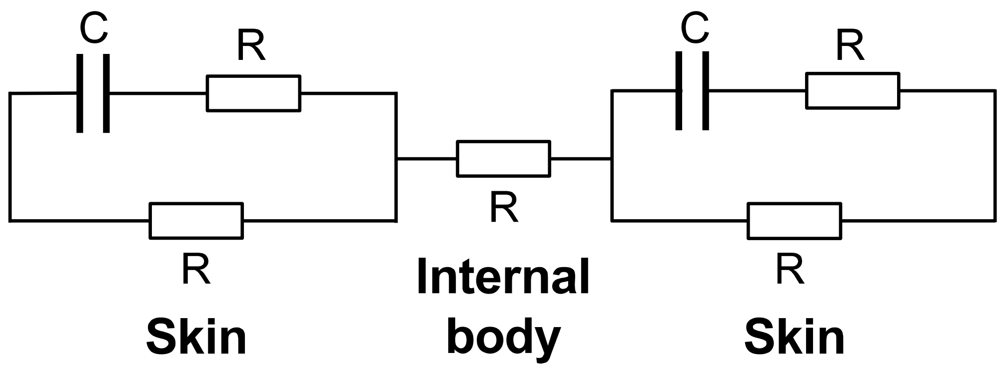


Figure 2.6 Electrical representation of the human body.

Electrical impedance of a body can be measured by exposing the body to a small alternating current, where the impedance corresponds to the ratio of the potential difference to the current. The impedance is also dependent on the frequency. At low frequencies, the cells can appear as nonconductive objects and the current flows mainly in the fluids outside the cells. At high frequencies, the current flows mainly inside the cells and through the cell membrane since the reactance is low *(Foster and Lukaski, 1996) (Satz, Hammerschmidt and Tumpold, 2009)*.

There are two intensive electrical properties of body tissue that affects the impedance of the human body: conductivity (conduction of current) and permittivity (accumulation of charge at interfaces) *(Foster and Lukaski, 1996)*. The human body is made out of around 70 percent water. Consequently, the water has the greatest effect on the permittivity. However, the water in the body contains dissolved ionic salts which make the water in the body act differently than bulk water, under an electric field *(Pethig, 1988)*. The relative permittivity of body water is lower than the relative permittivity of pure water, due to the dissolved electrolytes.

The properties also differ between the different types of tissues (figure 2.7 illustrates the skeleton and muscles in the human body). The skin contains around 70 weight-percent water, but is still the body's main resistance to current flow (around 99 percent *(Fish and Geddes, 2009)) (Foster and Lukaski, 1996)*, and can have a resistance of 100 000 ohms *(Fish and Geddes, 2009)*. The resistive properties of skin are determined by the outermost layer of the skin, corneum, which consists of dead cells *(Pethig, 1988)*. Nevertheless, the properties are dependent on the skin thickness, temperature, and degree of hydration *(Foster and Lukaski, 1996).*

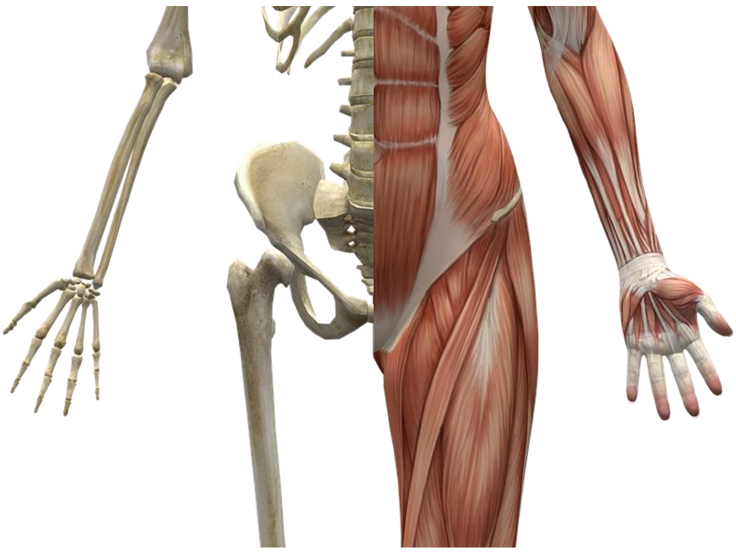


Figure 2.7. Skeleton and muscles in the human body.

The internal body has low resistivity (around 300 ohms *(Fish and Geddes, 2009))* and facilitate electrical conduction *(Odell, 1997)*. Bone and fat have a water content of approximately 45 respectively 10 weight-percent *(Pethig, 1988)* and have greater resistivity than muscles, which contains approximately 75 weight-percent water *(Pethig, 1988) (Foster and Lukaski, 1996)*. When a current flow through the body, the most part flows through muscle tissue. The resistivity of the muscles is directionally dependent and varies with the direction of the muscle fibres. The muscles are more conductive parallel to the muscle fibres, which means that current is more likely to flow along the fibres than across *(Foster and Lukaski, 1996)*.

The distribution of different tissue and water content differ between ages and genders, as well as from individual to individual. For example, infants have a higher weight percentage of water content than adults (*Friis-Hansen, 1961*), and females have a higher fat percentage than men (*Hernández-Morante et al., 2008*). Additionally, the size and anthropometry is individual. The differences in tissue distribution and body size consequently make the definition of the human body's electrical properties complex.

2.5 Anthropometric Data Children

As previously mentioned, the body is different for every human being. Since the 19th century, anthropometry (systematic collection of measurements of the human body) has been conducted. This data is used in several respects: to study human biological evolution, to determine normal and abnormal growth, as well as to design clothes and machines to fit the human *(Britannica Academic, 2017)*.

Children's growth has also been studied to create a growth standard and references for normal growth. In April 2006, the World Health Organization released a new global growth standard for children between 0-59 months. The growth curves are based on data collected during 1997-2003, for children living in six different countries with environments believed to support optimal growth *(Grummer-Strawn, Reinold and Krebs, 2010)*.

According to the World Health Organization's growth standard, the average length for a one-year-old boy is 75.7 cm while the average length for a one-year-old girl is 74.0 cm. The average weight for a one-year-old boy is 9.6 kg, while for a girl it is 8.9 kg *(World Health Organization, 2017)*. An extract from the growth standard is presented in table 2.2 for length and table 2.3 for weight.

Table 2.2. Length chart for children up to 30 months.

	Length, in centimetres [cm], for age					
Age [months]	**Girls (percentile)**			**Boys (percentile)**		
	5th	50th	95th	5th	50th	95th
4	58.5	62.1	65.7	60.5	63.9	67.3
8	64.9	68.7	72.6	67.0	70.6	74.2
12	69.8	74.0	78.3	71.8	75.7	79.7
16	74.0	78.6	83.2	76.0	80.2	84.5
20	77.7	82.7	87.7	79.6	84.2	88.8
24	81.1	86.4	91.7	82.8	87.8	92.8
30	84.9	90.7	96.5	86.3	91.9	97.5

Table 2.3. Weight chart for children up to 30 months.

	Weight, in kilograms [kg], for age					
Age [months]	**Girls (percentile)**			**Boys (percentile)**		
	5th	50th	95th	5th	50th	95th
4	5.2	6.4	7.9	5.8	7.0	8.4
8	6.5	7.9	9.7	7.2	8.6	10.3
12	7.3	8.9	11.0	8.1	9.6	11.5
16	8.1	9.8	12.1	8.8	10.5	12.6
20	8.7	10.6	13.1	9.4	11.3	13.6
24	9.4	11.5	14.2	10.1	12.2	14.7
30	10.4	12.7	14.4	11.0	13.3	16.2

3 Approach and Methods

The project was divided into four phases, see figure 3.1, inspired by Wheelwright and Clark's development process (Wheelwright and Clark, 2011); Problem Investigation, Concept Development, Product Testing, and Product Engineering.

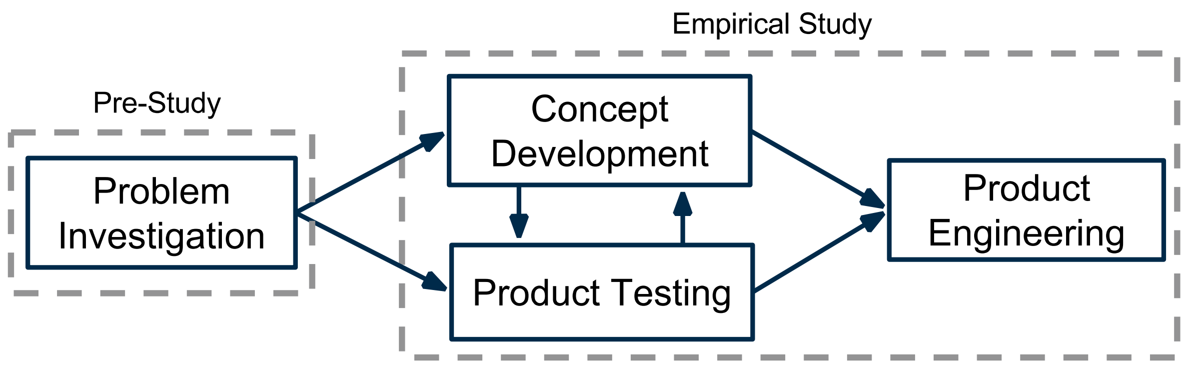


Figure 3.1. An illustration of the project approach.

To broaden the understanding, needed for an effective product development work, as well as to utilize existing theories and state of the art knowledge in the development, the project was initiated by a Problem Investigation phase. Once sufficient understanding of the problem had been acquired, the Problem Investigation phase was followed by the phases Concept Development and Product Testing. The Concept Development and Product Testing phases were conducted in an iterative and parallel manner with frequent exchange of partial results, to gradually improve the functionality and quality of the outcome. In the Concept Development phase, the aim was to generate conceptual designs for the CCTD, while the Product Testing phase aimed at testing the concepts through model building and small-scale testing, to later screen the concepts based on the findings. One final concept was selected, before continuing to the Product Engineering phase where the detailed design of the final concept was developed and a physical representation of the final concept was constructed.

The phases are grouped into two main blocks; a pre-study and an empirical study, according to figure 3.1, above. The blocks, with activities and methods, are further described in the following sections.

3.1 Pre-Study

A pre-study was done to acquire knowledge that exist externally, outside the project team. The knowledge obtained during the pre-study supported the problem understanding and established a foundation for the proceeding work. The pre-study consisted of gathering information from experts within relevant areas as well as from a variety of publications. The activities used to gather information were expert consultations, presented in section 3.1.1; literature research, presented in section 3.1.2; and benchmarking, presented in section 3.1.3.

3.1.1 Expert Consultation

By consulting experts, existing knowledge and experience of subsystems and subproblems can be acquired (*Ulrich and Eppinger, 2012*). Experts can be consulted through different forms of interviews or meeting. Unstructured face-to-face interviews are useful for gathering in-depth data on general themes and issues, i.e. to investigate and define a problem (*Wilson, 2014*). An unstructured interview constitutes a conversation that should have a general goal and an agenda of topics to cover, while strictly predefined questions are avoided.

The aim with consulting experts was to understand the system's different functions and to get a holistic view of the problem. The consulted experts were selected based on their field of knowledge and/or responsibility, and included university faculty as well as professionals from Volvo Car Corporation (VCC). The fields of interest were vehicle safety, restraints, ergonomics, seat development, and electrical engineering.

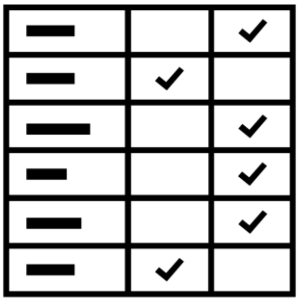
The interviews were conducted face-to-face, in the experts' work environment to enable deeper understanding through rich conversations where the experts feel comfortable and have access to their material and equipment. The topics for each interview were based on the interviewee's expertise. The conversations were noted, and later compiled and organised to provide a base of knowledge.

3.1.2 Literature Research

A literature research is done by reading published literature, such as journals, magazines, government reports, and product information, to gather information about existing solutions and other subjects of interest *(Ulrich and Eppinger, 2012)*. The literature research is constituted by three main steps; define the research questions and/or issues, collect data, and analyse the data *(Comerasamy, 2012)*.

The research issues treated during the literature research were established based on the information provided during the expert consultations as well as on internal reflections regarding admittance. To do an efficient data collection, the search for published literature was done electronically in databases and search engines such as Chalmers Library, Google Scholar, Google Patents, and Google's search engine. A great amount of gathered data was assessed, to determine the level of reliability and relevance, and then compiled. In the cases, when reliability assessments were difficult to do, the information was only used for personal understanding; no decisions or conclusions were based on information lacking reliable sources. To allow for appropriate decisions and conclusions to be made for the following project work, the scientific publications discovered during the research, constituted the foundation.

3.1.3 Benchmarking



By studying existing products, with similar functionality as the product under development, a benchmarking can be done. The benchmarking allows for acquisition of information about what concepts that have already been implemented *(Ulrich and Eppinger, 2012)*, and the performance of the competitors *(Bogetoft, 2015)*. The general process of a benchmarking study begins with selecting a product to benchmark and identifying what key performance metrics to consider. Data, regarding the performance of competitors' closely related products, is then collected and analysed *(Bogetoft, 2015)*. The analysis facilitates building awareness of how the competitors perform *(Wheelwright and Clark, 2011)*, as well as enabling opportunity identification *(Bogetoft, 2015)*.

As the product under development is a type of test dummy, the benchmarking focus was primarily put on dummies connected to occupant detection system testing. Due to difficulties finding information about test dummies, the focus was redirected to occupant detection systems with the purpose of enabling identification of test dummies. The search for dummies and occupant detection systems was conducted using secondary VCC research data, Google's search engine, and the electronic patent database Google Patents.

3.2 Empirical Study

Empirical studies provide both scientific knowledge and guidance for design. By performing a structured empirical study, unique and incomparable results are excluded. The study serves as a reliable source for obtaining evidence from observations and experiments *(Cash, Stankovic and Štorga, 2016)*. When conducting the study, the guidelines below can be followed to support the reliability of the study *(Antony, 2014)*:

- To minimise variability, the person responsible for the study should be present, and the same operator should be used, throughout the whole study.
- To find and enable handling of deviations in the result, the trials should be monitored.
- Response values should be recorded in a pre-defined matrix.

For this project, the empirical study followed the previously stated guidelines and was based on the pre-defined research questions, found in chapter 1. The empirical study was conducted through a set of experiments that were iterated and integrated with other methods to advance the concept development. The activities and methods carried out in the empirical study are described in following sections.

3.2.1 Experimental Testing

To conduct an empirical study and draw valid and objective conclusions, the experiments are carefully planned, designed, conducted and analysed *(Antony, 2014)*. Experimental testing aims to support the understanding of what effects various actions may have on an observed subject *(Nettleton, 2003)*.

The test starts with establishing the focus of the experiment. In the following stage, the planning is done by clearly defining the variables of interest and describing how to measure the output in a reliable way *(Cash, Stankovic and Štorga, 2016) (Antony, 2014)*. In the design stage the data collection, design matrix for compilation and data representation are specified *(Antony, 2014)*. There can be both primary data, collected by the researcher, and secondary data collected for other purposes *(Cash, Stankovic and Štorga, 2016)*. Depending on the focus for the study, the compilation and representation of data can be done in different ways; cause and effect (Ishikawa) diagrams *(Cash, Stankovic and Štorga, 2016)*, normal probability plots, pareto plots, and main effect plots *(Antony, 2014)*.

There are different ways of analysing the data. Two common analysis methods are descriptive and inferential statistics. Descriptive statistics takes measurements of each variable into account and includes studying average, variability and range. Inferential statistics includes examining differences or associations between variables *(Cash, Stankovic and Štorga, 2016)*.

In the empirical study, six experiments were conducted, referred to as Experiment A-F. To minimise noise from external factors, all experiments except Experiment A, were carried out in a specific vehicle, "vehicle X_c", with a specific front passenger seat with a capacitive occupant sensor (COS) system integrated, "seat X_s". Experiment A was managed as an exception by VCC and was carried out in a specific vehicle, "vehicle Y_c", with the same specific front passenger seat with COS system integrated, "seat X_s".

Experiment A aimed at building understanding regarding how the COS system behaves when integrated in the seat and when exposed to different user scenarios. The vehicle, used in the experiment, was located in an environment with minor temperature and humidity fluctuations. The experiment was performed with 18 volunteering human test subjects (HTS), ranging in length and weight according to table 3.1. The HTSs sat in 16 predefined positions when the admittance was measured. The data gained from experiment A was handled as secondary data and will only be presented as part of the analysis to get guidelines for further experimentation. In appendix A, lists of HTSs and positions are presented.

Table 3.1. Length and weight ranges for the volunteering Human Test Subjects participating in Experiment A.

	Min	*Max*
Length	127 cm	167 cm
Weight	24 kg	53 kg

Experiment B aimed at investigating variables affecting the measured capacitance and their contribution to the capacitance level. The experiment was done following a Design of Experiments (DOE) setup *(Fisher, 1966)*, where two variables were tested in two levels, with the objective to maximise the measured capacitance. Due to the few variable levels, and to the possibility of identifying multivariable interaction effects *(Ulrich and Eppinger, 2012)*, a full factorial experimental design was chosen.

Two specific containers, defined in appendix B, filled with tap water were used as test objects, where the design variables were width and filling height. Both containers had a depth of 350 mm, based on the depth of the centre surface of the seat, called "A surface". The high level of the width variable was based on the width of the seat's A surface, while the low width level was based on an assumed one-year-old child's width. The height levels were distributed with the same ratio as for the widths; a low level that was 2/3 parts of the high level. The setup for the test is presented in figure 3.2.

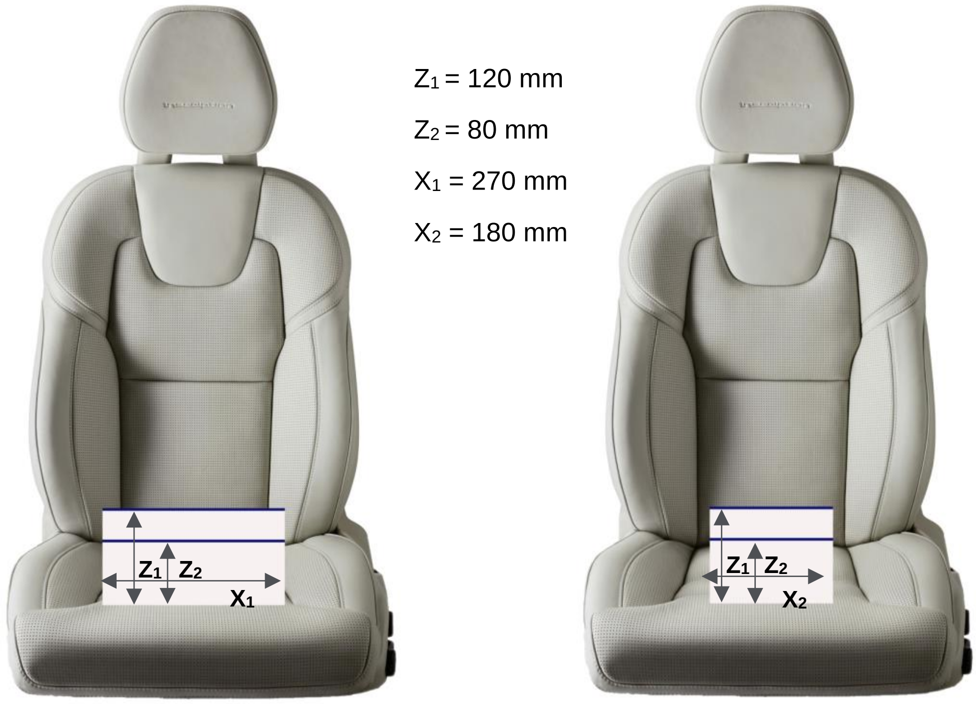


Figure 3.2. An illustration of the setup, including the low and high levels for each design variable.

The use of water was motivated by its sufficient capacitive properties and as it is easy to obtain with low expense. To reduce the amount of noise factors in the experiment, the water was acquired from one specific tap, and the water was re-used between the runs. To investigate if the tap water, used in the experiments, could be acquired from different taps without altering the result, two DOE sessions were done with the use of water from two different taps (still within the same location).

Experiment C aimed to define the 1yo group representative's admittance characteristics. The acquired data was also used to prove feasibility of the different concepts in Experiment E. The experiment was done by investigating the admittance values for different users. Twelve HTSs, within a predefined interval for length and weight (see table 3.2), volunteered to participate. The interval of the HTSs' sizes was based on the pre-study and corresponds to the normal distribution for one-year-old children, ranging from minus three standard deviations to plus three standard deviations for both weight and height. The volunteering HTSs are listed in appendix C.

Table 3.2. Length and weight range for the volunteering Human Test Subjects participating in Experiment C.

	Min	*Max*
Length	70 cm	95 cm
Weight	7 kg	15 kg

The HTSs were requested to wear thin cotton clothes and a jacket (not covering the buttocks) when needed. Each HTS tested two different positions (presented also in figure 3.3):

1 The HTS is placed in the seat without corrections.
2 The HTS is placed to cover the seat's A-surface as much as possible, sitting in the middle of the seat with straight legs and leaning against the backrest.

Figure 3.3. Position 1 (to the left) and 2 (to the right) used in experiment C.

In addition, two of the HTSs were selected to test one position in a specific child restraint system (CRS), as a preparation for the CCTD validation conducted in experiment F. The position and CRS are specified in the paragraph related to experiment F.

Experiment D aimed at identifying admittance values for different materials. The result was used as inspiration for the concept development. The materials to be tested were derived from the first idea generation output, and are shown in figure 3.4. A full specification of the materials is presented in appendix D.

To allow for the measured values to be compared, a specified volume (5.8 litres) of each material was used in the tests. One of the containers, specified in Experiment B, were used in this experiment as well and placed in the middle of the seat, covering as much as possible of the seat surface.

Figure 3.4. Materials tested in Experiment D.

Experiment E aimed at finding the best CCTD concept, by comparing competing concepts in a structured manner. Focused physical prototypes (presented in appendix E) of the concepts were created to be used in the tests. Three existing dummies were also tested, see appendix E. The prototypes and existing dummies were placed in the seat in similar positions as for the HTSs in Experiment C, previously presented in figure 3.3. The output from the test was compared with the result from Experiment C, as part of the screening process.

Concept Validation (Experiment F) aimed at validating the final CCTD solution. For the test, a physical representation of the final concept was created. The physical representation was tested in the second position specified in Experiment C.

In addition to the position right on the seat, the physical representation was also tested in a specific Volvo Car rearward facing CRS (see figure 3.5), in the recommended position for a one-year-old child. The position is defined in appendix F. The measured admittance values for the physical representations were validated against the measured admittance values of the 1yo group representative.

Figure 3.5. Volvo Car rearward facing child seat (for children between 9 kg and 25 kg), used in Experiment F.

In Experiment B-F, the seat was placed in design position; a specific position within the travel box, with specified backrest angle and height/length adjustments (see figure 3.6).

Figure 3.6. Seat design position used in experiment B-F. α is the backrest angle, a and c is the height adjustments in the back and front, and b is the length adjustment in the front.

Every test was repeated three times, each repetition lasting ten seconds, where the system measured the admittance in ten snapshots. The reason for doing three replications is to be able to observe if variances in measurements occur.

The COS system measures the admittance and a specific software is used to retrieve the measured values. The software provides discrete unit-less values that can be approximately converted to the SI-units nanofarad [nF] through (6) for capacitance and kilo-Siemens [kS] through (7) for conductance.

$$1 = 1120{,}4\ nF \qquad (6)$$

$$1 = 732.1\ kS \qquad (7)$$

3.2.2 Idea Generation

To explore the design space of possible solutions to a problem, an idea generation can be done. Idea generation is a systematic approach when searching for ideas *(Law, 2016)* and there are many methods and tools for it. One efficient way of finding solutions to a problem is structured brainstorming *(Osborn, 1963) (Wilson, 2013)*, which can be done both individually and in group, where the participant(s) follow a number of essential rules: suspend judgement, encourage new and wild ideas, and aim for sheer quantity *(Wilson, 2013) (Van Valin, 2014)*.

To maximise the generation of ideas, an individual brainstorming, also called "Brainwriting", can initiate the idea generation. If each participant notes their ideas individually, ideas can be produced in parallel. This can provide a maximised quantity of ideas, which can serve as a foundation for the brainstorming conducted in group *(Wilson, 2013)*.

Three idea generation sessions were done; each one in the same manner but with different questions to seek answers for. The sessions started with five minutes of individual brainwriting, where all thinkable ideas were noted, and continued with ten minutes of brainstorming in group, where new ideas were created both spontaneously and by evolving the already generated ideas. The ideas generated in the first and second session, served as subsolutions in the concept exploration activity. The following questions were posed for the three idea generation sessions:

- What materials can be used as internal body for a CCTD?
- What materials can be used as body cover for a CCTD?
- What concepts are there for a CCTD?

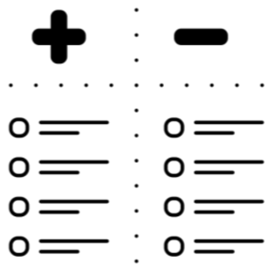
3.2.3 Concept Exploration

The purpose of performing a concept exploration is to systematically combine and explore generated subsolutions, to attain possible concepts that solve the overall problem *(Ulrich and Eppinger, 2012)*. A combination table *(Ulrich and Eppinger, 2012)*, also referred to as "Morphological matrix" *(Zwicky, 1969)*, can be used as a guide to effectively consider different combinations of subsolutions *(Pahl and Beitz, 1996)*.

In a combination table, the columns represent identified subfunctions and the subsolutions are presented under their corresponding subfunction *(Pahl and Beitz, 1996)*. Concepts are formed by combining one subsolution from each column. However, all combined concepts may not solve the overall problem but can be used to stimulate further creativity *(Ulrich and Eppinger, 2012)*.

The generated subsolutions were organised in a combination table, where the subfunction "internal body" was represented by the columns and the subfunction "body cover" was represented by the rows. The possible combinations were marked with three different grades of relevancy; possible but unnecessary application, possible application, or possible and relevant application.

3.2.4 Concept Evaluation



Concept evaluation is a process of narrowing the set of alternative concepts to only a few and eventually selecting a final concept *(Ulrich and Eppinger, 2012)*. There are several methods to support the selection and by using a structured concept selection method, objective decisions can be made. Prototype testing and selection matrices are both examples of structured selection methods. Prototypes can be used to evaluate feasibility and function of concepts and the decisions can thus be based on data from the evaluation, while selection matrices can be used to evaluate the concepts' fulfilment of pre-set criteria.

In early stage of this project, the concept evaluation was mostly based on test data from the different experiments. For the final selection, a Pugh selection matrix *(Pugh, 1990)* was used in combination with test data from Experiment E. In the selection matrix, the following predefined criteria were used to evaluate the concepts:

- 1yo group resemblance
- Represent 1yo group admittance
- Ease of use
- Ease of handling
- Robustness
- Safety in handling
- Lasting admittance value
- Ease of manufacturing
- Cost

By rating each concept, one criterion at a time, with plus “+”, minus “-“, or zero “0”, in comparison to a reference; the already existing aluminium dummy, a total score for each concept was acquired which formed the basis for the concept ranking.

3.3 Concluding Remarks for Approach and Methods

Input from the experts provided knowledge regarding the system and provided guidance for further literature research. The result from the pre-study’s literature research and expert consultation is presented in chapter 2.

Regarding the benchmarking, information concerning other original equipment manufacturers’ systems and dummies were inarticulate, and can therefore not be used to make any valid comparison. However, the benchmark resulted in a better understanding regarding the state of the art and is also presented in chapter 2.

Output from the empirical study stands for the major part of this project and is presented in chapter 4.

4 Result and Analysis

In this chapter, the results from the empirical study are presented, along with analyses of the results. The chapter is divided into three parts; Concept Development, Product Testing and Product Engineering, corresponding to the last phases of the development process.

4.1 Concept Development

The output from the empirical study concerning concept development, in terms of idea generation and concept exploration, is presented in this section.

4.1.1 Initial Concepts

According to theory, a simplification of the human body can be represented by the resistivity of the skin and the conductivity of the internal body. Consequently, the two functionalities, internal dummy body and dummy body cover, guided the brainstorming. During the idea generation, the brainwriting and brainstorming resulted in 46 subsolutions; 34 materials to use as internal dummy body and 12 dummy body covers.

Ideas were eliminated due to high cost, limited availability, and limited shaping possibilities. Materials with low conductivity and low relative static permittivity were also eliminated in accordance to the theory in chapter 2. The complete list of generated subsolutions, together with motivation for elimination, is available in appendix G.

The internal body and body cover materials, remaining after the elimination, are presented in the combination table, table 4.1, where possible combinations of subsolutions are shown; forming combined concepts.

Table 4.1. Combination table with possible combinations of subsolutions. The degree of relevancy for the combinations is indicated by the number of dots.

••• = relevant application •• = possible application • = possible but unnecessary application.		Internal body materials				
		Tap water	Salt water	Peas	Sand	Gel
Body covers	Non-waterproof textile			•••	•••	
	Waterproof textile	••	••	•	•	•••
	Waterproof coated textile	••	••	•	•	•••
	Silicone cylinders sewed into textile	•••	••	•	•	••
	Plastic bags sewed into textile	•••	••	•	•	•••
	Silicone shell	••	••	•	•	••

As peas and sand are dry materials, they are suited to be used together with a body cover made of non-waterproof textile. All other materials are however moist, which requires the body cover to be waterproof. Due to the low viscosity of water, there is a need of having a body cover that is well sealed when using water as an internal body material. Gel does not have the same demand on having a well-sealed body cover. As salt water as internal body material may affect the functionality of the body cover, the use of salt water is not classified as relevant in any combinations.

4.1.2 Combined Concepts

Seven combined concepts received the relevancy grade three, and were sketched for further development and investigation. Short descriptions of the combined concepts, which were in focus during the empirical study, are given below.

Peasy and Sandy are two concepts with similar body cover, made of cotton textile. The body has a zipper along the back, where the internal body filling is to be entered. Peasy has an internal body of dried peas while Sandy has a filling of natural sand, both illustrated in figure 4.1. Since both materials are dry they are filled right into the body and distributed evenly in the different body parts.

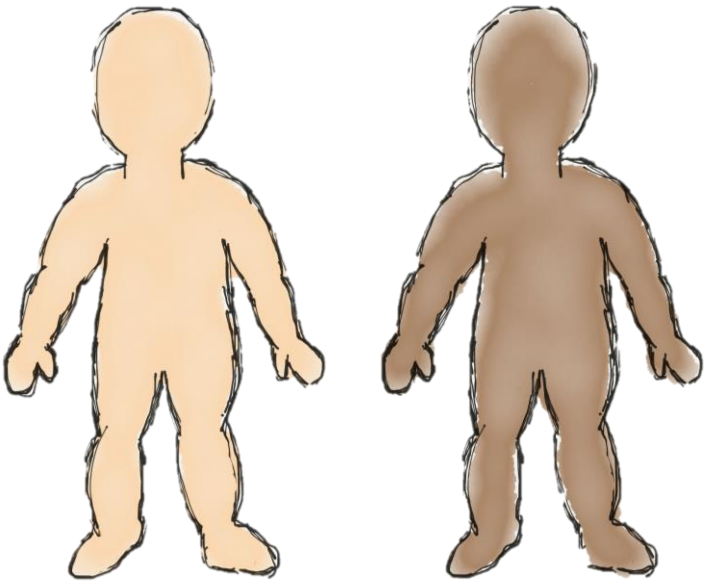


Figure 4.1. Sketches of Peasy and Sandy, with body covers of textile.

Gelena* is a concept with a body cover made of waterproof textile, and an internal body made of gel. The waterproof textile is sealed to be waterproof, by welding or sewing. As the gel have a higher viscosity than water, the risk of leakage decreases when using gel instead of water as internal body. Gelena is illustrated in figure 4.2.

*Due to practical reasons, Gelena was not tested in Experiment E.

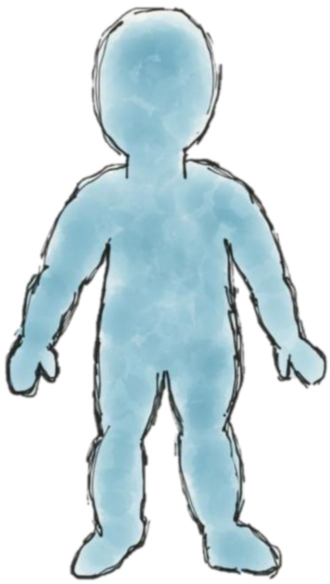


Figure 4.2. Sketch of Gelena, with body cover of waterproof textile.

Gelbert is a concept with a textile body made in cotton canvas that is coated with silicone. The silicone is spread on the inside of the textile body so that the silicone penetrates the textile and give a waterproof surface. The body cover is filled with gel. Gelbert is illustrated in figure 4.3.

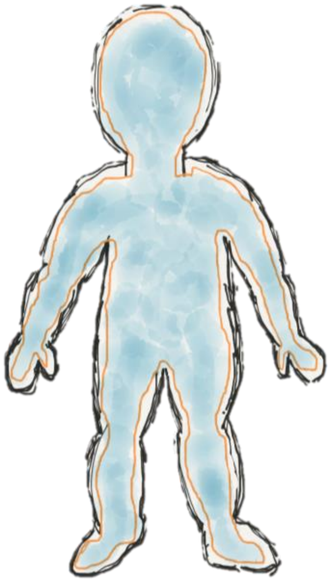


Figure 4.3. Sketch of Gelbert, with a body cover of textile coated with silicone.

Cyleen* is a concept where the body cover is made from cotton canvas sewed in to the shape of a one-year-old. Silicone cylinders are distributed in the body cover and acts as waterproof body parts. The internal body is constituted by water, which is filled in the waterproof silicone cylinders. Cyleen is illustrated in figure 4.4.

*Due to practical reasons, Cyleen was not tested in Experiment E. Instead of Cyleen, the concept Silva (in figure 4.4) was used in Experiment E. Silva is a concept with a silicone body, of simpler geometry, filled with water.

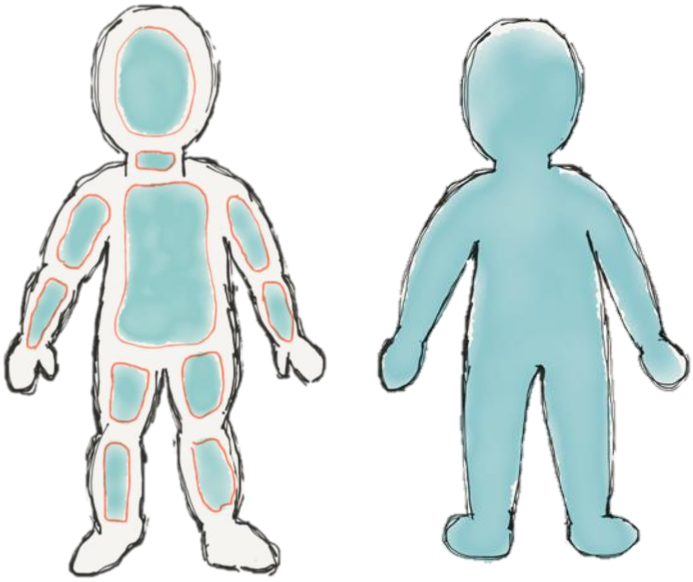


Figure 4.4. To the left, a sketch of Cyleen that has a body cover of textile with cylinders. To the right, a sketch of Silva representing Cyleen in experiment E.

Paval and Gelis are both concepts with textile body covers, similar to Peasy and Sandy. Paval and Gelis bodies are however filled with water-proof plastic bags; Plastic bags containing internal body of water for Paval and gel for Gelis. The concepts are illustrated in figure 4.5.

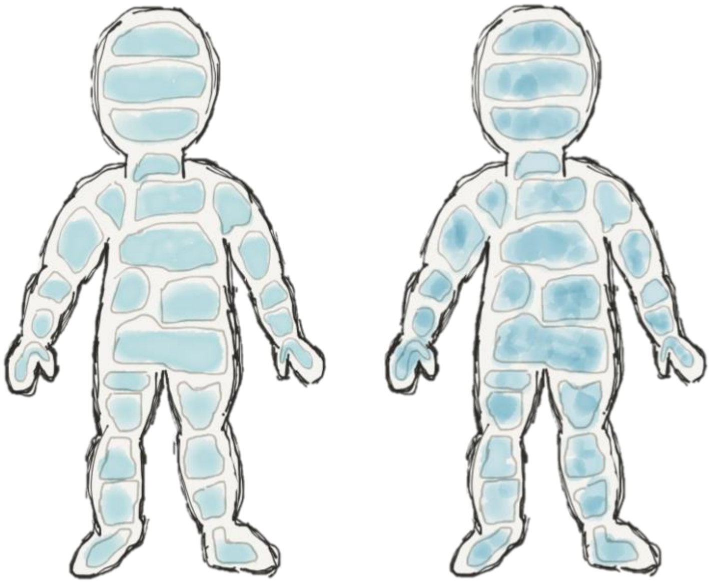


Figure 4.5. Sketches of Paval and Gelis, with body covers of textile and bags with water or gel.

4.2 Product Testing

The output from the empirical study concerning product testing, in terms of experimental testing and concept evaluation, is presented in this section. An overview of the different experiments is presented in table 4.2.

Table 4.2. Holistic view of the experiments conducted in the empirical study. Findings from Experiment F is presented in section 4.3.2.

Experiment A	Experiment B	Experiment C	Experiment D	Experiment E	Experiment F
COS understanding	Variable investigation	Human admittance investigation	Material testing	Concept comparison	Concept validation

4.2.1 Findings from Experiment A

In Experiment A, the aim was to build understanding regarding the Capacitive Occupant Sensor (COS) system. An Ishikawa diagram, illustrating the factors found to affect the capacitance measured by the COS system in a car, is presented in figure 4.6. The factors, based on theory and secondary data from Experiment A, are divided in four groups. Each group relates to one of the parts affecting the capacitance, according the capacitance expression (3) found in chapter 2.

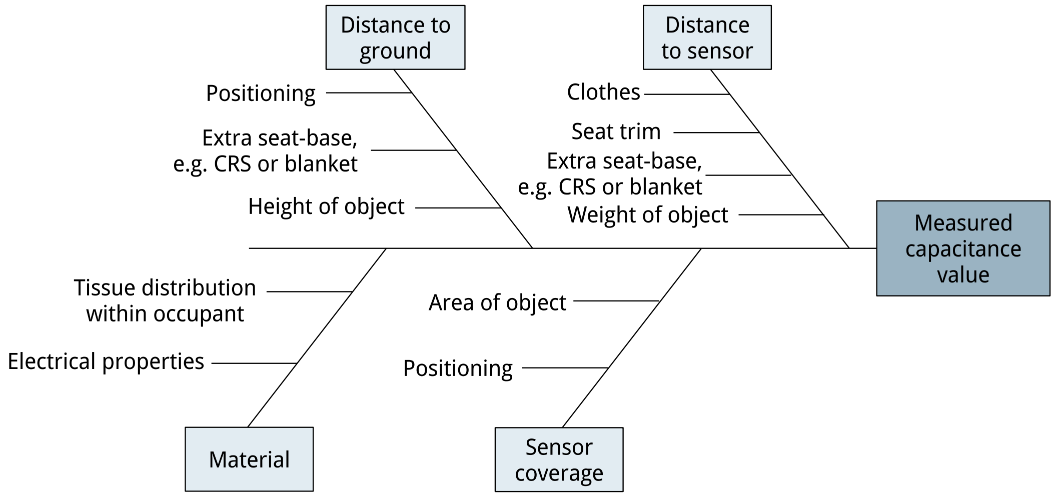


Figure 4.6. Ishikawa diagram presenting factors found to affect the measured capacitance.

The factors, found to affect the measured admittance values, are mainly related to the occupying object and its physical and electrical properties. If the occupying object is a human, the electrical properties depend on the physical properties, such as distribution of different types of internal body tissue. According to theory (chapter 2), different types of tissue have different electrical characteristics and the electrical properties will therefore depend on the distribution. Findings from Experiment A verifies that theory, as it could be seen that Human Test Subjects (HTS) of similar height and weight generated different capacitance values.

From experiment A, it could also be seen that HTSs of similar height but varying weight generated different capacitance values, which is realistic as different tissue also have different density. Apart from the differences in density of different tissues, a heavy occupant would press together the seat cover more than a light occupant, decreasing the distance to the sensor, and consequently increasing the capacitance value. The measured capacitance values also appeared to be higher for tall and wide HTSs, which may indicate that the decreased distances to ground and increased sensor coverage generates higher measured capacitance values.

In addition to human occupants, seat-bases of different sorts, such as a child seats or blankets, were also found to affect the measured capacitance. When the HTSs sat on different seat-bases, the measured capacitance decreased. Plausible reasons for that may be that the seat-bases have poor electrical properties, which isolates the capacitance of the volunteers, and high thicknesses, which increases the distance to the sensor.

These identified variables are further tested in Experiment B.

4.2.2 Findings from Experiment B

In Experiment B, the aim was to investigate which variable that have the largest effect on the measured capacitance. The output from the Design of Experiments (DOE) is represented by the cube plot in figure 4.7, showing the performance values for the different runs. Raw data and calculations for Experiment B are found in appendix B.

The DOE shows that maximum measured capacitance (equal to 21288 nF) is reached when both variable levels are high (width 270 mm and height 120 mm) and that the minimum measured capacitance (equal to 15686 nF) is reached when both variable levels are low (width 180 mm and height 80 mm).

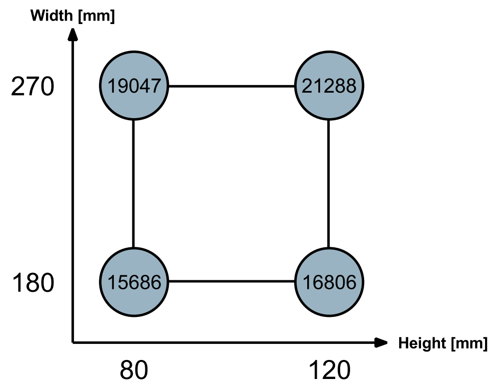


Figure 4.7. Cube plot of performance values in nanofarad for the different runs.

The level of dependency between the variables is evaluated in the interaction plot, in figure 4.8. The plot demonstrates a limited to moderate interaction between the variables, indicating that the effect of the width variable is nearly independent of the level of the height variable. At high level for the width the height has slightly higher impact on the capacitance, than at low level.

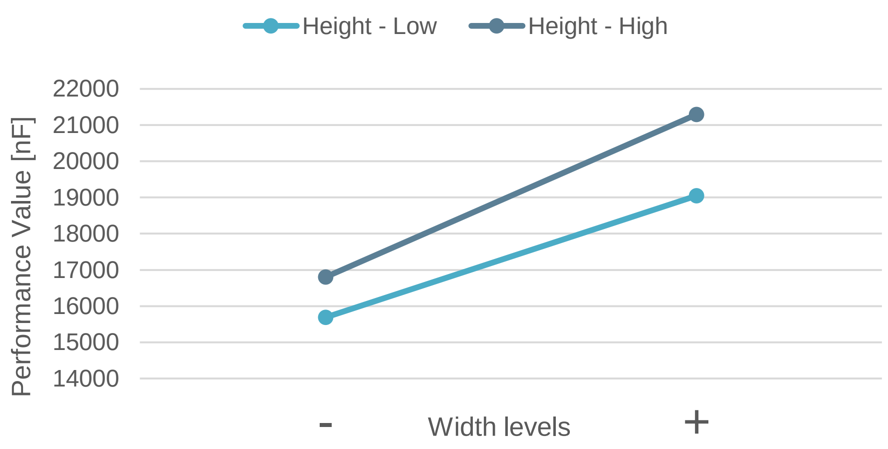


Figure 4.8. Interaction plot showing the interaction between the variables: height and width.

Since the variables show a limited to moderate interaction, it is assumed possible to take the effect of one variable into account at the time. Figure 4.9 illustrates the main effect of respective variable, together with the mean of all performance values. As the width has higher inclination, this variable seems to have the greatest effect on the measured capacitance value.

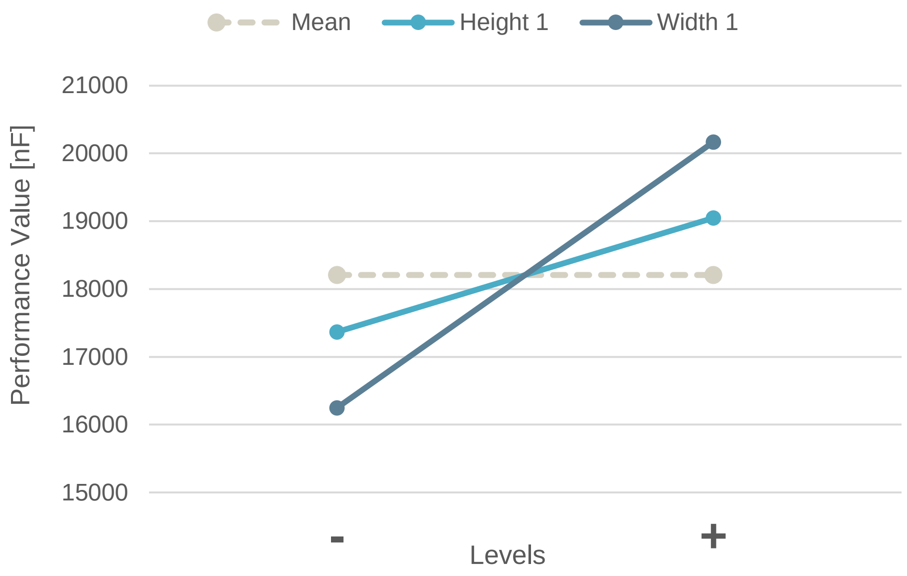


Figure 4.9. Main effects plot illustrating the main effects of height and width.

Even though there is a limited to moderate interaction between the height and width, a decision was made to focus on creating a Capacitive and Conductive Test Dummy (CCTD) with similar shape as a one-year-old. When comparing such a CCTD to a one-year-old, it would be possible to neglect the shape as noise factors.

4.2.3 Findings from Experiment C

In Experiment C, the aim was to define the 1yo group representative's admittance characteristics. The data for all HTSs in Experiment C are compiled in table 4.3. The admittance values for each HTS are presented per sit-in, where the first three sit-ins correspond to position 1 and the last three correspond to position 2. The data represents the most common capacitance and conductance values among the ten snapshots in each sit-in, per HTS. In table 4.3, there are small differences in admittance values between the HTSs, but also between the two positions.

Table 4.3. Measured values for all volunteering Human Test Subjects in Experiment C.

	Position 1						***Position 2***					
	Sit-in 1		**Sit-in 2**		**Sit-in 3**		**Sit-in 1**		**Sit-in 2**		**Sit-in 3**	
	C [nF]	**1/R [kS]**	**C [nF]**	**1/R [kS]**	**C [nF]**	**1/R [kS]**	**C [nF]**	**1/R [kS]**	**C [nF]**	**1/R [kS]**	**C [nF]**	**1/R [kS]**
HTS 1	21288	732	21288	732	21288	732	21288	732	21288	1464	20167	732
HTS 2	20167	732	21288	732	21288	732	20167	732	17926	732	19047	732
HTS 3	24649	1464	24649	1464	25769	1464	25769	1464	24649	1464	25769	1464
HTS 4	25769	1464	24649	1464	23528	1464	24649	1464	25769	1464	26890	1464
HTS 5	29130	1464	30251	1464	30251	1464	29130	1464	29130	1464	30251	1464
HTS 6	24649	1464	23529	1464	23528	1464	23528	1464	25769	1464	24649	1464
HTS 7	23528	1464	23529	1464	23528	1464	24649	1464	23528	732	23528	1464
HTS 8	22408	1464	22408	1464	22408	1464	22408	1464	22408	1464	22408	1464
HTS 9	22408	732	22408	1464	22408	1464	23528	1464	23528	1464	23528	1464
HTS 10	21288	1464	23528	1464	22408	1464	22408	1464	21288	732	22408	732
HTS 11	22408	732	22408	732	20167	732	22408	1464	22408	1464	22408	1464
HTS 12	19047	1464	19047	732	19047	732	19047	1464	19047	732	19047	732

In figure 4.10, the most common capacitance and conductance value for each HTS is plotted in a complex plane. The different colours present one or several specific HTSs. The output from the measurements show that the capacitance values vary between 19046.8 and 30250.8 nF on the imaginary axis, while the conductance values vary between 732.1 and 1464.3 kS on the real axis.

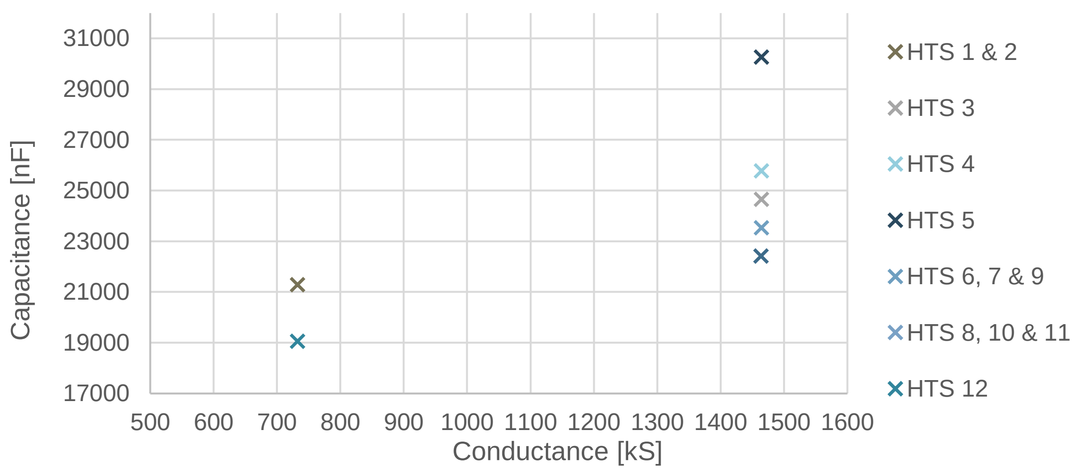


Figure 4.10. Most common capacitance and conductance value per Human Test Subject in Experiment C. A number of the Human Test Subjects get the same value, consequently giving the same data point in the diagram.

From the measured capacitance and conductance values, it was found that the capacitance and conductance increases with increased age, for the 1yo group, see figure 4.11.

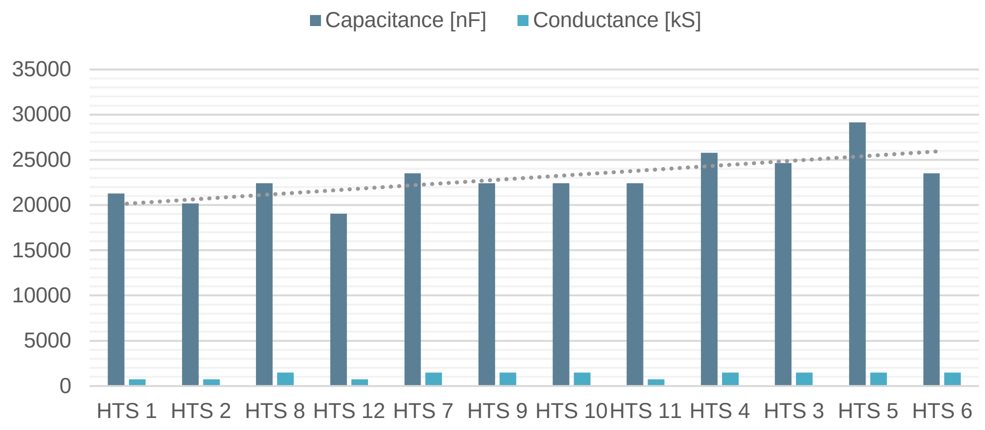


Figure 4.11. Capacitance and conductance values, sorted on the HTSs' ages, increasing from left to right.

However, as the trend line for age is not entirely stable. It is interesting to investigate how the values behave, when sorting the HTS based on weight (figure 4.12) and length (figure 4.13). When doing so, it can be seen that an increased weight and length also increases the capacitance and conductance values, but with smaller variations than for the values sorted on age. In accordance to theory (chapter 2) and findings from previous experiments, it is probable that the measured admittance depend more on weight and length than on age itself. Based on this, it is preferable for the CCTD to resemble the coarse dimensions and weight of an average one-year-old.

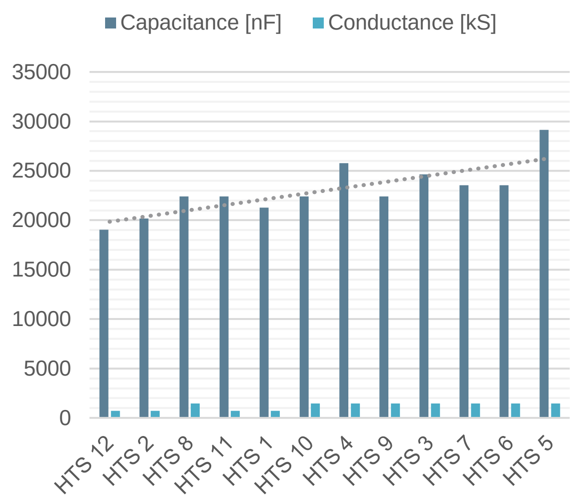


Figure 4.12. Admittance sorted on the HTSs' weights

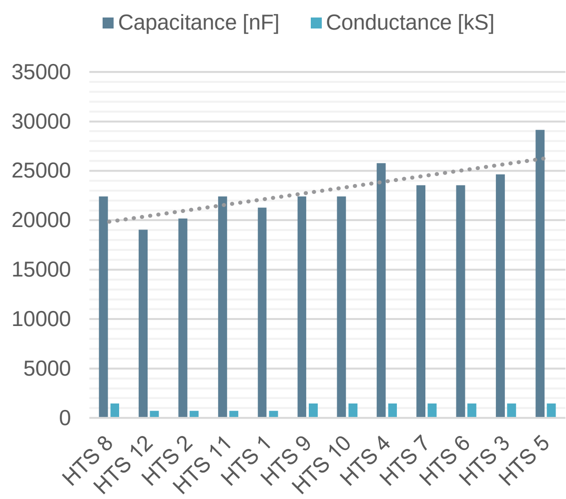


Figure 4.13. Admittance sorted on the HTSs' lengths

Due to previously stated findings regarding weight, length, and age in relation to admittance, the representative for the 1yo group is chosen to be HTS 9. HTS 9 has a measured capacitance of 22408 nF and conductance of 1464 kS. The choice of HTS 9 as a representative is motivated by the HTS's position on the growth chart, level of measured admittance, and low variances in the measured values (see appendix C).

4.2.4 Finding from Experiment D

In Experiment D, the aim was to identify admittance values for different materials. In the experiment, twelve different material runs were conducted. The materials tested are specified in appendix D.

The result from the experiment is presented in figure 4.14. Tap water B, Salt water with different salt concentrations and the gelatine give the highest measured values. The result indicates that the materials containing water give a higher measured admittance than the dry materials, which is in accordance to presented theory.

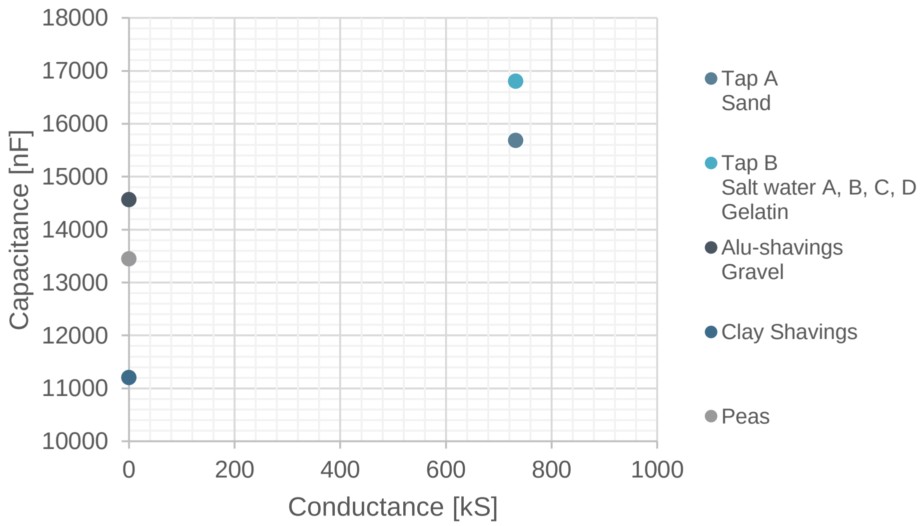


Figure 4.14. Most common capacitance and conductance value per material in Experiment D. A number of materials get the same value, consequently giving them the same data point in the diagram.

As the human body contain around 70 percent water according to theory and since water give high measured admittance, two additional tests were done to investigate the properties further.

One test was done to investigate how the water volume affects the measured admittance. Different volumes of tap water were tested, going from one to twelve litres of tap water. The test is specified in appendix D.

The result from the test is presented in figure 4.15, showing a clear relation between increased admittance and increased water volume. What also can be observed, is that the capacitance has an almost linear increase, while the conductance has a slower and step-wise increase.

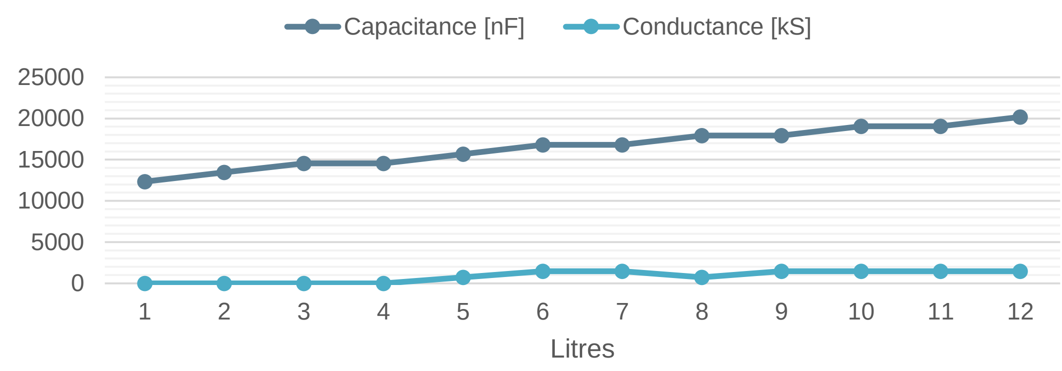


Figure 4.15. Measured admittance, divided in capacitance and conductance, per volume water.

Furthermore, four different types of water and mixtures of water were tested: tap water, tap water with salt, distilled water, and tap water with Super Absorbent Polymer (SAP). The materials are specified in appendix D. The result is presented in figure 4.16. Eight litres of purified, distilled water give slightly lower measured capacitance than the other three contaminated water types. However, the differences are small which indicate that the different levels of contamination, does not affect the measure admittance in a large extent.

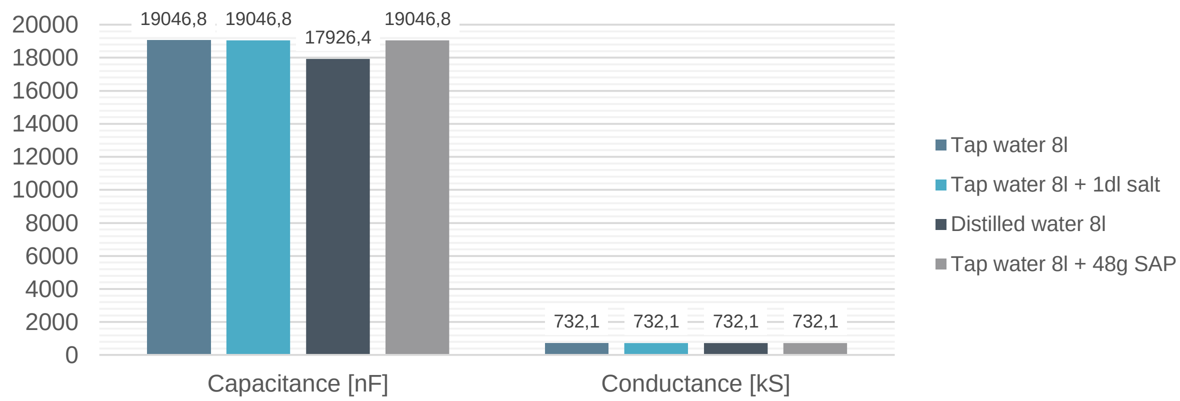


Figure 4.16. Measured capacitance and conductance for different types of water and water mixtures.

The SAP is in this case used to increase the viscosity of water and has a better reaction with purified, distilled water, than with tap water, containing salts and minerals. To observe differences in absorbing possibilities and admittance properties, mixtures of distilled water with SAP and tap water with SAP were tested. To represent the water volume of a child, the different mixtures were instead investigated for ten litres of mixture (ten litres mixed with 60 grams SAP). The output show that the measured admittance is the same for both mixtures (20167 nF and 732 kS). The consistency differs slightly; the mix with distilled water is a bit harder. However, both consistencies are satisfactory for the application.

Raw data from the different material tests are found in appendix D.

4.2.5 Findings from Experiment E

In Experiment E, the aim was to find the best CCTD concept by comparing competing solutions. The seven concepts, receiving a relevancy score of three in the combination table (in section 4.1.1) are evaluated and compared in this section. The concept comparison is done in two evaluation steps; based on the admittance output from experiment E and based the score given for the different criterion in the Pugh matrix.

In Experiment E, three existing dummies marked with (E) in figure 4.17, were tested along with six of the concepts, to evaluate the admittance output. Due to practical reasons, Gelena could not be tested in Experiment E. The other six concepts were somewhat simplified for the creation of focused physical prototypes to test. For Peasy, Sandy, Paval and Gelis a children pyjama was used as body cover. Gelbert was simplified to the form of a cylinder, with circumference similar to a one-year-old child. Cyleen was instead represented by the concept Silva. Pictures and further descriptions of the simplified prototypes are found in appendix E.

The result from Experiment E is presented in figure 4.17. The capacitance output for the existing dummies are significantly lower than the target value. The concepts Sandy and Peasy get even lower capacitance output than two of the existing dummies. In contrast, the concepts Paval and Gelis are closer to the target and have a capacitance value of 21287.6 nF. Concerning the conductance value, only Paval and Gelis reaches the target. The compiled data from the experiment is presented in tabular form in appendix E.

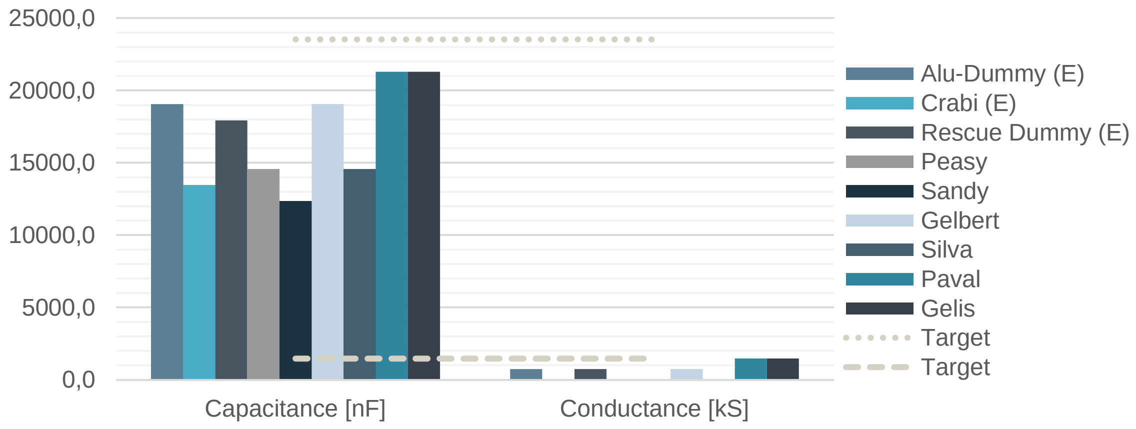


Figure 4.17. Measured admittance for concepts and existing dummies in relation to the target values.

The output from the Pugh matrix is presented in table 4.4. The existing aluminium dummy is used as reference since it is the existing dummy with measured admittance values closest to the 1yo group representative. The score for 1yo group admittance representation is based on the admittance output from Experiment E.

Table 4.4. Pugh matrix for competing concepts.

	Criterion	Al-Dummy (reference)	Peasy	Sandy	Gelena	Gelbert	Cyleen	Paval	Gelis
1	1yo resemblance (design)	0	+	+	+	+	+	+	+
2	Represent 1yo admittance	0	-	-	0	+	0	+	+
3	Ease of use (represent positions and behaviours)	0	+	+	+	+	+	+	+
4	Ease of handling	0	+	0	0	0	0	0	0
5	Robustness (endure normal handling)	0	-	-	-	-	-	-	-
6	Safety in handling	0	+	+	+	+	+	+	+
7	Lasting adittance value (one development cycle ~ three years)	0	0	0	-	-	0	-	0
8	Ease of manufacturing	0	+	+	0	-	-	+	+
9	Cost	0	+	+	+	+	+	+	+
Sum -			2	2	2	3	2	2	1
Sum +			6	5	4	5	4	6	6
Sum 0			1	2	3	1	3	1	2
Score			4	3	2	2	2	4	5
Ranking			3	4	7	5	6	2	1

Through the holistic view created by the Pugh matrix, it is evident that, of the concepts investigated, Paval and Gelis give the best representation of the 1yo group. There is only minor difference between Paval and Gelis; both have the same body cover, only the consistency of the filling material differs. Consequently, both concepts were selected as final concepts, to be validated in the final phase of this project.

4.2.6 Concluding Remarks for Product Testing

Several factors, effecting the measured admittance, were identified through theory and the conducted experiments. Apart from the already presented factors in the Ishikawa diagram in section 4.2.1, environmental factors may have a significant impact on the measured admittance. For example, variations in temperature and humidity of the surrounding air have an effect on the HTSs' electrical properties and may consequently affect their admittance values, which all is in accordance to theory (chapter 2).

How the factors affect the measurements and the relation between them have not been established. However, the factors should be kept in mind when measuring the admittance since it can cause variations and noise in the output. For this reason, the Ishikawa diagram, illustrated in figure 4.18, is further developed to include these types of variables.

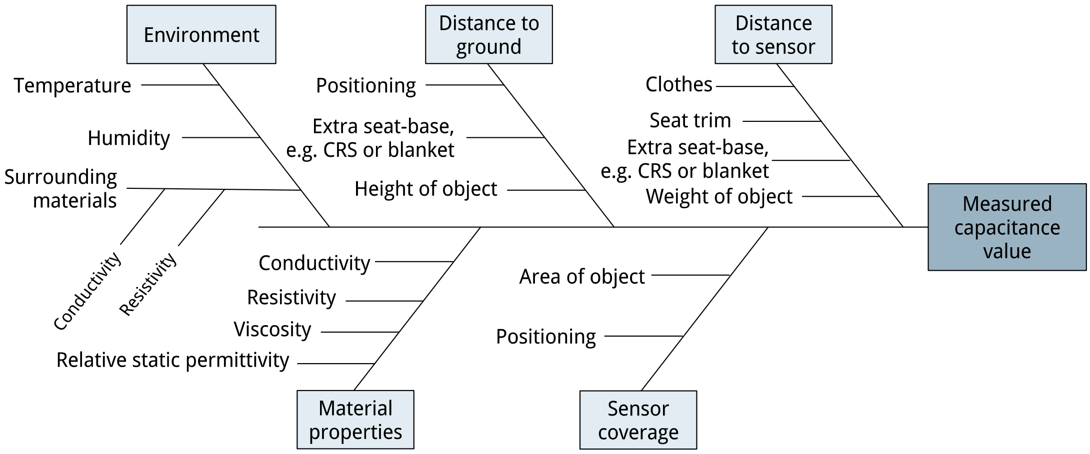


Figure 4.18. Developed Ishikawa diagram.

Other findings, from the conducted experiments, that are of importance for the product engineering phase are listed below.

- Materials with a high water content give admittance values in level with the HTSs' admittance values.
- HTS 9 is selected as representative for the 1yo group, with a capacitance value of 22408 nF and conductance value of 1464 kS.
- The concepts Paval and Gelis, presented relevant admittance output and HTS resemblance, and are selected as final concepts.

4.3 Product Engineering

In this section, the output from the empirical study is composed, to derive a final solution. The final solution for the CCTD, along with a validation of the dummy's properties, are presented.

4.3.1 Final Solution

The final solution for the CCTD, named Kim, is illustrated in figure 4.19. Kim has been made in to two versions: Kim v1 and Kim v2, derived from the concepts Paval and Gelis. The two versions have the same body cover, where thin cotton textile is formed into the shape of a one-year-old child. The dimensions are based on measurements of an anthropometric one-year-old manikin. The body cover has zippers, to enable the body cover to be filled with the internal body material.

Figure 4.19. The concept Kim

The internal body material differs between the two versions; Kim v1 has an internal body based on tap water while Kim v2 has an internal body based on tap water mixed with a SAP (six grams SAP per litre water). Both filling materials are contained in sealed plastic films, resulting in filled plastic pads. The pads are dimensioned to fit the different body parts of the body cover. As water has low viscosity, dummy Kim v1 obtains a rippling consistency. The mix of water and SAP does however increase the viscosity of the fluid, which gives Kim v2 a consistency leading to a haptic feeling closer to human flesh.

The dummy Kim resembles the shape of a one-year-old child (see figure 4.20). The combination of a resistive body cover and a conductive internal body, also give the dummy capacitive and conductive characteristics similar to a one-year-old child. The admittance values for both versions of Kim does not differ, even though they have differing internal body fillings. These properties are proved in the following section.


Figure 4.20. The dummy Kim, resembles the shape of a one-year-old.

Finally, the output from previous phases is combined into a product specification, including target values for the metrics, describing what is required of the CCTD. The specification in short is described in the bullet list below, while the full product specification is presented in appendix H.

- The dummy is required to have admittance characteristics as a one-year-old.
- The dummy is desired to represent human positions and scenarios
- The dummy should have one-year-old human resemblance, considering coarse proportions and dimensions.
- The dummy is required to be made of materials with environmental and health aspects consideration.
- The dummy is desired to have a lifespan correlating to the seat development cycle.
- The dummy is desired to be designed for manufacturing and maintenance.
- The dummy has requirements for an accepted purchase price.

A physical prototype of Kim was made, weighing 9.5 kg and being 78 cm tall. The prototype fulfils the majority of the requirements in the product specification. The process used to produce the prototype can be used for producing the final product. However, improvements to increase the accuracy of the process is needed.

Based on the findings from the different experiments, the conclusion is that dummy Kim also is possible to scale to resemble users from other user groups. The water content in the internal body, seems to be the vital parameter. With increased size of the body cover, the body can contain more water and as a result a higher measured admittance.

4.3.2 Capacitive and Conductive Test Dummy Validation (Experiment F)

In Experiment F, the aim was to ensure validity of the developed dummy. The output from the experiment is presented in three parts. Both prototype versions of Kim are tested.

The prototypes are first tested directly on the seat, according to figure 4.21. The result, presented in figure 4.22, prove satisfying correlation to the 1yo group representative. The diagram is based on the most common measurement, taking 30 snapshots into consideration. Both versions of Kim present the same capacitance (23528 nF) value as the 1yo group representative, for more than 90 percent of the measurements, and the same conductance (1464 kS) value as the 1yo group representative, for more than 70 percent of the measurements. The result also shows that both filling material represent the 1yo group representative’s admittance values equally good, thus the choice between the two types of filling material can be based on other preferences than the measured admittance.

Figure 4.21. Dummy Kim positioned in the seat according to the test procedure.

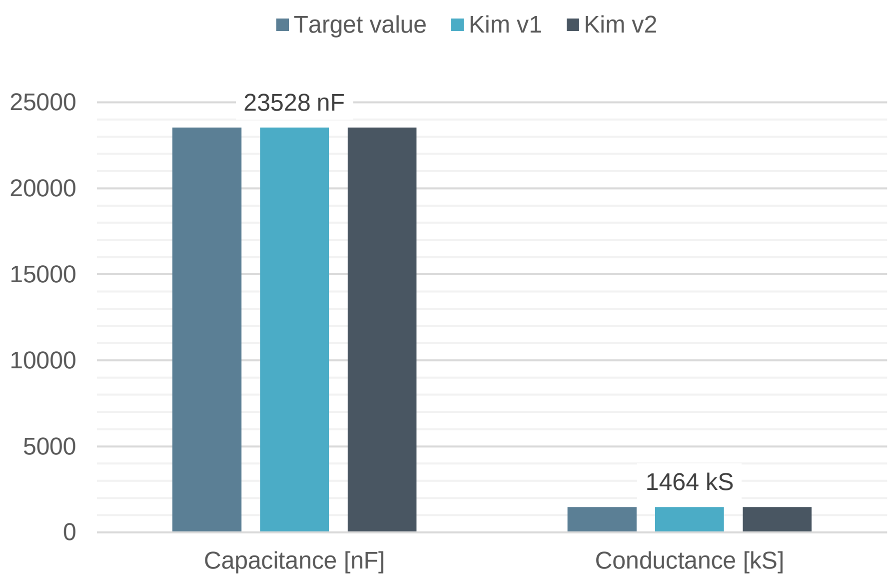


Figure 4.22. Measured admittance values for the concept validation experiment.

Kim was also tested in four different positions, directly on the seat, illustrated in appendix F. The result from the test is presented in table 4.5, and indicates that the dummy gives minor alterations for the measured admittance when placed in different positions. The minor variation in admittance seen in the test, can also be observed with HTS, due to small changes in positions between the sit-ins. The output therefore, provide evidence that the dummy corresponds to a human in different scenarios.

Table 4.5. Different sitting positions for Kim V1.

1 – Normal sitting		2 – Sitting, turned to side		3 – Slouching		4 - Sitting, leaning forward	
C [nF]	1/R [kS]	C [nF]	1/R [kS]	C [nF]	1/R [kS]	C [nF]	1/R [kS]
1464.3	23528.4	1464.3	25769.2	732.1	22408	732.1	22408

To ensure that the concept will represent a one-year-old in Child Restraint System (CRS), one additional test in CRS was done. The result from this test show that the 1yo group representative and the prototype of the concept Kim have similar measured values also in a CRS (11204 nF and 0 kS).

5 Discussion

This chapter presents a discussion regarding the conducted project work. First the research questions are answered and discussed. This is followed by a discussion regarding the proposed dummy, and presented approach and result, where the validity of the project outcome is argued for. Ethical considerations are also treated.

5.1 Answering the Research Questions

The answers to the research questions, presented in the introductory chapter, are discussed in this section.

1. *How does the admittance vary for different users, within the 1yo group?*

The focus for this project was based on the idea that the measured admittance somewhat differs between users in a certain user group. This due to the unique composition of every individual's physical properties.

The result from the project demonstrates a trend in increased admittance with increased weight, length, and age, while the conductance provides indications to increase in a more step-wise manner for one-year-old children. On the other hand, the variances in measured admittance are relatively small. A reason for this can be the smaller variations in body compositions presented by children within the defined 1yo group, compared to for example a group of adults with the same age difference.

Children have a growth curve (weight and length) that progresses with age. As this effect is reduced closer to maturity, the relation between admittance and age is expected to diminish accordingly. Through this, it is assumed that the admittance mainly varies as a function of weight and length.

2. *What physical variables, of the object occupying the seat, have the greatest effect on the COS system output?*

This question was posed as an attempt to more thoroughly analyse the occupants effect on the capacitive occupant sensor (COS) output. Both the question and the answer to it, are closely connected to the first question and answer.

Through the experiments, it was possible to investigate visible physical variables of the human test subjects, in relation to their measured admittance. Except the supposed relation between admittance, and weight and length, internal variables were not possible to investigate for the human test subjects. However, in the experiments were different materials were tested with controlled unit volumes and dimensions, the visible physical parameters (e.g. length and volume) could be excluded. The materials different properties and compositions, in relation to the measured admittance suggests that the internal properties for the human test subjects also play an important role in the COS-output.

To answer the question of which of the identified variables that have the greatest effect, further studies are needed. Many of the variables have unknown dependencies, leading to interactions that can not be distinguished at this stage.

3. *What properties are necessary for the CCTD to possess, to correspond to a 1yo group representative's measured admittance?*

The question's purpose is to generalise the properties of the dummy, to be material independent. The result from the project indicates that the dummy requires a combination of properties of what can be seen when looking at the human test subjects and what is measured in the material experiment.

The developed dummy presents the sought admittance, corresponding to the 1yo group representative. Through the previously answered questions, the complexity in separating the properties' contribution to the measured admittance is stated. The properties of the developed dummy, have therefore not been broken down into specific properties.

5.2 Proposed Capacitive and Conductive Test Dummy

The main objective of the master's thesis project was to develop a dummy with measured admittance values similar to the admittance values of a one-year-old child. The objective demonstrates the uniqueness of the situation; at the time the project started, no dummies with measured admittance values correlating to the values of a one-year-old child could be found. However, there are existing dummies that show admittance characteristics. When these dummies were studied, no one reached the measured admittance value of the 1yo group representative, signifying the necessity of a new Capacitive and Conductive Test Dummy (CCTD).

The CCTD Kim (see section 4.3.1) originating from the development work, fulfils the admittance expectations and will accordingly, simply by its existence, contribute as a novel dummy within the area of seat development. Except for its sheer existence, the CCTD will also contribute with more specific offerings. As seats are developed iteratively during a period of around three years, and as children grow a lot during such a period, it is not possible to achieve repeatable results with Human Test Subjects (HTS). Due to the CCTD Kim's ability to stay unchanged over a three-year period, is can be assumed that the use of the CCTD is preferred. The CCTD will also support easier handling when doing tests, as it is harder to predict how children follow test procedures. However, due to the CCTD's static appearance, the dummy will not be able to represent real-life scenarios or behaviours in the way that real humans can.

The data, upon which the dummy has been developed, will also contribute with further understanding in the area of human admittance. The gathered data will most possibly assist in trying to understand functioning principles of the COS system. It will also extend the data collection with admittance values for children, which currently seems to be lacking, possible to use in the field of occupant detection. The admittance values for children sitting directly in a car seat (without Child Restraint System (CRS)) can also enable development of the calibration method for airbag suppression.

5.3 Project Execution

The development process, followed during the thesis project, was inspired by Wheelwright and Clark. The chosen project process does not focus on the general product development activities (such as idea generation and concept development) that usually constitutes the foundation in regular product development projects. Due to the nature of the problem, as there is not a great amount of other solutions to conquer or further develop, the thesis project focused on establishing a base of understanding for the functioning principles of the desired product. Consequently, the majority of the project resources were spent on building the foundation of understanding through an empirical study.

The empirical study comprised several experiments that contributed with entirely new findings and adding insights to the development of the dummy. Each experiment (except Experiment A) was guided by the outcome from the previous ones, and thus a stepwise foundation of understanding and guidance to the dummy development could be acquired. As an empirical study aim to provide both scientific knowledge and guidance for design, the project outcome demonstrates that the empirical study suited the project well.

However, the repeatability and reproducibility, that empirical studies strive for, are areas in this thesis project that are relevant to discuss. The empirical study done in the thesis project was arranged so that it would be possible to repeat the experiments, thus the thesis project's empirical study is repeatable. It is however not possible to ensure that the measured values will be identical, independent of when a certain procedure is done. Thus the exact measured values from the empirical study are assumed to have limited reproducibility.

5.3.1 Comments on Experiment Set-up

Throughout the whole empirical study, sources of error have been strained. Differences between test results, due to variations in factors inherent in the test methods, may exist. For example, that the COS system, in similarity with all other technical equipment, may have internal disturbances that can affect the output. However, the inaccuracy due to that source of error seems to be negligible as the small variations in the gathered data, presumably can be related to more obvious factors. The presumed, two most obvious factors of variations are:

- **The children volunteering in the project**

  As is is hard to predict how small children act, the test procedures varied and had to be adapted to the certain situation. Even though a specified dress code was requested, the children were dressed in different clothes. Furthermore, the children wore diapers and the diaper’s level of contamination could not be controlled due to respect for integrity.

- **The environment in which the experiments were conducted**

  Even though one specific vehicle was used in all experiments (except for Experiment A) to minimise variations, the vehicle was situated in different locations during the tests. The different locations led to varying temperature and humidity, which might have affected the measurement output. However, the COS system is design to compensate for such variations, which imply that environmental effects on the output should be limited.

5.3.2 Comments on Analysis

It is hard to avoid analysing uncertainties, inherent in the test method. Due to that the analyses have been done on results with uncertainties, the analyses themselves will consequently possess uncertainties.

The exact measurement output, from the tests with HTS, will probably not be possible to obtain when repeating the test. It will especially not be possible to obtain the same values with the same children, that were participating in the original test, as their physiology evolve. Consequently, the result acquired and analyses made, regarding the tests with volunteering children, can not be ensured through repetition of the test. It is assumed possible to do other tests, where the output can indicate that the analyses made are reasonable.

As the measurement output is presented in discrete values, it is hard to evaluate the accuracy and variations in the values that are obtained. The limited understanding of the COS system's functioning principles and sensitivity makes it difficult when trying to understand the severity of possible variances that may hide behind the discrete output values.

5.4 Ethical Consideration

In our study, young children have participated, which requires careful consideration of ethical aspects. The young participants, can not verbally express their consent to participate in the research, and have therefore volunteered through their guardians. The guardians have obtained a consent agreement and have been informed of their right to withdraw the participation at any time. The data collected in the research are treated according to "Personuppgiftslagen" and will remain secure and confidential to the researchers. All data are presented in an anonymous manner.

Furthermore, the position used in the study is not a position that is recommended, nor encourage, for children when travelling by car. The reason for studying this position is solely to retrieve the true value for the participants' admittance instead of an admittance value affected by a CRS. The vehicle was standing still with engine turned off, throughout the whole study.

The participants' well-being was the main priority throughout the research. It has therefore been of great importance for us to have the guardians present during the whole test procedure, since they know the children and their needs the best. The participatory tests went smooth and we trust that the children have had a pleasant time throughout the research.

6 Conclusion and Future Work

In this chapter, the project is concluded and areas for future development and research are presented.

6.1 Conclusions

This project was undertaken to develop a Capacitive and Conductive Test Dummy (CCTD) and evaluate its possibility of replacing Human Test Subjects (HTS) in development of seats with integrated Capacitive Occupant Sensor (COS).

The findings, from conducted experiments, show that children within 1yo group give small variations in admittance value. It is therefore possible to establish an admittance value for a CCTD, to correspond to the majority in the 1yo group. This supports the use of the CCTD Kim (see section 4.3.1) for seat development. The findings will also serve as support for future development of CCTDs, corresponding to other user groups, and broader understanding in the area of human admittance.

A limitation of the study is that the result is only validated in relation to the vehicle X_c and seat X_s. Consequently, it has not been demonstrated if the CCTD will correspond to the 1yo group in other vehicles with other seats. Even so, the findings suggest that the admittance for the HTSs and Kim will vary accordingly.

In addition to the conclusion regarding the fulfilment of the thesis project purpose, the following aspects need to be highlighted for proper use of the CCTD:

- The human body is complex and always changing, regarding tissue distribution and electrical properties.
- No test dummy or manikin will be able to fully mimic the complexity and changeability of a human.
- Awareness of the differences in test procedures when using test dummies instead of HTSs is needed.
- Broader understanding of the COS system enhances the development of test procedures using test dummies.
- When defining occupant detection classes, it is more relevant to define user groups based on sizes rather than ages.

6.2 Future Research and Development

The project has provided insights in the need for future research in the area, but also highlighted development possibilities for the CCTD.

The electric properties of human beings constitute an interesting, yet complex field. Definition of the necessary properties, in detail, for a CCTD would benefit from further research concerning changes in electric properties for young children, linked to e.g. growth, health and activity level.

Additionally, the conducted project leave room for development possibilities for the CCTD. The most important development areas are listed below:

- To fully represent human position and behaviour, concepts for increasing the CCTD’s stability in neck and back (without affecting the admittance) could improve the functionality. Also concepts for locking arms and legs in certain positions could be developed.
- The manufacturing process, used for building the prototype of the CCTD, has limited robustness. The amount of filling material for the internal body, as well as the distribution of filling material and emptiness in the pads are difficult to accurately control. Thus, the process needs to be developed to ensure that the dummies always end up within defined tolerances.
- The durability and lifespan for the CCTD have not been investigated in this project. There is a need for ensuring exact admittance and function for the CCTD, over a three-year period, to be able to use the same dummy throughout a seat development cycle.

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Figure references

In chapter 3, icons from thenounproject.com have been used. The creators of the icons are presented below, in the same order as the icons appear in the report.

1. Logan
2. Arthur Shlain
3. RomanP
4. Anthony Bossard
5. Mikicon
6. Mungang Kim
7. Mitchell Eva

Appendix A – Experiment A

The Human Test Subjects (HTS), volunteering to participate in Experiment A, are listed below along with information regarding weight, stature and year of birth for each one.

Test person #	*Weight (kg)*	*Stature (cm)*	*Year of birth*
TP1	34	140	2006
TP2	27.5	129	2008
TP4	37.9	145	2006
TP5	31.4	150	2005
TP6	50.6	147	1980
TP7	28	133	2008
TP8	30	127	2009
TP17	34.4	146	2006
TP18	23.8	130	2009
TP20	25.7	130	2010
TP21	37.6	146	2003
TP22	28.6	134	2009
TP23	46.1	161	2006
TP24	34	140	2007
TP25	48.5	166.5	2004
TP26	30.2	140	2007
TP27	42.6	152	1974
TP28	52.7	165	2003
TP29	47.1	159	2005
TP30	49.2	155	2005

16 positions are tested in Experiment A, which are defined in the table below.

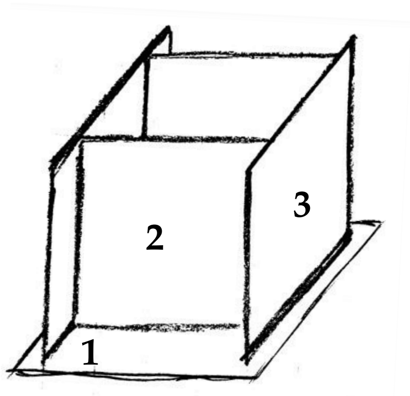
Seat position	Seating position	Explanation
Design	A	Normal sitting position
Design	A-BL	Normal sitting position on MDF (wood board)
Design	A-R30R	Rotated knees to the right
Design	A-R30L	Rotated knees to the left
Design	ALIQ3	Normal sitting position with 3 L liquid in lap
Design	D5	Feet on Seat (Feet close to buttocks)
Design	D4	Legs crossed on seat
Design	XFTAIR	Normal sitting position with feet not touching ground
Design	XFTUP	Feet on Cockpit
Design	XTOUCHW	One hand touch car door through window
Design	A-SL100	Slouch (Normal position +100mm)
Design	A-SL200	Slouch (Normal position +200mm)
Design	A-OUTMAXR	Normal sitting position to the right of the centreline (against the door)
Design	A-OUTMAXL	Normal sitting position to the left of the centreline (against the centre console)
Design	XFREE	Any preferable position
Design with reclined backrest	A-RECMAX	Backrest max reclined, normal sitting posture

Appendix B – Experiment B

The two containers used in the test are made in Polypropylene, with the following inner dimensions:

1. 344x180x280 mm
2. 344x270x280 mm

The shape of the containers is illustrated in the figure.



BOM – Container 1

	Quantity	Dimensions
1 - Bottom plate	1	370 mm x 190 mm
2 - Side plate	2	360 mm x 280 mm
3 - Side plate	2	180 mm x 280 mm

BOM – Container 2

	Quantity	Dimensions
1 - Bottom plate	1	370 mm x 280 mm
2 - Side plate	2	360 mm x 280 mm
3 - Side plate	2	270 mm x 280 mm

The raw data from the two DOE runs are presented below. Water was taken from taps in Torslanda, Gothenburg. In the first run, tap water was taken from tap A and in the second run, tap water was taken from tab B.

Tap Water A		A	B	AxB	Y – Capacitance [nf]
Run1	HH	+	+	+	21287,6
Run2	LH	-	+	-	19046,8
Run3	LL	-	-	+	15685,6
Run4	HL	+	-	-	16806,0
Estimated effects		1680,6	3921,4	560,2	
				Mean	18206,5

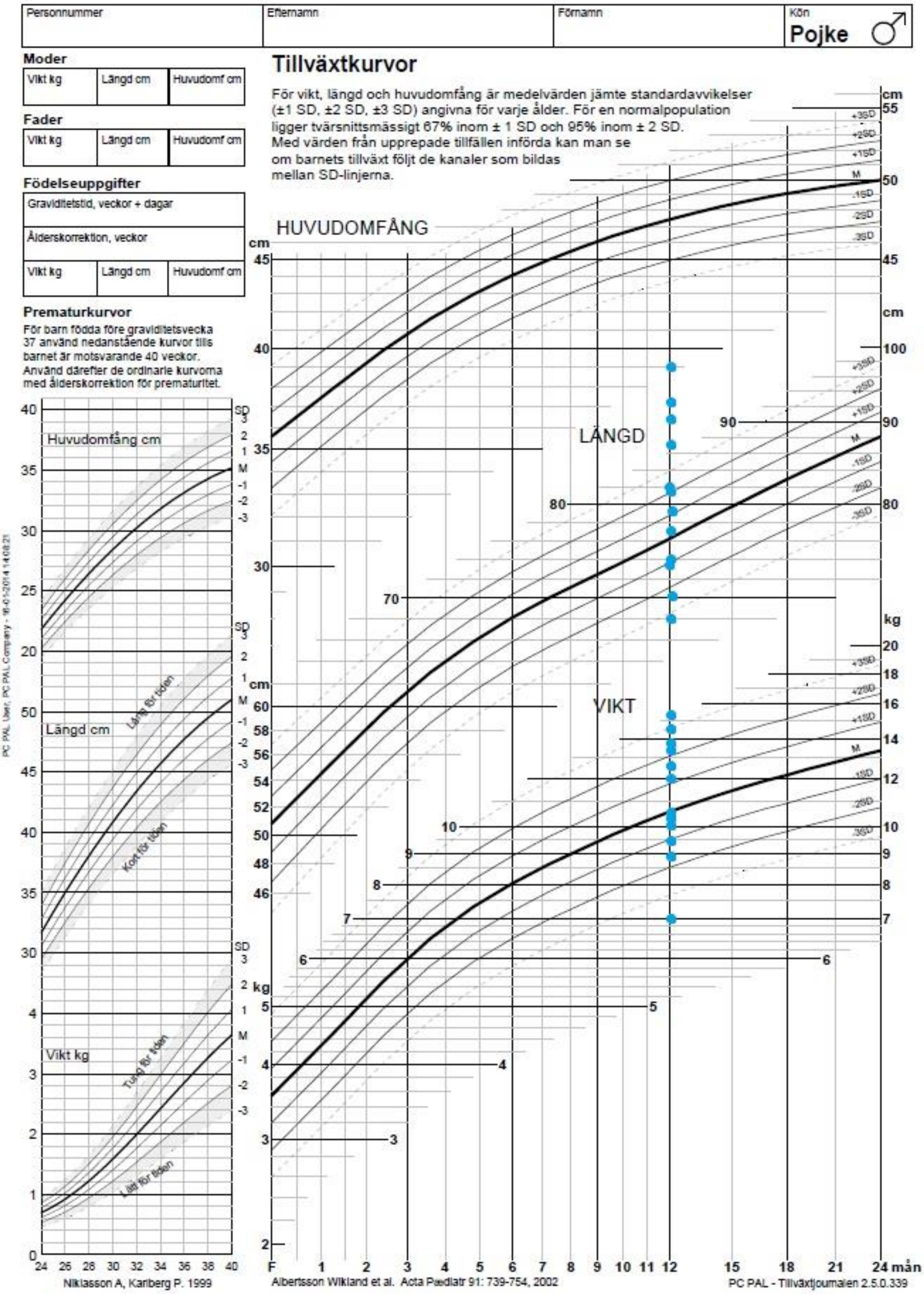
Tap Water B		A	B	AxB	Y – Capacitance [nf]
Run5	LH	-	+	-	19046,8
Run6	LL	-	-	+	15685,6
Run7	HH	+	+	+	21287,6
Run8	HL	+	-	-	16806,0
Estimated effects		1680,6	3921,4	560,2	
				Mean	18206,5

Appendix C – Experiment C

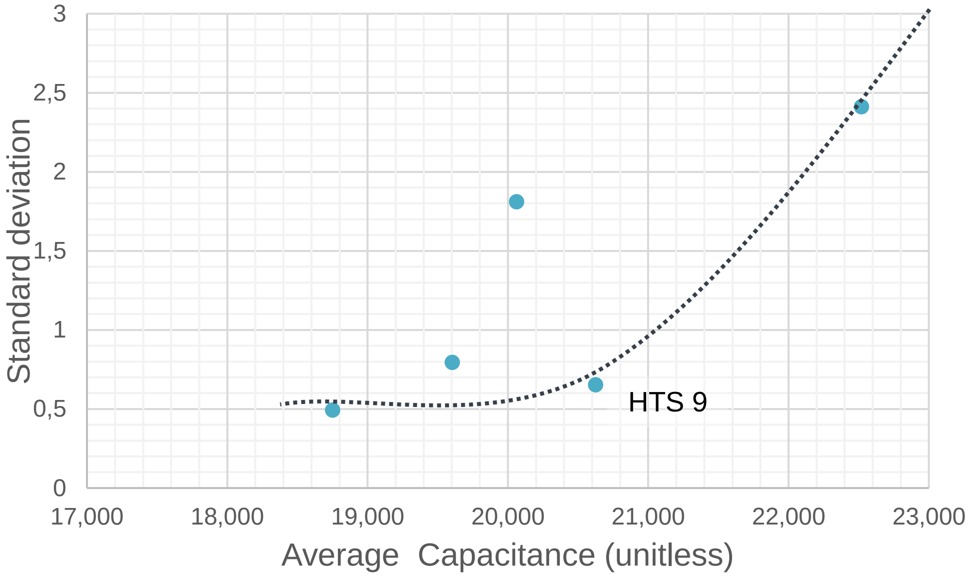
The Human Test Subjects (HTS) that participated in experiment C are listed below.

Test person #	Age	Length [cm]	Weight [kg]	Clothes
HTS 1	10 months	77	10,3	Thin sweater and short winter jacket, jeans and thin baby shoes
HTS 2	8 months	74	8,9	Thin sweater and short jacket, cotton pants, socks and hat
HTS 3	2,5 years	93	13,4	Thin cotton pants and sweater. Fleece trousers and jacket. Hat and winter shoes.
HTS 4	1,5 years	82	12	Jeans, sneakers, thin sweater and fleece jacket, thin hat
HTS 5	2,5 years	97	15,3	Jeans, cotton sweater, rain jacket, winter shoes and thin hat
HTS 6	2,5 years	91	14,7	Jeans and thin cotton sweater, socks
HTS 7	1,5 years	87	13,6	Jeans, socks, thin sweater and hoodie
HTS 8	6 months	68	9,5	Cotton-body, hoddie, thin baby shoes and thin hat
HTS 9	1,3 years	79	12,5	Cotton pants, sweater and a hoodie, cotton hat, socks
HTS 10	1,5 years	82	10,6	Cotton pants, sweater and hoodie. Socks
HTS 11	1 year	74	10,1	Cotton pants and sweater. Spring jacket, thin hat, socks
HTS 12	6 months	70	7	Cotton pants and sweater. Socks

The distribution for the HTSs on the one-year-old growth chart (based on previous list for weight and height), is marked in the chart below.



The trade-off curve show the standard deviation and average capacitance measured for the five HTSs that are closest to an average one-year-old for age, weight and length.



Appendix D – Experiment D

The materials tested in Experiment D is specified in the table below.

Material	*Origin*		*Specification*
Tap water A	Water from tap A	The drinking water in Gothenburg origins from Göta Älv and Delsjöarna. For water spec. and values see **[1]**	5,8 L tap water
Tap water B	Water from tab B		5,8 L tap water
Salt water A	Salt with iodine Water from tap A		5,8 L salt water - Salt concentration: 1 dl salt in 10L water
Salt water B	Salt with iodine Water from tap A		5,8 L salt water - Salt concentration: 2 dl salt in 10L water
Salt water C	Salt with iodine Water from tap A		5,8 L salt water - Salt concentration: 4 dl salt in 10L water
Salt water D	Salt with iodine Water from tap A		5,8 L salt water - Salt concentration: 6,5 dl salt in 10L water
Balistic gel	Gelatine powder of animal origin (pig) Water from tap C Rapeseed oil		Plastic box (8 L) used as mould Mix - 9 jars (á 65g) gelatine for 5 litre of water --> total volume of around 5,8 L
Peas	Dried yellow peas (Swedish origin)		5 kg, 5,8 L
Sand	Natural sand		7 kg, 5,8 L
Gravel	Macadam 2/5mm		8.5 kg, 5,8 L
Aluminium shavings	Shavings from aluminium milling machine at VCC		2 kg, 5,8 L
Clay shavings	Shavings from clay milling machine at VCC		2,8 kg, 5,8 L

[1] http://goteborg.se/wps/portal/start/vatten-och-avlopp/dricksvatten/dricksvattnets-kvalitet/!ut/p/z1/hY7BCoJAGISfxuv-_6q42s0ORippEGh7CY1tFdSVdWuhp8-OQdHchvmGGeBQA5-aRy8b06upGVZ_5sGlpOkx3NIYi12U4P6Ulckhywu_oFD9A_ga4w_FCCnwvh2JvY4EicfcgPmU-RFjYeCy93w8tV4ogWtxE1poctfrq86Yedk46KC1lkil5CDIIhz81ujUYqD-AGEe62cuqvgFWdnBdw!!/dz/d5/L2dBISEvZ0FBIS9nQSEh/

Compiled data for the material test is presented in table below.

	Capacitance [nF]	*Conductance [kS]*
Tap A	15685,6	732,1268
Tap B	16806	732,1268
Salt water A	16806	732,1268
salt water B	16806	732,1268
Salt water C	16806	732,1268
Salt water D	16806	732,1268
Alu shavings	14565,2	0
Clay shavings	11204	0
Peas	13444,8	0
Gravel	14565,2	0
Sand	15685,6	732,1268
Gelatin	16806	732,1268

For the test of different water volumes, container 1 in the figure to the left (specified in appendix B) was used. The container was placed in the middle of the seat and filled with one up to twelve litres of water (increasing with one litre per run → 12 runs). One sit-in á 10 snapshots were taken for each volume. The water origin from tap A.

Compiled data for the different volumes of tap water are presented in table below.

Amount [l]	*Capacitance [nF]*	*Conductance [kS]*
1	12324,4	0,0
2	13444,8	0,0
3	14565,2	0,0
4	14565,2	0,0
5	15685,6	732,1
6	16806	1464,3
7	16806	1464,3
8	17926,4	732,1
9	17926,4	1464,3
10	19046,8	1464,3
11	19046,8	1464,3
12	20167,2	1464,3

For the test with different water and mixtures of water, the plastic box in the figure to the left was used. The container was placed in the middle of the seat and filled with eight litres of the different water types and mixtures. Three sit-ins á 10 snapshots were taken for each run. The water tested are presented in the next table.

Type	*Tap water*	*Tap water with salt*	*Distilled water*	*Tap water with SAP*
Amount	8l	8l + 1dl salt	8l	8l + 48g SAP

Compiled data for different types of water and mixtures are presented in table below.

	Capacitance [nF]	*Conductance [kS]*
Tap water	19046,8	732,1
Tap water + salt	19046,8	732,1
Distilled water	17926,4	732,1
Tap water + SAP	19046,8	732,1

Appendix E – Experiment E

Existing dummies tested in Experiment E

Alu-dummy Weight: 11 kg Length: 72 cm	**CRABI 12-month dummy** Weight: 11 kg Length: 72 cm	**Rescue dummy with water** Weight: 5.3 kg Length: 62 cm

Physical prototypes tried in Experiment E

The seven concepts derived from the combination table are represented by the following physical prototypes.

Peasy/Sandy/Paval/Gelis: Represented by a pyjamas filled with peas/sand/water/gel.

Gelbert: Represented by a big cotton cylinder, internally coated with silicone and filled with gel.

Silva: Represented by a silicone ball, filled with water.

Data table from Experiment E

	Capacitance [nF]	*Conductance [kS]*
Alu-dummy	19046.8	732.1
CRABI 12 mo	13444.8	0.0
Rescue Dummy w. water	17926.4	732.1
Peasy	14565.2	0.0
Sandy	12324.4	0.0
Paval	21287.6	1464.3
Gelis	21287.6	1464.3
Gelbert	19046.8	732.1
Silva	14565.2	0.0

Appendix F – Experiment F

Child Restraint System (CRS)

The Volvo Car CRS used in Experiment F, was installed in the front passenger car seat according to instructions.

Dummy Kim was placed in the CRS according to the picture below.

Pictures of the different positions used in Experiment F

To investigate how the admittance would vary when changing position for dummy Kim, four different positions were tested, shown below. The left pictures show the positions as seen from the front, while the right pictures show them as seen from the side.

1. **Normal position**

2. **Turned position**

3. Slouching position

4. Forward-leaning position

Appendix G – Concepts

List of generated subsolutions (internal dummy body materials and dummy body cover alternatives). Eliminated subsolutions are presented together with motivation for elimination and description of when the elimination was done.

	Unfeasible	Limited availability	High cost	Elimination phase	Comment
Internal body					
Tap water					
Distilled water					
Salt water					
Animal Blood		×			Unethical efforts to access
Gel dummy - gelatine base	×			Refinement	Good capacitive values but rottens --> Synthetic gel base
Water-absorbing pearls		×	×	Before testing	Consumables --> expensive
Wood shavings	×			Before testing	Low permittivity constant
Wood piece	×			Before testing	Difficult to shape, not an appropriate representation of a human
Wood pieces	×			Before testing	Low permittivity constant
Wood MDF	×			Experiment A	Isolating properties found in experiment A
Styrofoam	×			Before testing	Low conductivity/permittivity constant
Plastic chips	×			Before testing	Low conductivity/permittivity constant
Plastic piece	×			Before testing	Low conductivity/permittivity constant
Rubber	×			Before testing	Low conductivity/permittivity constant
Rubber foam	×			Before testing	Low conductivity/permittivity constant
Metal shavings	×			Experiment D	Low conductivity/permittivity constant
Metal piece	×			Before testing	Metal shavings acted as representative for the material group
Magnetic powder		×		Before testing	Metal shavings acted as representative for the material group
Gravel	×			Experiment D	Low capacitance value
Sand					
Kinetic sand (silicon oil mixed sand - kids toy)			×	Before testing	Sand acted as representative
Clay	×			Experiment D	Low capacitance value
Rice	×			Before testing	Dried peas acted as representative for the material group
Dried Peas	×			Experiment E	Low capacitive value, food

Grains	×			Before testing	Dried peas acted as representative for the material group
Sugar	×			Before testing	Low conductivity/permittivity constant
Toothpaste			×	Before testing	Big amount is needed to fill the dummy
Gel			×	Before testing	Big amount is needed to fill the dummy
Slime		×		Before testing	
Foam (watery bubbles)	×			Before testing	Collapses with time
Towels	×			Before testing	Low conductivity/permittivity constant
Feathers	×			Before testing	Low conductivity/permittivity constant
Fur	×			Before testing	Low conductivity/permittivity constant
Leather	×			Experiment A	Low conductivity/permittivity constant
Body cover					
Plastic shape welded together	×			Experiment D	High isolating properties
Silicone mould					
Non-waterproof textile					
Touch-glove textile					
Waterproof coated textile					
Waterproof textile with sealed seams					
--> Dry suite					
Silicone moulds with basic forms sewed in to textile body					
Plastic bags sewed in to textile body					
--> Balloons sewed in to textile body					
Plastic shells sewed in to textile body	×			Before testing	High isolating properties, similar to plastic shape welded together
Glass cylinders sewed in to textile body	×	×		Before testing	Fragile
Bucket	×			Before testing	Not the shape of a human
Sponge	×			Before testing	Difficult to keep cheap and to light (not appropriate representation of human

Appendix H – Product Specification

Chalmers

Requirements Specification **Created: 2017-05-16**

Project:
Capacitive and Conductive Test Dummy R=Requirements F=Fulfilled

Issuer: Cornelia Andersson D=Desires N=Not fulfilled

Ida Olsson I=Investigation needed

Function
Capacitive and Conductive Test Dummy

Criteria		***Target value***	***R/D***	***Prototype Fulfilment***
1. Performance				
1.1	Hip/leg movement	2 Degree of Freedom - Rotation	R	F
1.2	Knee movement	1 Degree of Freedom - Bending	D	F
1.3	Shoulder movement	2 Degree of Freedom - Rotation	R	F
1.4	Elbow movement	1 Degree of Freedom - Bending	D	F
1.5	Posture locking	Knee locking	D	N
		Hip locking	D	N
		Shoulder locking	D	N
		Elbow locking	D	N
1.6	Positioning	Sitting with straight legs	R	F
		Sitting with bent legs	R	N
1.7	Capacitive performance* *Measure directly on "Seat Xs" in "Car Xc" in normal sitting position	>80% of snapshots at 23528.4 nF(ADC 21) +/- 732.1 nF (ADC 1)	R	F
1.8	Conductive performance** **Measure directly on "Seat Xs" in "Car Xc" in normal sitting position	>80% of snapshots at 1464.3 kS (ADC 2)	R	F
1.9	Functionality in vehicle temperature variations -20°C-75°C	100% functionality	R	I
1. Design				
2.1	Coarse human one-year-old proportions	80% recognition	R	I
2.2	Full length	75 cm +/- 5 cm	R	F
2.3	Sitting height	47 cm +/- 2 cm	D	F
2.4	Hip breadth	18 cm +/- 2 cm	D	F
2.5	Waist circumference	48 cm +/- 2 cm	D	N
2.6	Weight	9.5 kg +/- 1.5 kg	R	F

3. Material				
3.1	Recyclable material (incl. energy recovery)	≥95 % of product	R	F
3.2	Recyclable material (incl. energy recovery)	≥99 % of product	D	F
3.3	Reusable material	≥10 % of product	D	F
3.4	No Poisonous Materials	100% approved materials	R	F
3.5	No Environmentally Hazardous Materials	100% approved materials	R	F
3.6	Dirt (household and road dust) resistant	Regain 80% of "original" appearance through the use of a damp cloth	R	I
3.7	Sustain temperature variation	0°C-40°C	R	I
3.8	Sustain moisture	100% functionality	R	I
3.9	Internal dummy body resistance	300 Ohm	D	I
3.10	Dummy body cover resistance	100000 Ohm	D	I
4. Durability				
4.1	Life Span, In normal** use **Gentle handling of dummy	750 hours	R	I
4.2	Life Span, Passive*** ***Laying position	27000 hours	R	I
4.3	Sustain five falls from 120 cm height	100% functionality	R	I
5. Manufacturing and Maintenance				
5.1	Mean time to produce**** ****Fist time production	40 hours active production	R	F
5.2	Mean time to repair	1 hour active repair	R	F
6. Cost				
6.1	Purchase price	7000 SEK	R	I