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Digital tools for developing customized co-design platform with integration of comfort and fashion

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Digital tools for developing customized co-design platform with integration of comfort and fashion.

Abstract

Textile is a sector where quality is one of the key competitive factors. The quality of finished garment products received by a customer is a result of interconnected phases in the manufacturing processes. As one of the crucial steps, design process determines the future fit of a garment. Therefore, due to the increasing purchasing power in an online environment, the garment industry has to make much effort to improve the technological solutions in this aspect.

However, despite modern technological progresses, the apparel industry is still anchored in the traditional 2D-to-3D design approach. Furthermore, the fundamental issue of consumers’ body recognition in an online environment has still not been appropriately resolved. Moreover, a relevant garment design is generally realized by using numerous repetitive adjustments based on an initial prototype, which takes considerable time and heavy overall cost.

The aspects of the relation between human body and garment are not sufficiently explored in order to provide satisfactory performance of virtual try-on in the aspects of providing not only right fit and comfort to the customer but also avoiding returns to the retailer.

In my PhD research, we challenge those gaps by proposing a foundation of a digital and knowledge-based platform for garment design and fit and comfort evaluation by integrating customers' and experts’ knowledge with the design parameters. By building a new 3D design strategy, we proposed an original method to calculate and adjust the 3D ease allowance values, which constitutes the key issues of satisfaction perception. Our 3D design method is linked to the consumer’s virtual representation, which come from a new pattern recognition method permitting to identify individual morphology from a single web-camera. It was experimentally shown that using the supervised method to create 2D shape descriptors enables to detect wearers’ morphotypes for a target population.

The complex relationship between wearers’ body recognition, 3D garment design and garment fitting in virtual try-on has been tested and analyzed in the scope of this research project to build a suitable design solution applied to the remote environment.

For this purpose, we presented the principles of garment modelling directly fitted to the wearer's morphology to cover the full range of body shapes and measurements.

One important issue in our approach is to set up an appropriate relationship between virtual and real design environments so that the designer can freely make use the advantages of each side in different scenarios.

Through the goods and services, producers can build the value of their products which is increasing the active life of clothing and thus contributes to the sustainable development strategy.

Keywords: Morphology pattern recognition, virtual garment modelling, 3D Prototyping, online retail, garment fit and wearer's comfort, interaction between real and virtual design environments, ease allowance, fuzzy models.

French

Résumé

Le textile-habillement est un secteur où la qualité du produit fini est l'un des principaux facteurs de compétitivité. Cette qualité est le résultat de différentes phases de conception et de fabrication interconnectées dans lesquelles intervient l'ajustement du vêtement qui est considéré comme une étape cruciale dans le processus de validation. De plus, en raison de l'augmentation du pouvoir d'achat dans un environnement en ligne, ce secteur doit aussi faire de nombreux efforts pour améliorer les solutions technologiques dans ce domaine lié à la vente par internet.

Cependant, malgré les progrès technologiques modernes, l'industrie du vêtement est toujours ancrée dans une approche traditionnelle de conception numérique en 2D, éventuellement en 3D lors d'essayage virtuel. La question fondamentale de l'accessibilité aux données morphologiques du corps du consommateur dans un environnement en ligne n'a toujours pas été résolue de manière appropriée. La validation des vêtements est toujours ralentie par de nombreux ajustements répétitifs basés sur un prototype initial, ce qui engendre un coût global élevé.

L'interactivité et le relationnel entre le corps humain et le vêtement ne sont pas suffisamment explorés pour atteindre une performance satisfaisante lors de l'essayage du vêtement dans cet environnement virtuel en ligne. Sous certaines conditions, un essayage virtuel 3D du produit sur le consommateur pourrait non seulement conduire au bon ajustement du vêtement sur son corps, mais aussi à un confort nettement amélioré, ce qui éviterait les retours clients.

Mes travaux de recherche ont donc pour objectif de combler ces lacunes en proposant une plate-forme numérique intégrant à la fois la connaissance des experts du secteur de l'habillement lors de l'évaluation des produits (ajustement et confort), et les retours sensoriels des clients lors du porté de ces mêmes produits.

Sur cette plate-forme, une nouvelle stratégie de conception de vêtement en 3D a été mise en place afin de calculer et d'ajuster les valeurs de l'aisance 3D de celui-ci, lesquelles représentent les points clefs lors de la perception et la satisfaction du produit par le client. Pour cela, nous avons utilisé une représentation virtuelle du consommateur dont la morphologie a été reconstruite à partir de ses images 2D frontale et sagittale issues d'une caméra web, suivi d'une phase de reconnaissance de forme parmi une population scannée en

3D. C'est à partir d'une méthode de classification supervisée associée à un descripteur de forme 2D que nous avons retrouvé le morphotype du client. Cette étape a permis de l'assimiler à l'un des morphotypes adaptifs issus de la population classée et de créer finalement son avatar en lui affectant sa propre stature.

Cette relation complexe entre la reconnaissance morphologique du corps du porteur, la conception et l'ajustement du vêtement en 3D lors d'un essayage virtuel, a été testée et analysée dans le cadre de ce projet pour bâtir une solution de conception adaptée à un environnement à distance.

À cette fin, nous avons présenté les principes de la modélisation du vêtement directement adaptés à la morphologie du porteur afin de couvrir toute la gamme de formes et de mesures corporelles.

Une question importante dans notre approche est de mettre en place une relation appropriée entre les environnements de conception virtuels et réels afin que le concepteur puisse utiliser librement les avantages de chacun dans différents scénarios. Grâce aux biens et services, les producteurs peuvent valoriser leurs produits car ce concept permet d'augmenter la durée de vie des vêtements et contribue ainsi à la stratégie de développement durable.

Mots clés: Reconnaissance de formes morphologiques, modélisation de vêtements virtuels, prototypage 3D, e-commerce, ajustement et confort d'un vêtement au porté, interaction entre les environnements de conception réels et virtuels, aisance d'un vêtement, modèles flous.

Swedish

Sammanfattning

Textil är en sektor där kvalitet är en av de viktigaste konkurrensfaktorerna. Kvaliteten på färdiga plaggprodukter som en kund erhåller är ett resultat av sammankopplade faser i tillverkningsprocesserna. Som ett av de avgörande stegen bestämmer designprocessen framtida passform av ett plagg. På grund av den ökande köpkraften i en onlinemiljö måste klädindustrin därför göra mycket för att förbättra de tekniska lösningarna i denna aspekt.

Trots moderna tekniska framsteg är klädindustrin dock fortfarande förankrad i den traditionella 2D-till-3D-designmetoden. Dessutom har den grundläggande frågan om konsumenters kroppsdetektering i en onlinemiljö fortfarande inte lösts på ett lämpligt sätt. Vidare realiseras en relevant plaggdesign genom att använda flera upprepade justeringar baserade på en initial prototyp, vilket tar lång tid och är väldigt dyrt.

Aspekterna av förhållandet mellan människokroppen och plagget undersöks inte tillräckligt för att ge tillfredsställande prestanda i virtuella provningar med hänsyn till att tillhandahålla inte bara rätt passform och komfort för kunden utan också att undvika returer till återförsäljaren.

I min doktorsforskning utmanar jag dessa luckor genom att föreslå grunden för en digital och kunskapsbaserad plattform för plaggdesign, anpassning och komfortbedömning genom att integrera kunders och experters kunskaper med designparametrarna. Genom att bygga en ny 3D-designstrategi föreslog jag en originell metod för att beräkna och justera 3D-ease-allowance-värdena, vilket utgör den viktigaste faktorn för tillfredsställelse. Vår 3D-designmetod är kopplad till konsumentens virtuella representation som kommer från en ny mönster-igenkänningsmetod som möjliggör identifiering av individuell morfologi från en enda webbkamera. Det visades experimentellt att användandet av den över-vakade metoden för att skapa 2D-formdeskriptorer möjliggör detektering av bärarens morfotyper för en målpopulation.

Det komplicerade förhållandet mellan bärarens kroppsigenkänning, 3D-plagg-design och plaggmontering i virtuell provning har testats och analyserats inom ramen för detta forskningsprojekt för att bygga en lämplig designlösning som tillämpas i onlinemiljön. För detta ändamål presenterade vi principerna för plaggmodellering direkt anpassad till bärarens morfologi för att täcka hela sortimentet av kroppsformer och mätningar.

En viktig fråga i vårt tillvägagångssätt är att skapa ett lämpligt förhållande mellan virtuella och verkliga designmiljöer så att konstruktören fritt kan utnyttja fördelarna med varje sida i olika scenarier. Genom varor och tjänster kan producenterna bygga upp värdet av sina produkter vilket ökar det aktiva livet för kläder och bidrar därmed till strategin för hållbar utveckling.

Nyckelord: Morfologimönsterigenkänning, virtuell plaggmodellering, 3D-prototyper, online-detaljhandel, garment fit och bärarens komfort, interaktion mellan verkliga och virtuella designmiljöer, ease allowance, fuzzy-modeller

Chinese

用数字工具开发融入舒适和时尚的个性化联合设计平台

摘要

在纺织领域，质量因素是具有竞争性的关键问题之一。实际上，顾客所得到的最终服装产品是直至流程不同阶段相互作用的结果。设计流程作为一个关键步骤，决定着所设计服装的合身度，因此，在在线服装购买不断增强的背景下，服装工业必须下大力量改善远程设计技术。

然而，尽管由于现代技术进步，服装工业仍处于传统的两维到三维的设计流程中。另外，在远程设计中，消费者的体型识别的基础问题还并没有得到解决。还有，在传统设计中，一个合适的服装设计是由对基础款式进行一系列调整而实现的，这需要花大量时间和高昂费用。

当前，人体和服装的关系并没有充分发掘，深入研究二者关系，可以提供顾客在舒适度和合身度上满意的虚拟试穿效果，同时避免向商家退货。

在我的博士研究中，我们尝试着通过建立融合顾客和专家设计知识的服装设计流程以及合身度及舒适度评估的数字知识平台，来解决以上问题。通过建立新的三维设计策略，我们开发出一个新的方法，以计算和调整三维的宽松量，来满足服装的满意度。我们的三维设计方法是和消费者的虚拟人体展示密切相连的，为此，我们开发出新的模式识别方法，以通过单独的摄像头识别人体体型。通过实验，我们已经证实了，使用可监督学习的方法建立的二维形状描述因子，可以检验人体的体型。

穿衣者的人体识别、三维服装设计和在虚拟环境中的服装试衣各因素复杂关系已经在本研究项目中得到了检验和分析，这些结果将有利于在远程环境下找到合适的设计方案。

因此，在本论文内，我们介绍了服装建模的新方法，该方法直接把服装模型试穿在人体模型上，可以包含所有人体的体型和测量。

本论文一个关键问题是对虚拟和实际的设计环境二者关系建立合适的关系模型，使得设计师可以在各种场景里充分地、自由地利用不同环境的优势，以达到其需求。

通过产品和服务，生产者可建立他们自己的产品价值，使得服装的生命价值进一步增强，以建立相关的产业可持续发展战略。

关键词：人体模式人别，虚拟服装建模，三维服装设计，在线营销，服装合身度和舒适度，实际和虚拟设计环境交互，宽松量，模糊模型

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LIST OF ABBREVIATION

2D——two Dimensional

3D——three Dimensional

GENERAL INTRODUCTION

Garments constitute an extension of human body shape and an expression of what we identify with. Despite, that clothing is an important part of everyone daily life, customers are constantly complaining about the lack of availability of clothing sizes. The satisfaction level is equal to the return rates and this in turns constitutes about the revenues of the companies. Research that has been carried out on return rates in online environments suggests that garment fit (too small, too large or general wearing dissatisfaction) represents 52% of total returns. It follows that the ill-fit is the main reason of returns rates generated by the individual consumer. Remembering that, the fit is strongly related to the body dimensions and perception of the individual consumer, the concept of products customization is growing in importance. The way of accomplishing these challenges have to be controlled by producers by improving the digital manufacturing technology.

It has led to the development of new CAD software, hardware and other applications supported by the aid of new techniques including 3D body scanning, 3D human modeling and 3D garment design for the fashion e-commerce.

Despite the emergence of many new technological solutions, the fundamental issue of consumers' body recognition in an online environment has still not been resolved properly. The aspects of relation between body and garment are not sufficiently explored to provide satisfactory performance of virtual try-on both for customer to provide right fit and for retailers to avoid returns.

In my PhD project, we aim to build a foundation for a digital knowledge-based platform, which integrates the wearer's profile by means of novel approach in use of technological solution and systems. We take into consideration a spectrum of services; like wearers' body recognition, 3D garment design and garment fitting in virtual try-on. To support the virtual try-on process we propose a recommendation system for predicting 3D ease allowance. This study can be considered as a new methodological concept accessible to any user who aims to acquire 3D personalized clothing adapted to the digital manufacturing technology. In this regards, our project is focused on personalization and fit into the mass customization scenario.

As first, we proposed a new pattern recognition method to identify individual consumer morphology with a single web-camera. This method enables to quantify the size and shape of measured customer and assign these quantities in order to find the most relevant one in a predefined database of representative 3D morphotypes by comparing the corresponding pictures from anterior and lateral view. Concretely, each picture is processed by a 2D shape descriptor to link with the database of 3D morphotypes. The presence or absence of certain characteristics is computed and, using a similarity coefficient, the classification is completed. The complex relation between consumer's body measurements and 3D morphotype result in creation of a representative consumer model for the purpose of virtual try-on.

Secondly, we focus on 3D garment creation with relation of virtual try-on. Virtual try-on is a relation between consumer body virtual representation, three-dimensional (3D) garment and fabric specification. To avoid morphological interpretation errors we work directly on the 3D wearer's morphology. We set up 3D wire frame model of the garment which is connected to the wearer by its morphological contours and anthropometric points, explained in the Chapter 4. Moreover, in the scope of this work we have examined a method of gradation of the spatial distance between a body surface and a garment in real and virtual try-on used for determining the value of 3D ease allowance in respect to the good fit.

As a third step in my research, we analyze the garment well-being, in particular the value of 3D ease allowance. 3D ease allowance together with other design parameters, like body measurement or fabric mechanical properties, stands for well-being and constitutes the fitting of a garment.

The modeling procedure used at this stage was in coincidence with that used in the techniques of artificial intelligence. Especially, the fuzzy set theory had a fundamental role in modeling of the process. The data were derived from the sensory evaluation of experts and wearers. The imperfect semantic information appearing in such database was connected to the comfort and fit conditions. The human knowledge is prone to ambiguity and external stimuli and as such is unstable, imprecise and in often incomplete due to the lack of sufficient or more precise knowledge. For such semantic data it is impossible to define sharp or precise borders. To overcome this problem, we have worked out a data-based modeling approach. A series of models have been set up to characterize the relationship between garment design parameters (fabric properties, garment styles), wearers' morphologies and postures, as well as ease allowance values. Mastering this relationship is significant in the context of 3D design. The objective is to control and adjust the garment patterns according to designer's and consumer's perceptions. Our model can be taken as part of a garment design recommendation system for e-commerce, where the individual clients can create their personalized avatar and manage comfort zones in the garment design process.

Summarizing my PhD project, covers the three main parts as follows:

1. To recognize a consumer's morphology by using a supervised classification methodology and image processing procedures.

2. To develop a personalized 3D garment creation process in context of 3D ease allowance controlling.

3. To control and optimize the relationship of garment well-being and concerned design elements by exploring sensory evaluation data.

The overall layout of the thesis is organized as follows:

CHAPTER 1 State of the art, give a comprehensive picture on the broad phenomenon as is the 3D process of garment creation in remote environment. The state of the art on human body analysis and its representation in virtual environment are presented. Next the examples of traditional and digital garment modeling processes with the ease allowance phenomenon are outline to familiarize the reader with the research area. As the next, the garment fit evaluation tools and methods are presented. The end of Chapter1 placed the virtual prototyping in concept of mass customization.

CHAPTER 2, Tools used in the research, introduce the various scientific and technological tools used for acquire the morphological data and used in the process of 3D garment design. Moreover, computation tools for formalizing and modeling used in sensory evaluation are described.

CHAPTER 3, Modeling the human body, outline the processes for the pattern recognition of morphology. First, the general analysis of the human body morphology and five wearers are presented. Next, the pattern recognition methodology of individual in remote environment is deeply investigated.

CHAPTER 4, Process of garment creation, present the new 3D creation process of the garment.

CHAPTER 5, Acquisition of sensory data and modelling, describe the concept, modeling process and application of sensory evaluation and design parameters. The two Models are developed, by using fuzzy techniques, to elaborate the learning model of 3D ease allowance in remote environment

CHAPTER I: STATE OF THE ART

In this chapter, we review a state of the art various research works that have helped to advance the world of clothing. It is not possible to achieve this goal without a thorough analysis of the human body and the modeling of it to consider a new process of creating an entirely digital garment. The human body has always been by far one of the most intriguing and explored topics from ages past to the present day. In this process, the modeling of the garment is also very important. The major difficulty is that if we want to use it for e-commerce or mass customization, the digital model must be developed in a 3D environment like the human model. Among other things, these models must be closely related by a dimensional and relational interface defining a spatial distance requires the development of a specific model affecting the comfort aspect of the garment. This model called the ease allowance model must be defined in a 3D space because it represents the gap between the garment and the human body over the whole body. Since comfort requires a feedback on the well-being of the garment by the wearer, sensory analysis is also at the core of this study. One of the difficulties the profession is facing today is how to analyze the 3D fit of a garment on a human avatar in this 3D digital environment.

These different needs to change the world of clothing in developing a new 3D digital process will therefore be presented from existing work.

I.1. HUMAN BODY ANALYSIS

The depiction of a human body has its origins in ancient sculpture. By adopting natural forms to a mathematical system of the golden ratio, the artists have created the concept of a beautiful body which continues to this days (**Figure 1)** [1].

This perspective shapes the way how people look at themselves and others. In this context, the imagination of people's ideal symmetry and proportion continue to influence today's fashion. However, never two people are alike in all their measurable morphological characteristics. Seen from this angle, the beauty canons are an attempt to classify and unification the structure of the human body. One could say it is a certain simplification in the perception of a man. This approach is used by the apparel industry to manage their products for a large group of people.

The starting point to create matching and comfortable clothing is to learn the specifics of the structure of the human body. Introducing some essential notions related to human morphology classification is necessary. For that, it is vital to know techniques of acquisition the body measurements and shapes. We can demarcate two general techniques, traditional and automatic, which is the contribution of new technology like 3D scanning or image capturing.

Figure 2: Concept of beauty by Loomis.

Another point concerns the way how the human body is represented nowadays. The changing dynamics in lifestyle and demographic patterns generates the new consumer needs and as a reply creates the innovative approaches of designers. They have to answer on the growing demand for proper fit and well-adapted size, and faster changes in fashion trends which is driven by strengthening of media, like the Internet and the Internet of Things. Also, the very fact of computer and software technology is not without significance. Above mentioned factors have high impacts on the product's presentation and give tools to mimic the real world' sale experience. One of the angles is to achieving realism in a virtual environment. For the apparel industry, the mean to achieve it is by virtual try-on and the human body modeling. Initially, first virtual body representation was made for the purpose of effective visualization in computer graphic [2] to reflect the beautiful body in an artificial environment. In the area of motion control, garment and body deformation CAD software made substantial progress. Nowadays, the virtual body representation is used in textile, automotive, medicine and sport [3]. To acquire client's virtual counterpart, from techniques can be applied. We may distinguish: 3D body scanning, 3D data acquisition from 2D images, procedures to generate body model by using 3D design tools [2] and motion capture systems. Regarding virtual Try-on, all above approaches have to be completed by the anthropometry and anatomical knowledge. Understanding the morphological changes and body characteristics is crucial in garment visualisation on virtual bodies. Also, parametric modeling requires knowledge on body proportion to simulate a variety of sizes and morphotypes. Additionally, to build the realistic human model the body composition has to be known.

The beauty of man lies in his individuality. As many people as many different morphological characteristics. Therefore, to create comfortable clothing, first, the comprehensive information about body measurements, shapes and postures have to be provided.

I.1.1. Morphological analysis of the human body

The prototype of human model assumes the specific proportions which define a universal sense of beauty. Beauty consists in the proportion. Polykleitos, the fifth-century Greek sculptor, introduce the Canon of the perfect proportion of the human body. He uses the mathematical basis to divide the body into seven equal segments. Polykleitos's system assumed the symmetry and harmonious proportion. The ideal of male and feminine body principles assumed that the total stature is seven heads, the head-heights of Polykleitos's Doryphoros [4], is presented in **Figure 3**.

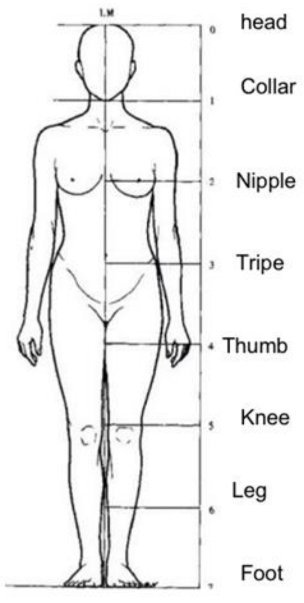


Figure 3: Seven-head body model.

In the Book of Architecture, De architectura [5], by Roman architect Marcus Vitruvius lived in 1st-century bc. we find that the harmony and beauty should reflect the human model concerning its ideal proportion and symmetry design by nature [6]. Vitruvius presented a model called the homo bene figuratus, "the well-shaped man". After fifteen centuries Leonardo da Vinci perfected Vitruvius's vague descriptions graphically in his famous model of "Vitruvian Man", **Figure 4**

The model demonstrates two positions of the man. First, with his arms stretched out and placed within a square. Second, with his arms tilted/rotated so the whole body is inscribed in a circle [7]. Leonardo constructed eight-head-high system [4]. The proportions illustrated by Leonardo's model had become wildly accepted as a 'golden ratio' or 'golden proportion'.. This classical modular system of the human body was used by the classical sculptors, and it is still in use.

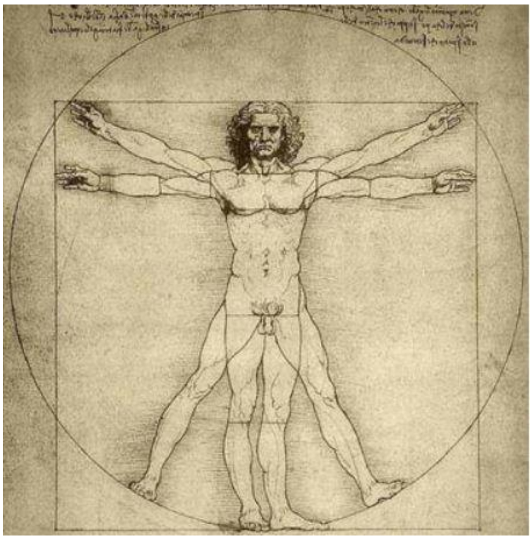


Figure 4: Vitruviu's man by Leonardo da Vinci.

However, it is no longer incontestable as a unique definition of beauty. The classical notion of beauty is inseparable from symmetry and strictly defines by proportion. In modern society, the concept of beauty has a broader meaning and goes beyond the classical beauty canons. Lack of symmetry and ideal proportion do not significant lack of beauty. Human imperfection and its limitations are part of life and are accepted.

Current human body research (anthropometry) goes well beyond this ideal pattern. Researchers meant to explore and to understand the real human body and its classification to meet the demands of today's market. The measurement of human morphology is *Anthropometry* [8] (from Greek "anthropos" – human, "metron"- measure [9]). Since ancient time people from different fields have an interest in Human Body. An attempt to quantify the knowledge about human measurements resulted in the creation of anthropometry. Anthropometry, as the study of human body dimensions, is a knowledge used in a range of disciplines. It is considered to indicate sizes and proportion of the human body [10, 11] necessary in garment design.

This notion of proportion of the human body has also been studied in the art of drawing'art [1]. The trends would be to follow the ratio of Leonardo's model for ideal proportion of the male/female (**Figure 5)**. This author has declined different variations of proportion according to the activity and age of the person that are still relevant (**Figure 6**). This declination, called "drop" in the sizing systems [11], is very connected to the activity. Research works have redefined a new concept by classifying morphologies into different morphotypes.

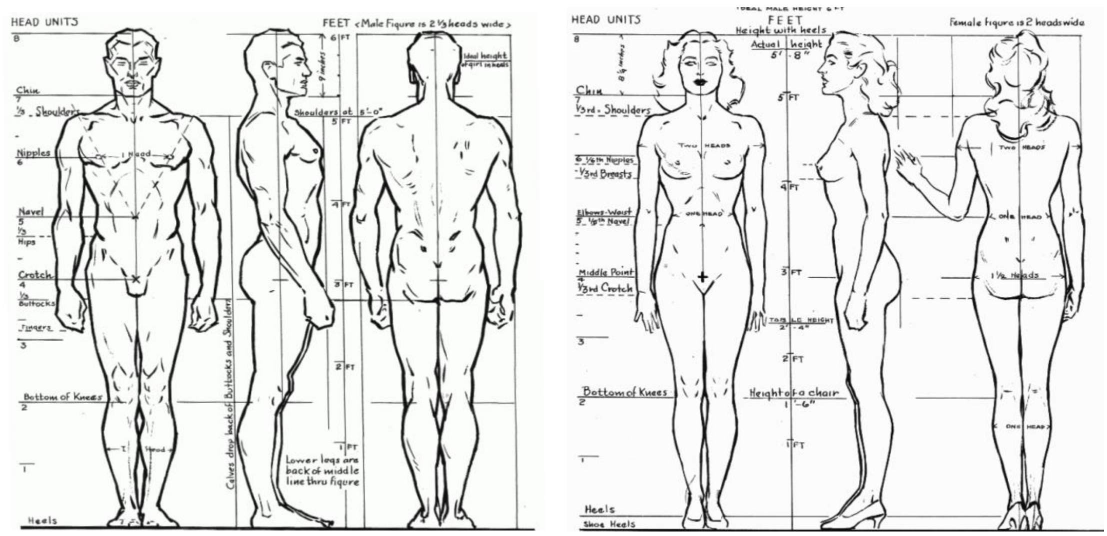


Figure 5: Ideal proportion of human body for male and female.

Chaffin [12] presents one of the most suitable definitions of anthropometry: "Anthropometry is a science that deals with the measurement of size, weight, and proportions of the human body. It is empirical in nature and has developed quantitative methods to measure various physical dimensions". It is the knowledge which is used to standardize specific population by grouping individuals into categories. The term anthropometry is dedicated to describing the quantification of the external geometry of the human body. As an applied since the goal of anthropometry is to collect valuable information and make them available for the designers' purpose.

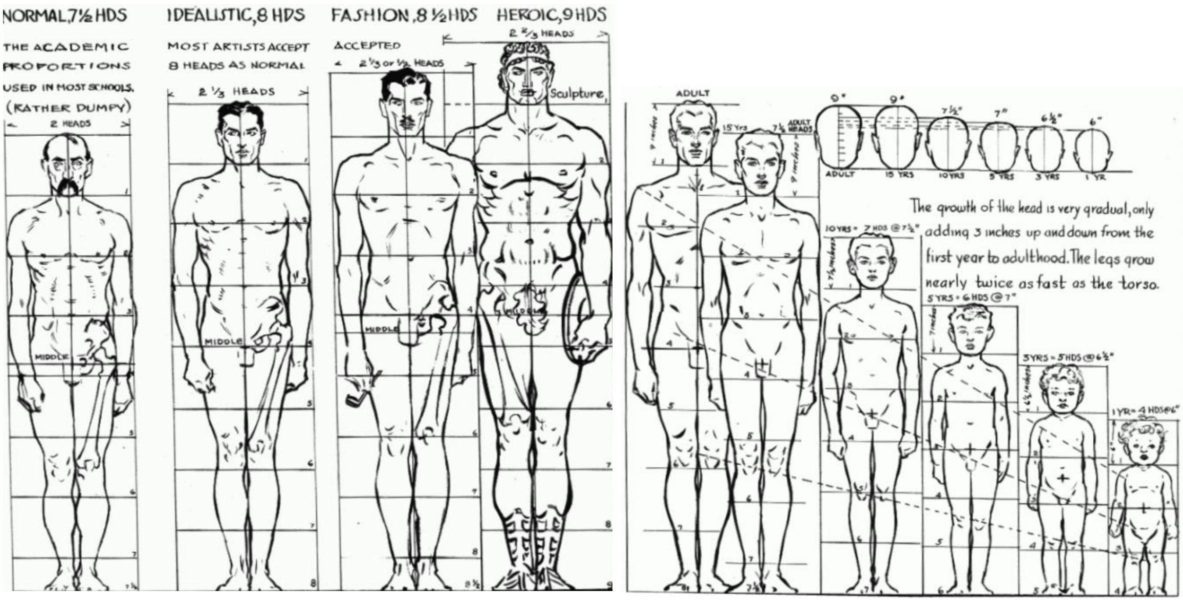


Figure 6: Activity and age effects on proportion human body.

The apparel industry is principally concerned with the anthropometric side of body size and shape. The body measurements are fundamental to the design of clothing [13] where measurements are determined by wearing purposes. Therefore, accurate anthropometric planning is a necessary procedure depending on the use. The first step is to define the standard anatomical position or reference that describes the human body. The body is in a standing position, facing forward with arms hanging loosely at the sides with palms facing forwards [14]. The standard planes and axis are presented in **Figure 7** [15] :

- Sagittal plane XZ (anterior-posterior, AP) divides the body into left and right section. If both sides are equal in size, it is called a Midsagittal plane. If the sides are unequal, the plane is called the Parasagittal plane.
- Frontal plane YZ (lateral, coronal) divides the body into front and back section
- Transverse plane XY (axial, horizontal) divides the body into upper and lower segments

The intersections of planes mentioned above make it possible to define the three reference anatomical axes oriented perpendicularly to the reference planes (**Figure 7**):

- Longitudinal Axis, perpendicular to the Transverse Plane,
- Anteroposterior Axis, perpendicular to the Coronal Plane,
- Mediolateral Axis, perpendicular to the Sagittal Plane.

Planes describe the static position of the body while axes determined the rotation and defined the movement.

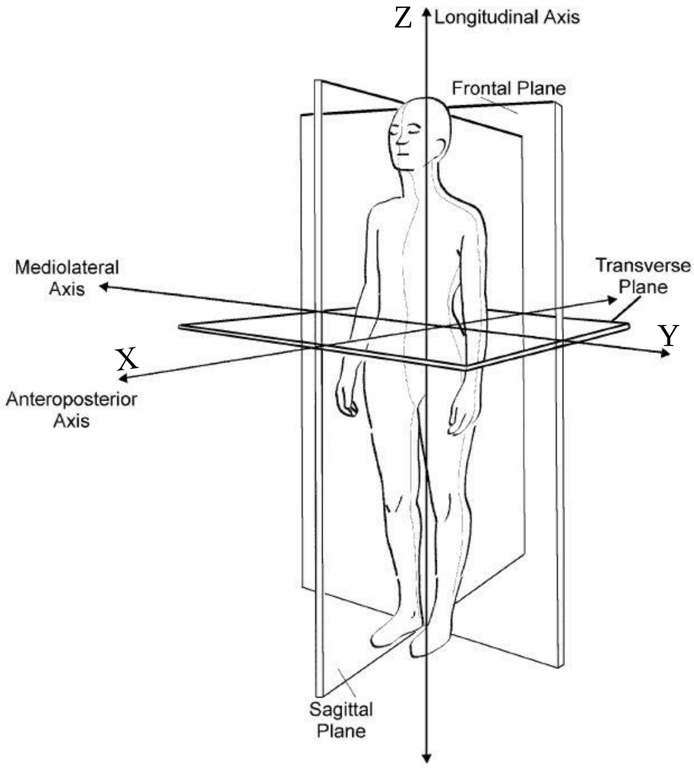


Figure 7: Body reference planes and axes.

The next step is to define the positioning of the anthropometric points and measurements. The specific body landmarks are determined by the unified standards (e.g. ISO-7250, ISO-8559, Polska Norma P-84500). Serwatka [16], based on the polish norm [17], presented a comprehensive summary of the anthropometric points (**Figure 8**).

The positioning of the anthropometric points is the basis for determining the construction and design lines with a specific shape that takes into account all the body proportions for a given size of clothing. For the purpose of the clothing industry, the measurements are taken from a sample of the population or from a particular target group to create an anthropometric database. One thing which is incorporated into the credibility of the anthropometric database is a need for systematic updates. Updating the anthropometric information is necessary due to constant morphological change in population. This in turns is necessary to create the well-made pattern and the same well-made garment.

Developing all steps in the anthropometrical planning requires doing things “right from the beginning”. In this case, it means the precision in taking the measurements at first.

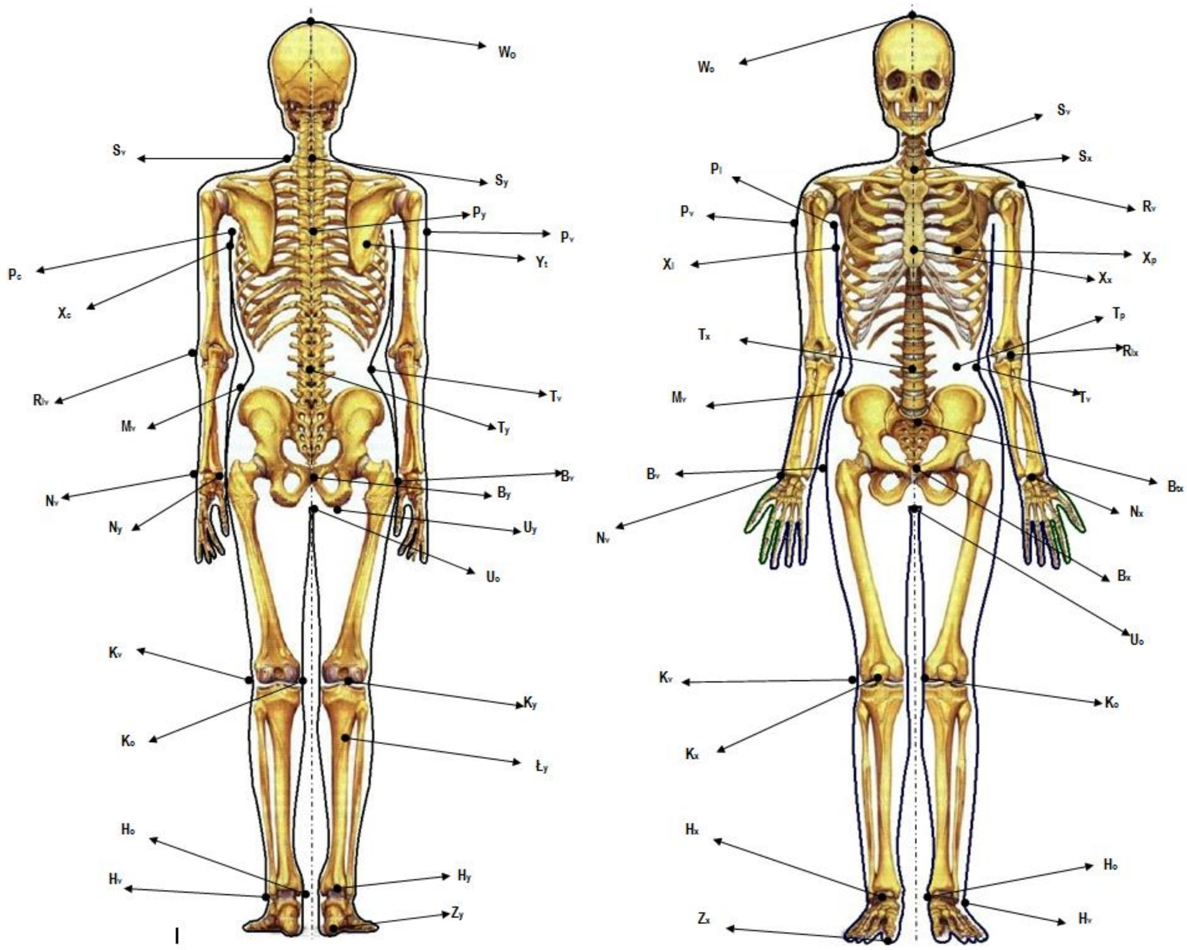


Figure 8: Anthropometric points on the human body.

I.1.2. Anthropometric measuring methods

Anthropometry is the interpretive and restrictively method to describe the human body shape. The tools and procedures of anthropometric measuring methods depend on the application. Depending on whether they are dedicated to measurements for a single person or for a broader population, they require adequate know-how. We can distinguish two main branches of anthropometric measuring methods: manual called traditional (for human modeling) and automatic called digital (for digital human modeling). The first is also called contact method, as it involves the physical participation of both person and measuring instrument. All methods from the second group are called non-contact, and it can be two- or three-dimensional.

I.1.2.a. Traditional methods with contact

Traditionally, this method is manual and requires strong expertise in landmarks' positioning and procedures by a well-trained operator. Tools being in use have a long tradition and are simple and not very expensive. The main instruments used in traditional anthropometry are described in [18] and are as follow:

- anthropometer (**Figure 9.a**)
- large sliding calipers (**Figure 9.b**)
- small sliding calipers (**Figure 9.c**)
- spreading sliding calipers (**Figure 9.d**)
- measure tape (**Figure 9.e**)

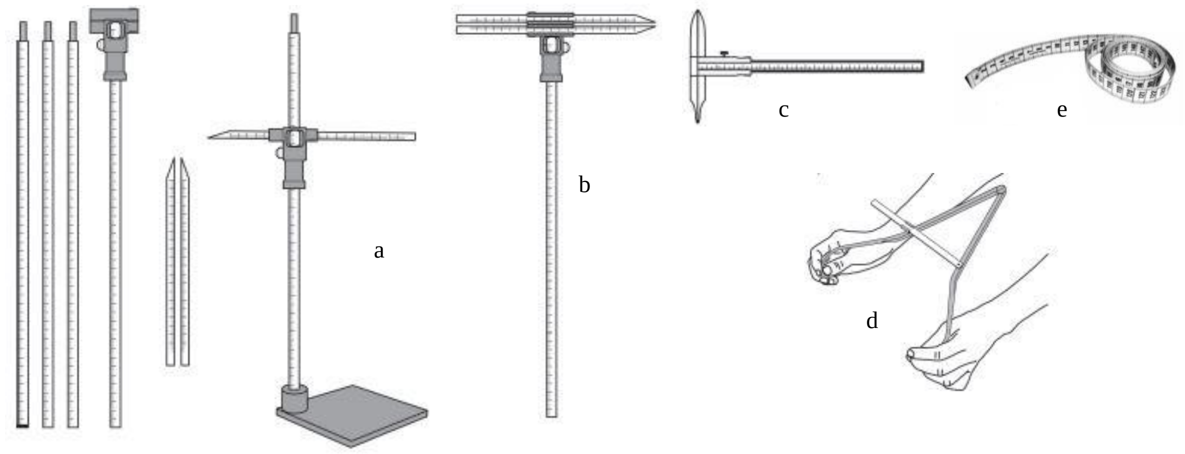


Figure 9: Traditional instruments.

The person being measured has to be in standing posture. The data obtained from traditional anthropometry give the static dimensions of the human body in a specific pose.

The manual measurements are prone to error. There is a discrepancy between measurements taken by two different measures [18]. It is observed especially during anthropometric surveys for industrial needs. The repetitive tasks and differences between the level of measurers' experience influencing the final results. Also, each measurement process is time-consuming.

To conduct the anthropometric surveys on a big population technology is coming to help. The methods without contact are then very appreciated by their quality and speed of measurement despite very important investments.

I.1.2.b. Digital methods without contact

Within the range of the non-contact methods several approaches can be mentioned:

- 3D body scanning systems (three-dimensional)
- Depth cameras (two and a half- dimensional)

- Photographing (two-dimensional)

3D body scanning systems

Non-contact body scanning began to appear and develop in the last thirty years. Depends on technology 3D body scanning systems can be divided into five groups: laser and Kinect scanning (**Figure 10.a**), infrared Depth sensor (**Figure 9.b**), structured light projection (**Figure 10.c**), stereo photogrammetry (**Figure 10.d**), millimeter waves (**Figure 10.e**) [19] and infrared waves (**Figure 10.f**). Depending on the requirements of use and accuracy specific scanner can be chosen. 3D Scanning is deemed as the most reliable tool for human body measures, and remedies for frustration comes with current sizing system mainly from the ill-fitted garment. For the purpose of Measuring Campaigns, the laser scanning is the best choice. It is a three-dimensional whole body scanner with integrated body measurement system. This technology has opened up a new approach, and design possibilities move towards mass customisation and made-to-measure clothing. The 3D scanners were used in the most prominent sizing surveys called Measuring Campaigns (CAESAR, IFTH, SizeGermany, SizeUK, [TC2]).

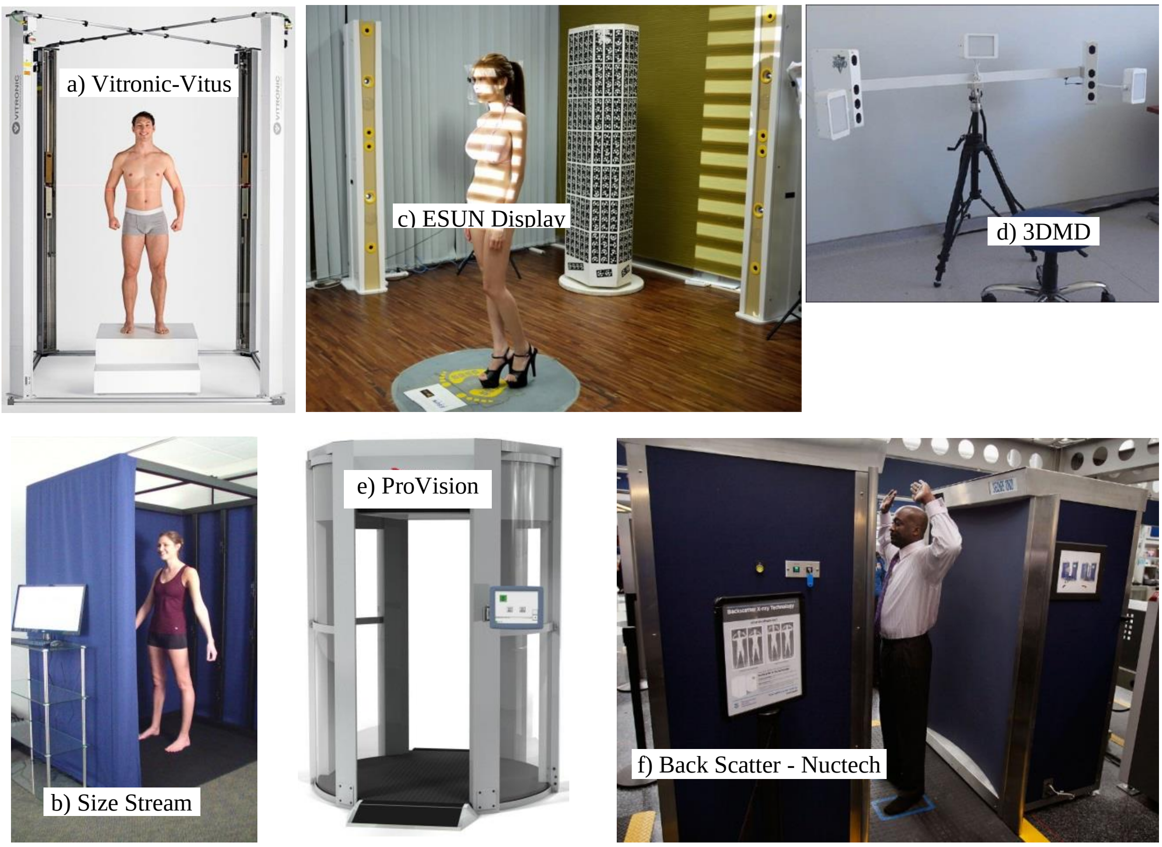


Figure 10: Technology 3D body scanning systems.

Using 3D scans for Body Measuring is the most reliable way of obtaining proper data. However, it is important to remember that no single person measured twice gets the identical values. The cause lies in the evolution state of the body during the day. Body dimensions differ before and after a meal, before physical activity and after, and depend on the daytime when the person is measured. The scanner capture the points cloud of the human body then converted to surface for a specific posture at a given moment within several seconds. The advantage of such situation in comparison to the manual method is that results are not subject to errors resulting from movement during breathing, posture instability, or the varying degrees of experience of the person performing the measurement. Additionally, the landmarks locations are calculated automatically, and all measures are taken in a precise, strict and repetitive manner. Validity and reliability of the 3D full-body scanners for apparel have been investigated by several researchers [20, 21, 22, 23]. Interesting studies were conducted by [24] where the scan measurements were compared with the traditional method. According to this research, on a large anthropometric survey, the same measurements obtained with both ways are not compatible. It was mainly caused by difficulties with maintaining the horizontal position of the measuring tape while measuring the circumference.

However, the problem arises when we want to standardize the methodology of measurements for all models of scanners. The reason is that the full-body scanners available nowadays differ in how each capture and draw individual measurements [21]. As regards the anthropometric data analysis there is no unified method or procedures by which the database of anthropometric measurements is used to estimate a representative sample [25, 3]. In other words, the interpretation of measurements data is not standardized. Therefore, there is a need to create the standards which will work for all scanners and traditional method [20].

The advantage of a body scanner is its compatibility with CAD systems. More precisely, the 3D scanners by capturing required body measurements give the data for pattern creation. And, more importantly, is possible to obtain a virtual mannequin (avatar) of a customer or a representative of the target group or population that allow direct 3D modeling or virtual fitting simulation. Finding the link between virtual body and pattern is crucial for digital fashion application.

The virtual body representation is essential for clients while buying the garment. It is understandable, therefore, that clients want to simulate the experience of try-on as in a real scenario. The economics reasons necessitate a commercialized solution, so the tools to simulate the body and the garment have to be wildly available. Because the primary purpose of using 3D scanners is full body scanning and human model reconstruction it seems it could be the best way to use this method. However, the costs of using the 3D full-body scanners and proper analyses the 3D data are very high. To fulfil clients' demands and at the same time be profitable producers proposed the diversity of 3D body simulation based on the depth and RGB camera. Even the smart phones have the application to create the 3D models or make the real-time body capturing with the ability of cloth matching. That service is design to encourage and engage the client in the process of buying. The precision of measurements is not essential in this scenario.

Depth cameras

Another group of tools to capture the 3D body are cameras used the infrared light and depth information. Most known is Kinect from Microsoft. This depth camera is used mostly in multiple variations to obtain a 3D representation of human body (**Figure 10.b**) [26, 27, 28, 29]. However, comparing to the 3D scanners, it is hard to obtain the complex structure and the low accuracy is a still limitation of such solution [26, 30].

As part of an application on augmented reality of on-line shops, works has been done to investigate the sensibility of the Kinect sensors regarding to body measurement extraction [31]. The goal being to know if from the depth images and skeleton data is it possible to extrapolate the main body measurements relative to a database (**Figure 11**). Results have shown that the measured person should be in tight cloths in order to extract accurate data.

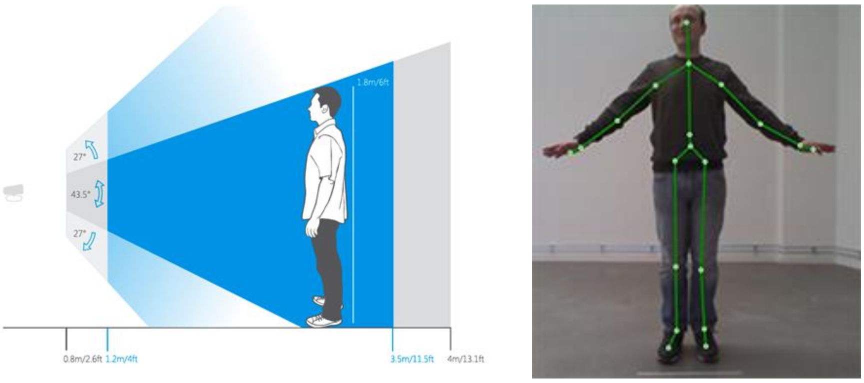


Figure 11: Kinect vertical field of view in default range, 2D image with skeleton.

During experiment following the recommendations of Microsoft [32], few important details have been highlighted:

- to provide joint tracking stability the measured person cannot make fast movements
- hands have to be positioning in small angle from the body
- the measured person has to stand with feet slightly apart.

Photographing

Between manual and three-dimensional methods of human body recognition, we can mention the two-dimensional measuring process, ***Photographing***. The principle is to detect the feature points on the human body silhouette [33]. Several studies applied the image-based techniques to generate the three-dimensional representation of the body [34, 35, 36]. This method is relatively inexpensive but getting the 3D body representation cannot be obtained by using the simple picture. To reconstruct 3D human model, several images have to be taken from different angles. This method often has to be supported by additional measurements, like stature and external reference database. Information from photography is extracted into the process in *image analysis.*

Finally, 3D whole body scanner technology and 3D human body modeling are an answer for changing approach from fast-fashion to mass-customisation given that the sector of made-to-measure garment rises in importance. Therefore, create an avatar of a customer or representative mannequin of target population fits in today's market requirements. It is from the analysis of the population, the pattern recognition and the image of the consumer under different poses that we are considering to create his avatar.

I.1.3. Pattern recognition of the human body

In the Internet age, the life of almost every person has moved its part in the digital world. We do shopping there, we use media to communicate, and we watch the reality through a computer monitor.

Virtual reality requires reflection of the real world. This aspect is closely related to the need to imagine a digital human being. What should it be? In a purely fictitious world, i.e., games, animations, commercials, we can have a wide range of body proportions, head size, length of the trunk or legs have no significant role.

It is different in the world of buying clothes online. Here, the client wants to know how the cloth will fit, whether the cut fits his figure, if the fabric suitable for the style and his imagination of himself. In the ideal scenario, the client would like to try-on the chosen garment. This need drives researchers to look for a solution to meet such requirement.

The first step to identify the morphotype of an individual client as well as morphotypes of a target population is to know their anthropometric measurements. Those are known either from scanner or photographs [37]. But, this requires creating sufficiently knowledges of morphology and proportions of the human body from the whole population.

Then, identification is made between the morphology of the client and the different morphotypes of the population to build an avatar close to him from adaptive morphotypes of the population.

I.1.3.a. 3D pattern recognition methods

Based on the anthropometric database, people are assigned to appropriate clusters.. The classification profile is an objective to distinguish the clusters and its representatives. For apparel industry, the cluster can be a target population defined by certain morphological similarities, and the representative is a centroid called a morphotype for a particular cluster. The morphological classification is carried out to define a sizing system appropriate to the body shape and no longer to the measurement. Despite the fact that the sizing system is crucial in developing and design of clothing, the apparel industry has not applied any system that works for all brands [38, 3].

In the scenario of mass-customisation in the apparel industry, the consumer's body shape determination is crucial. The classification of body shapes facilitates the final garment pattern fitting and limits them to certain sizes or styles. Many researchers tried to answer the question, what is the true body shape.

One of the first attempts to classify people using photographs and anthropometric measurements were made by American psychologist W.H Sheldon. In 1940 he presented the term of somatotype, which was a part of his constitutional theory of personality [39]. Based on the external morphological features the tree human types can be distinguished [39]:

- **endomorphy** characterized by increased fat storage, a wide waist and a large bone structure,
- **mesomorphy** characterized by large bones, solid torso, low fat levels, wide shoulders with a narrow waist,
- **ectomorphy** characterized by long and thin muscles/limbs and low fat storage; receding chin, usually referred to as slim.

A somatotype number of three digits is determined for an individual classified by the system, with the first digit referring to endomorphy, the second to mesomorphy, and the third to ectomorphy; each digit is on a scale of one to seven. Hence the extreme endomorph has the somatotype 711, the extreme mesomorph 171, and the extreme ectomorph 117. The classification numbers are negatively correlated, so that a high number in one class precludes high numbers in the others; in practice, extreme types (711, 171, 117) are rare or nonexistent, and the person of normal build has a somatotype approaching 444, evenly balanced between extremes Sheldon's theory is interesting from the perspective of the apparel industry. It shows that it is possible to cluster people based on their body shapes. Recent studies [40] of clustering the shapes derived from three-dimensional whole-body scans, shows the close link between the traditional somatotypes and division into groups of the studied population.

The techniques to model the human body can be divided depending on the application. The most precise technique is to use 3D whole-body scanners. This technique gives a very detailed anthropometric data. It generates a realistic counterpart of the original subject. The 3D whole-body scanning gives a very large data which narrows its field of use for engineering applications. Like anthropometric surveys or anatomical body reconstruction for medical purpose. The first step in this process is the digitization of the human body in a predefined posture. The data acquired through 3D scanning are in a mesh form. This digital data are processing and transformed into a surface model, which may be used in CAD systems [16]. The 3D data also gives precise information for clustering of a target population and finding proper morphotypes [41]. Moreover, by studying the relationship between dimensions of different body parts the sizing changes are possible to define. Thus, the parametric body modeling leads to the creation of 3D body model of the individual [42].

I.1.3.b. 2D pattern recognition methods

Another methods is to use the depth information [43]. One of the most used tools to capture the depth information is a Kinect Microsoft camera. This technique is primarily devoted to the video gaming, where the accuracy is up to cm which is enough to capture body movements. It is also an alternative for expensive 3D scanners.

The expected error in its depth measurements is proportional to the distance squared. However, the accuracy of the Kinect is greatly affected by the intrinsic and the extrinsic calibration of the Kinect cameras. To complete the work previously cited [31], research of [30] shown that in the 1 m distance between the camera and object the point spacing in the depth direction is, as they say, quite small because of about 2 mm. So, we can conclude that the determination of the distance between camera object, after proper calibration, will be marked with an error of 2mm at a distance of 1m. The distance data from the Kinect varies in accuracy from sub-centimeter up close to as much as a 5cm error at its maximum range. This is a consequence of how it measures distance.

The images do not give the consistent information and are prone to error and incomplete shapes [44].

Another approach is taken to make a distinction of body shapes, which are found in the online environment, are flat/2D descriptions of the body. The morphology is described by dividing the body based on figure types or shape categories. These two defined notions are sometimes used alternately but, indeed, they both represent two different approaches to body description. Figure types are based on the height and the drop value, which is a subtraction between hip and bust circumference, and are used mostly to create the size charts [45].

Shape categories, however, are often utilized by the stylist to advise the style of a garment dedicated to the particular silhouette. The HOAX reference concept appeared with the Duffy book [46].This classification is based on the 3 principal girths: the bust, the waist, and the hip. Designers use letters to refer to these typical shapes. The “pencil” or “tubular” shape is an H, the “pyramid” shape is an A, the classical “hourglass” is an X shape, and so on. Most common shape categories are [47, 48, 49] (**Figure 12**):

- triangle,
- inverted triangle or ‘V’,
- rectangle or ‘H’,
- hourglass or ‘X’,
- oval or ‘O’.

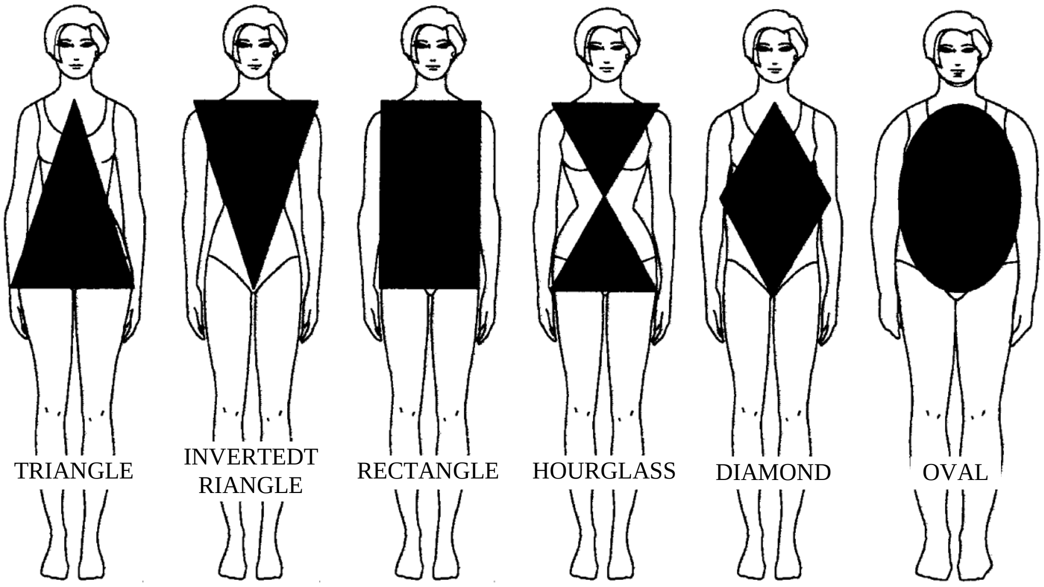


Figure 12: Types of women shapes [153].

This division is aimed for specific pattern garment or styles and is dedicated to linear body representation. Therefore, it not permits to build the 3D body representation.

Because of the large disfigurements between different age group and changing body shape information over the years, the classification should be dedicated to the precisely defined group, and it should be updated periodically.

I.2. MODELLING OF THE HUMAN BODY

Following the need to represent the human body in 3D, researchers focused on the modeling of the human body and the creation of parametric mannequin. The distinction between this two modeling appears during the using of the model in his application.

A first application was mass personalization using a non-adaptive model based on a generic reference model during the works of N. Magnenat-Thalmann [50]. Works of X. Ju have focused on the creation of a realistic animation of a model integrating a very realistic geometry of the body [51]. Some authors have studied [52] the correspondence between scanner data and the virtual model of the human body by converting the mesh of the scanned body into a volumetric model.

The second application was in the field of ready-to-wear using an adaptive model. The work of Y. Cho & all [53] have been very promising because they developed a parametric model that can be adjusted according to the different contours of the human body. A contrario, parametric approach of the human body from the cloud of points from the scanner was made by Wang [54]. It extracts the semantic features that are then applied to the wired model of the human body in 3D. In the same spirit and same time as Y. Cho, A. Cichocka & all was carried out to create an adaptive virtual mannequin in a 3D space from a scanned body [55]. They introduce the notion of primary and secondary morphological contours to create a parameterized mannequin from the scan of a human body assimilated to a morphotype.

The results (**Figure 13**) show that the virtual mannequin obtained throughout their methodology is close to the initial morphology whatever the parameterization imposed, despite they have not taken into account the upper limbs.

But this lack has been filled by later work [56]. They allowed by a more refined modeling of the body to improve its realism by integrating complementary morphological contours allowing to take into account the shape of each muscle (**Figure 14**).

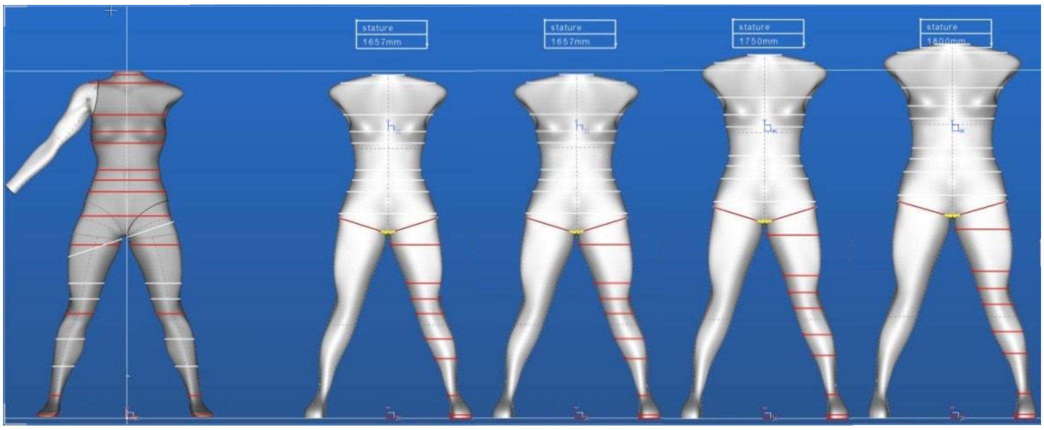


Figure 13: Parameterized morphotype mannequin.

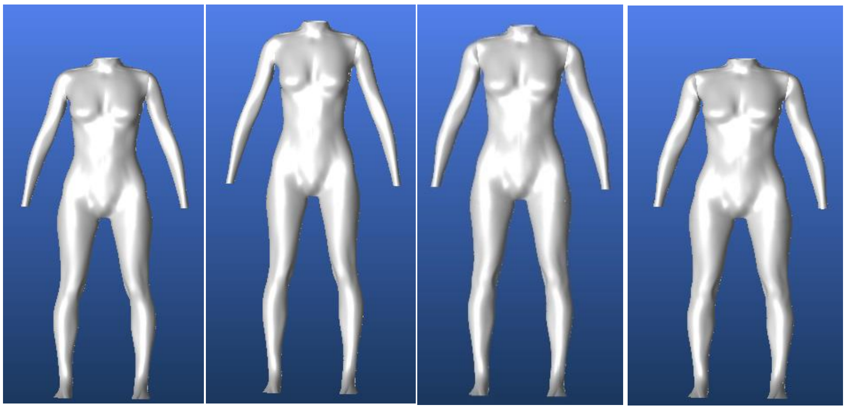


Figure 14: New generation of parameterized morphotype mannequin.

I.3. MODELING OF THE GARMENT

Garment modeling is a process of obtaining model forms (prototype) based on the designer draft and imagination. Nowadays, the developing Information Technology, specifically the Internet and 3D software, change the way of thinking about the garment modeling. Depending on the sector of application the art of modeling requires specific skills. For the advertising or the entertainment industry, like gaming, movies or commercial, the most important is to render garment realistically. In this context the modeling focus on employment of a proper geometrical, physical or hybrid techniques to compute the shape of the garment [57]. Those techniques allowed modeling the garments' shape and drape. Looking from the perspective of fashion and textile industry the purpose of garment modeling faced the additional challenges. The garment modeling on one side has to provide virtual try-on taking also into account the measurements of the specific customer [58]; on the other hand, has to be compatible with the ability to generate the patterns. The definition of garment modeling for the fashion industry has to take into account the garment production, which makes it much broader subject.

A. Matyga describes the garment modeling as a process which consists in shaping the contour lines and cut lines of the model forms so that the received clothing elements - that make up the whole of the product-type - correspond to the design of the model regarding proportions and composition [59]. Simplifying, the clothing first created as a design is then interpreted into the pattern, and then sewn. Also, it has to be noted that whatever the type of garment design is, traditional or digital, the pattern is always a 2D representation of clothing. Therefore, a practical understanding of garment construction and its relation to the human body is of crucial importance for effective process of garment making.

The transfer between flat pattern and the three-dimensional garment is a very challenging task, both for the traditional and digital garment production.

I.3.1. Traditional methods of pattern design

The typical methods of traditional pattern design used in the apparel industry are classified as two-dimensional (2D) and three-dimensional (3D).

- *the 2D pattern design* is developed from drafting and is called as the block pattern method. It is a flat pattern technique which is based on anthropometric measurements and added value of ease allowance. The patterns are made from paper, card or plastic [60] for standardised body measurements or for the individual.
- *the drapin*g methods called as a moulding is a 3D pattern design technique. It used an uncut length of fabric and stitched over a dummy or a fashion mannequin according to the design [61].

The traditional methods are used in a tailor (made-to-measure) approach. About the developing technology and the Internet, an attempt is being made to transform those techniques into the numerical data to reduce the design cost and time or to permit importation this information directly on the web sites.

On the ground of CAD systems and 3D visualization the garment pattern can be developed using different scenario:

- the two-dimensional to three-dimensional (2D-3D),
- the three-dimensional to two-dimensional (3D-2D).

For the purpose of simple 3D visualisation some companies propose three-dimensional to the three-dimensional solution (3D -3D). The 3D approach refers in all scenarios to the virtual try-on. In the 2D-3D approach, the garment is created as a draping of flat pattern in a three-dimensional environment [62, 63]. The goal is to verify the behavior of the garment on the body in order to validate it without real tests. In the 3D-2D approach, he garment is designed directly on the 3D virtual mannequin and the pattern is obtained by flattening the 3D mesh of the garment. Before the block pattern is used as garment template, it is undergoing corrections of construction lines and darts position. This solution is mostly in the use of designers.

Every garment has to be fit before buying it. The 2D-3D approach could be the ideal tool to solve this problem. However, in the mass production scenario, there is no special pattern adaptation in a software product of clothing [64]. People with a morphology that deviates significantly from the standard one cannot find clothes. Therefore, an increasing number of people are heading towards the made-to-measure brands.

I.3.1.a. 2D-3D methods

The digital age, more specific in the realistic rendering for the 3D synthesis image, has allowed the garment CAD industry to develop a specific environment for the 3D virtual try-on. The most famous CAD products are Clo3D de CLO, Modaris 2D/3D de Lectra, OptiTex de EFI, V-Stitcher 3D de Browzwear [65]. The kernel of these tools is based on fabric simulators whose quality of the simulation results is distinguished by the calculation method used [66]. On the other hand, these tools have a similar 2D/3D environment composed of seven main modules whose functions are:

- choice of the 3D mannequin (parametric mannequin, real human body scanned, dummy) (**Figure 15.b**),
- sewing of the pattern in 2D or 3D (**Figure 15.c**),
- applying of the properties of fabric (**Figure 15.d**),
- simulation of the drape on the mannequin [67, 68, 65] (**Figure 15.e**),
- analysis the fit of the garment (**Figure 15.f**),
- 3D touch-ups,
- fashion design or application of the material visual (**Figure 15.g**).

The first module allows to quickly create an avatar according to the body measurements of the customer resulting from his body scan (mass customisation) or to create a human model representing the average customer of the brand (mass production) [69, 55, 56]. The second module virtually assembles the garment's patterns in a 2D or 3D environment. The following module informs the fabric simulator about the properties of the fabric. The mechanical parameters of the material proposed to the simulator can be obtained from mechanical tests on the kawabata's chain (traction, bending, shear, weight) or the FAST system. The purpose of the draping module is to simulate the fall of the garment subjected to gravitation, taking into account the intrinsic mechanical stresses of the material. The module analyzing the garment fit represents the decision-making tool to validate the notions of well-being and comfort of the product. The retouching module can be separated or integrated during the simulation. Finally, the last module increases the realism on the visual rendering of the product by printing the material design (texture, light) on the 3D clothing [70].

Figure 15: Creation steps of a virtual image of Chanel's dress 1920 in Modaris 2D/3D.

La **Figure 15.a** shows the different steps of the method 2D-3D in the case of a virtual reconstruction of a Chanel's dress 1920 whose D. Panaget had only the actual product. This product had to be restored but it was impossible to deposit it on the real dummy given its bad state. The **Figure 15.h** is an old image of the dress allowing to compare the quality of the results between the real and simulated product [71].

One of the special features of K. Liu's works is that he uses the 2D-3D tool to create a passage between the designer's style drawing (2D) and the 3D garment model [72]. This tool also allows him to retouch very quickly this one according to the requirements of the customer and his morphology (**Figure 16**).

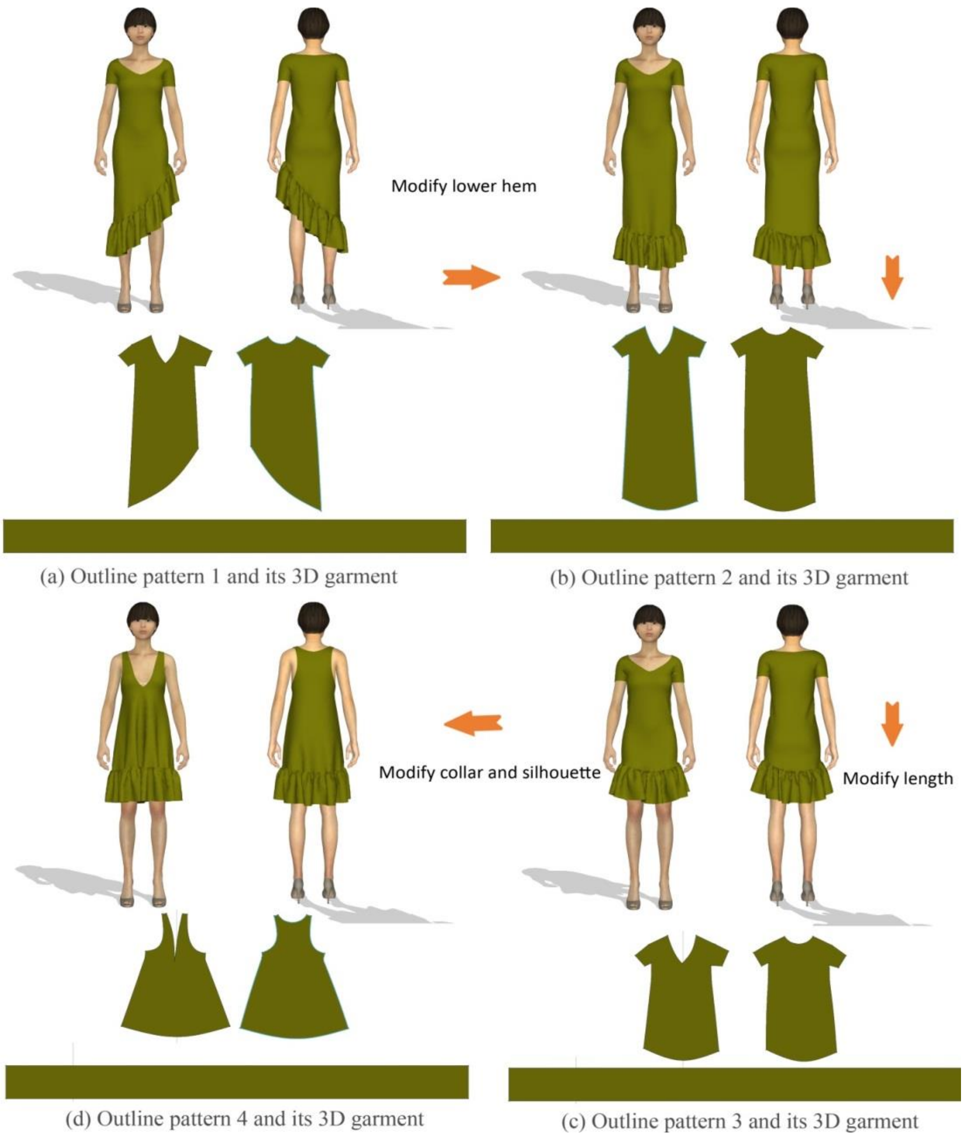


Figure 16: 3D garment adjustment approach.

I.3.1.b. 3D-2D methods

This solution can be used by designers. It is a design method widely used by different industrial sectors working with Tuts covering an object with stretching constraints. This method is found in the automobile or furniture industry (**Figure 17**).

Two lines of research have been considered for the clothing sector:

- garment close to the body (ease allowance = 0 or negative),

- loose-fitting garment (positive ease allowance).

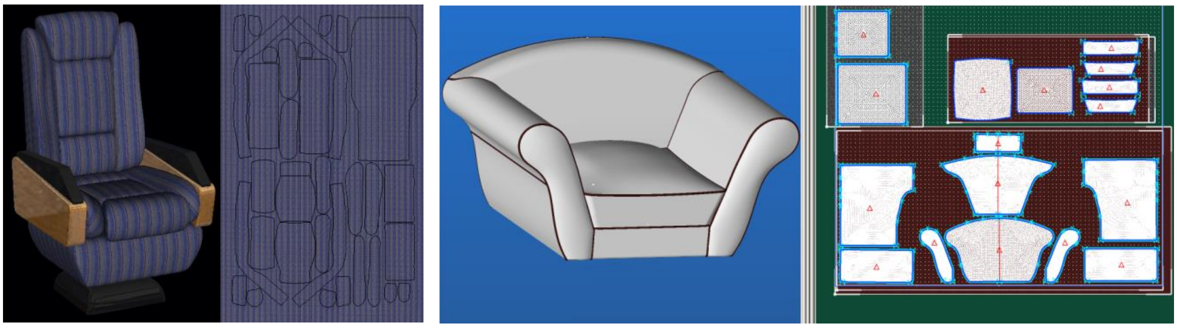


Figure 17: 3D Design Concept in seating and furnishing industries.

Garment close to the body

Research works of S. Krzywinski et al. of the University of Dresden have been pioneers in this field. Based on Lectra's 3D CAD concept design tool, they developed a method to design a wetsuit she presented during her international courses in an ERASMUS + program. The methodology was then taken up by Y. Edgar during his final end-school work in 2008 (**Figure 18)**. This method begins with the acquisition of a body scanned in the CAD tool (**Figure 18.a)**, the direct creation on the body of style lines (**Figure 18.b)**, the mesh of the different pattern surfaces delimited by these previous style lines (**Figure 18.c)** and the flattening of the meshed surfaces (**Figure 18.e)**. This tool has the particularity to reduce precisely the volume of the garment final mesh (**Figure 18.d)**; this change of volume could be likened to a negative ease allowance.

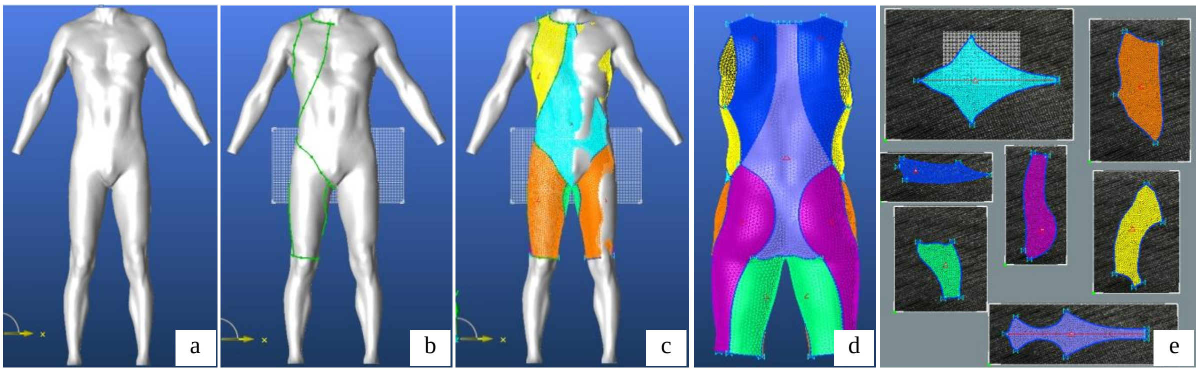


Figure 18: process to design with 3D-2D method.

In the corsetry sector, similar work has been done to fill the lack of 3D design tools for this sector of activity [73]. In his project to establish a new garment design process for ballistic protection, M. Abtew et al. analyze the field of corsetry and develop a new 3D design process for the achievement of comfortable and well fitted 3D bra design with the 3D design concept software. This work allows them to create female adaptive bust volume on a 3D female virtual mannequin. La **Figure 19** describes the process to create the bra: **(a)** creation of the style lines, **(b)** mesh of the different patterns surfaces, **(c)** flattening the meshed surfaces and comparison with the traditional method, **(d)** gradation results after modification of the bust volume.

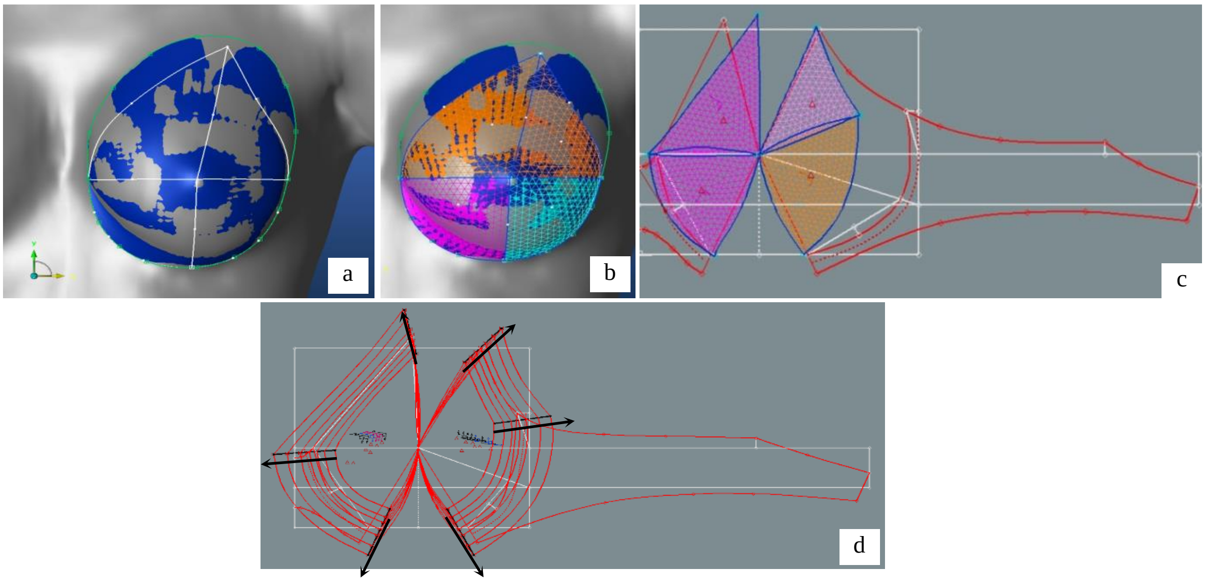


Figure 19: Process to create bra on female adaptive bust.

Loose-fitting garment

S. Krzywinski and al. continued his research works with a great interest in the garment with ease allowance. Recent works show that they use parametric mannequins to create different types of relatively complex morphology [74] (**Figure 20**). The method used to create the 3D mannequins using spline surfaces is interesting and gives very good results. After, they use the body cutting curves to define the contours allowing to create the garment. To integrate ease allowance, a punctual homothetic with the gravity center of these curves has been used. Similarly, works have been realized by S. Thomassey & P.Bruniaux where the ease allowance has been obtained by the measurement between the garment and the body scan [75].

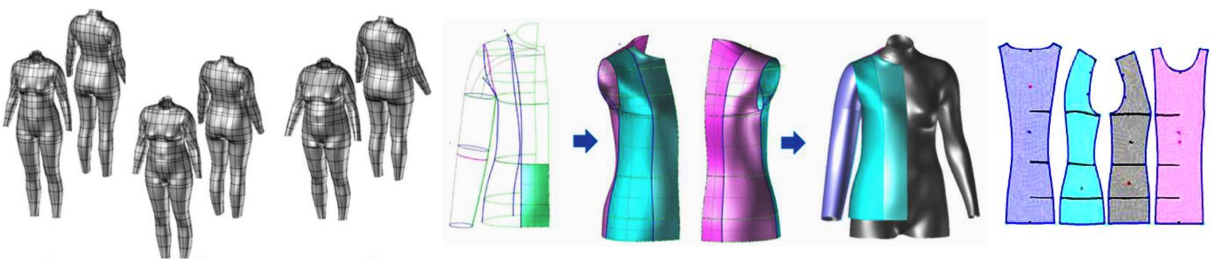


Figure 20: 3D product development for loose-fitting garment on parametric human models

Their results have been improved by A. Cichocka et al. with an adaptive mannequin [76]. In this work, the method for creating the 3D garment is based on the traditional 3D drape techniques (**Figure 21**). The variations of the parametric mannequin have shown that it is possible to directly obtain the gradation of the patterns like [73] and the results correspond to the industrial reality, the difference is that the process is automatic and the garment is more adapted to the customer's morphology.

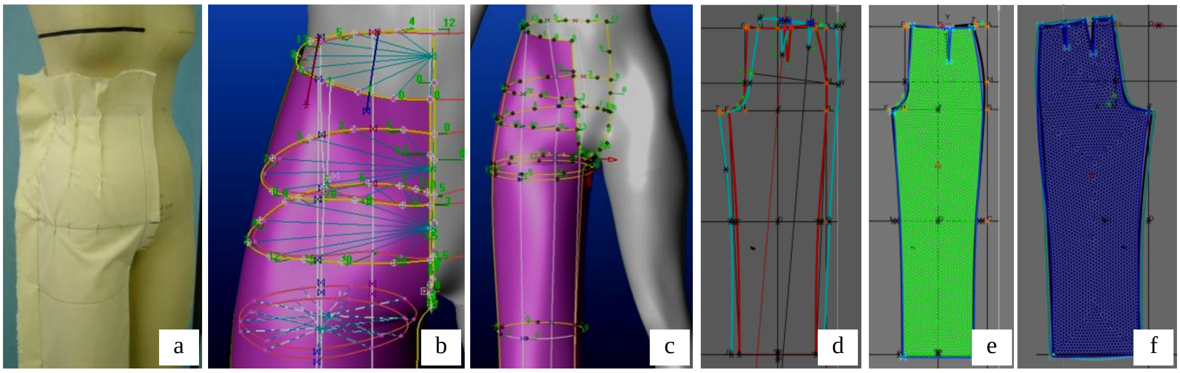


Figure 21: 3D-2D process of creation by drape technique.

Other researchers have developed their own technology in the same spirit of design. For example, Kang et al. developed a fitting 3D garment on a specific mannequin and unfolded the 3D garment to obtain the 2D patterns [77]. In the works of Hinds et al., the process to unfold 3D surfaces into 2D patterns has been developed surround 3D mathematical model based on the Gaussian curvature [78]. Au et al. use the shape of 3D virtual dummy to create different sub-surface managed by the human body's characteristic lines. The 3D surface of the prototype garment is then flattened into 2D patterns [79, 80].
Daanen and Hong use the point clouds of the human body scanned between the waist and the hip. After the points were converted to triangles and merged with their neighbors to obtain 40 triangles [81].

I.3.1.c. 3D-2D-3D methods

The evolutions of CAD allow nowadays to work and modify directly in 3D the garment during its virtual fitting by the 2D-3D method. For example, Lectra's Modaris 2D/3D tool allows to cut the bottom of a dress so that it is parallel to the ground, pinch the garment in 3D to adjust a size, create styling lines to open the bottom of a dress or create plies on this line. This 3D work represents the touch-ups that could be done on real products during the real try-on on the mannequin, but it can also be a way to create a new product design. P. Bruniaux et al. used this technique to adjust a standard garment to the morphology of a disabled person with strong scoliosis [82] by subjective method (**Figure 22**). They then compared these results with his new 3D-2D-3D method (**Figure 23**). The conclusions were that, in this particular case, the new method was faster and more rigorous.

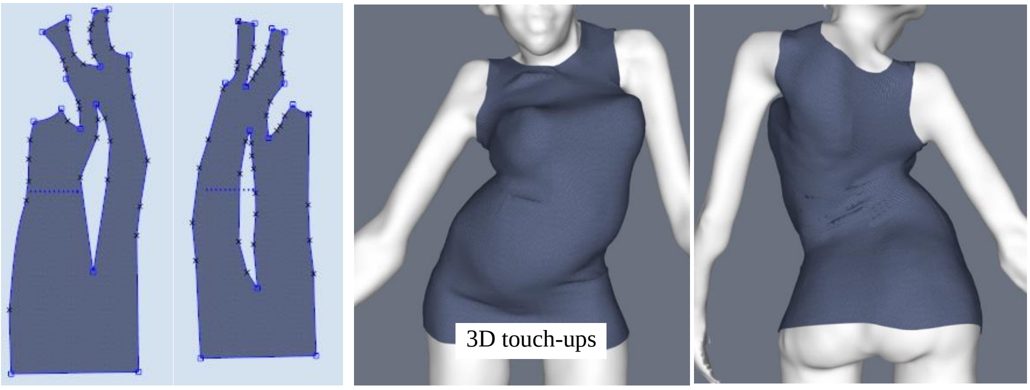


Figure 22: 3D pattern-making by subjective method.

But the two previous methods can also be combined to emerge towards a new 3D-2D-3D styling method. 2D patterns of the 3D-2D method can be exported and imported separately in a standard format (.DXF) in the 2D-3D method environment.

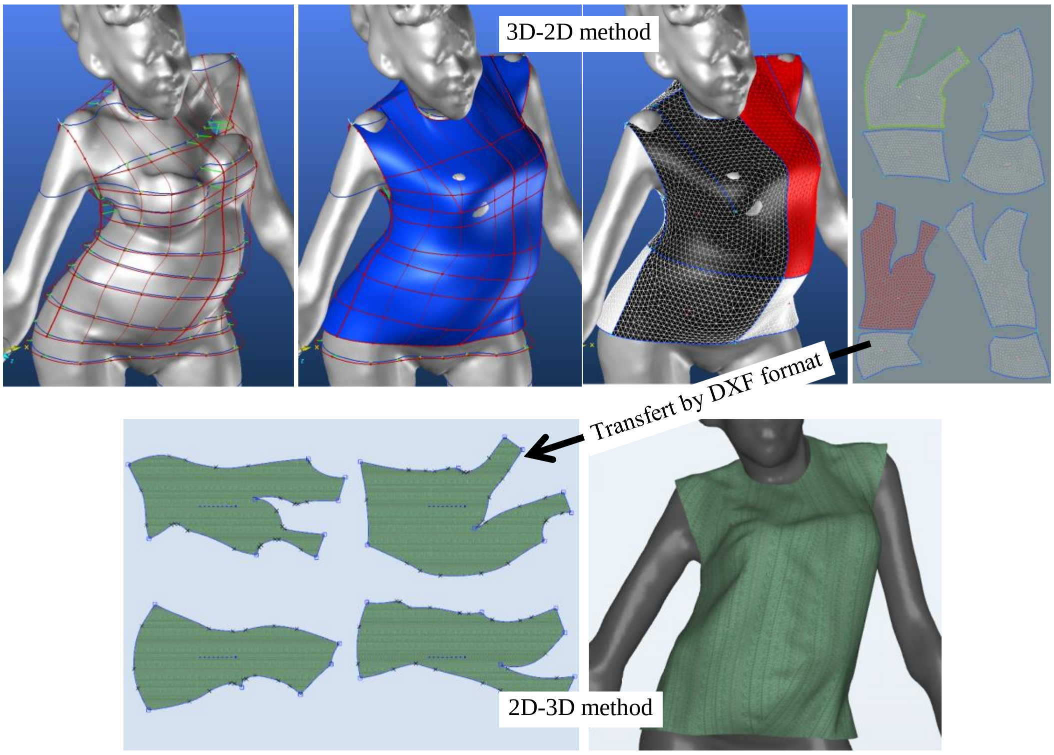


Figure 23: 3D pattern-making by objective method.

This work was improved by Y. Hong by developing a new block pattern design method in his virtual 3D-to-2D Garment Prototyping Platform. The procedure used follows the conical principle developed by S. Efrat [83] (**Figure 24.a**). The goal of this method is to detect on the 3D body shape the feature points by selecting anatomical landmarks for garment design (**Figure 24.b.c**) and to create then the garment block framework from shape controlling points of the breast and scapula points (**Figure 24.d)**.

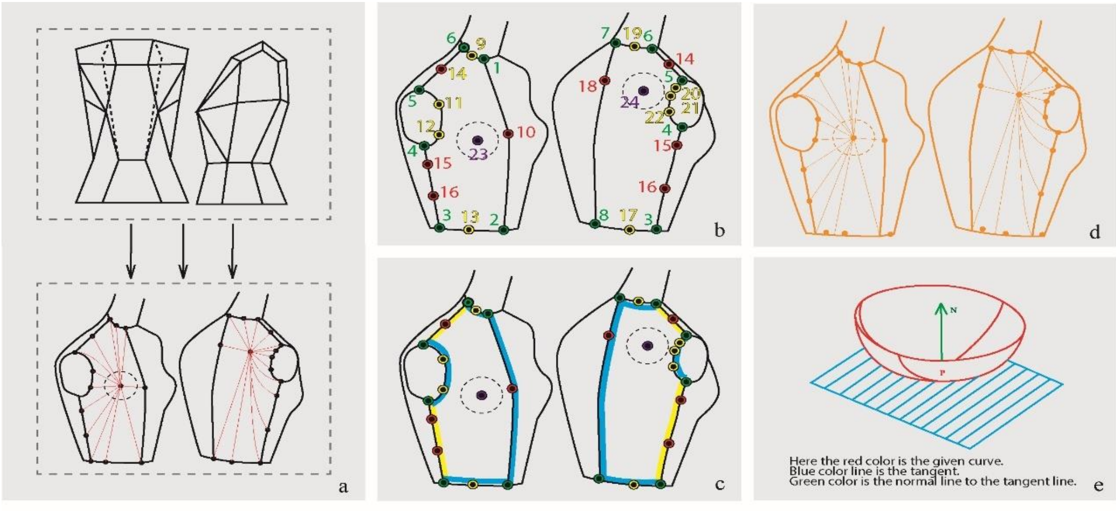


Figure 24: Block pattern design method.

The **Figure 25** shows the different design steps that were used by Yan on the morphology of a disabled person. The difference between this work and [82] is that the block pattern is a pattern very close to the body, i.e. with an ease equal to 0 in the zones of the contact points (breast and scapula).

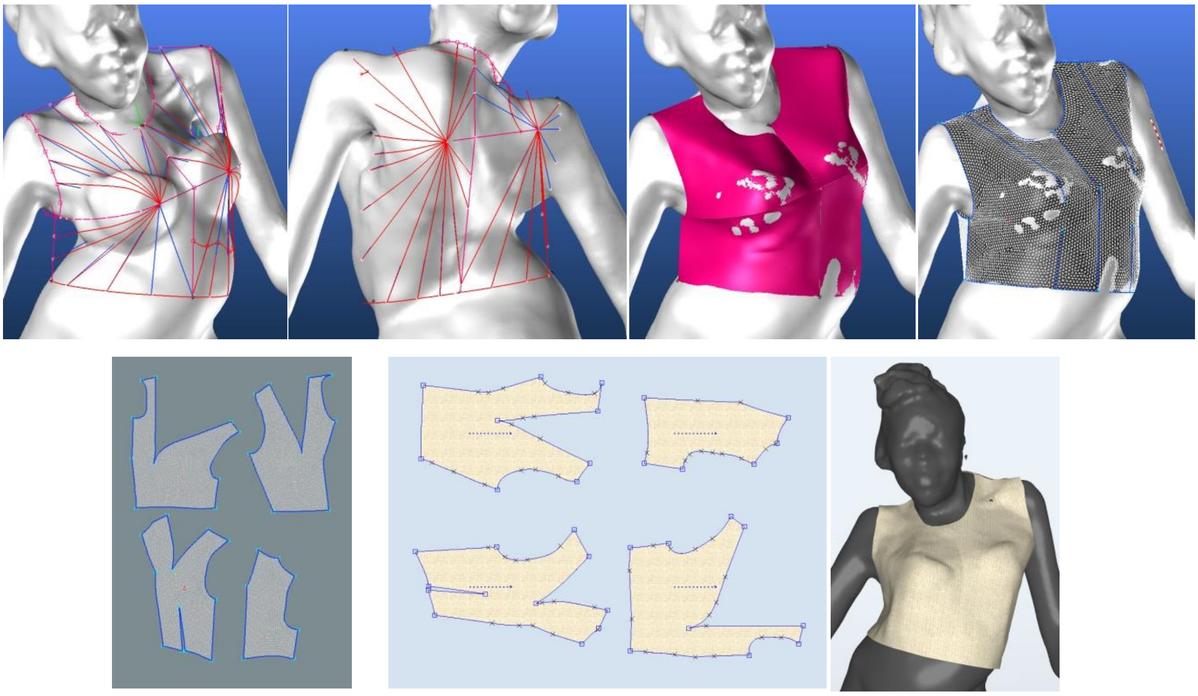


Figure 25: Design process for a personalized garment block.

K. Liu's set up a "3D Interactive Pattern Making Technology" for developing garment patterns in a “what you see is what you get” way. A fashion collection has been developed with the 3D-2D-3D process [72].

I.4. EASE ALLOWANCE

The ease allowance is a phenomenon closely linked to the garment style and fit. It is essential for the development of two- and three-dimensional pattern making. Visually, the ease allowance can be read as a gap between the body shape and the garment. This gap represents the shortest distance between the last two (**Figure 26**).

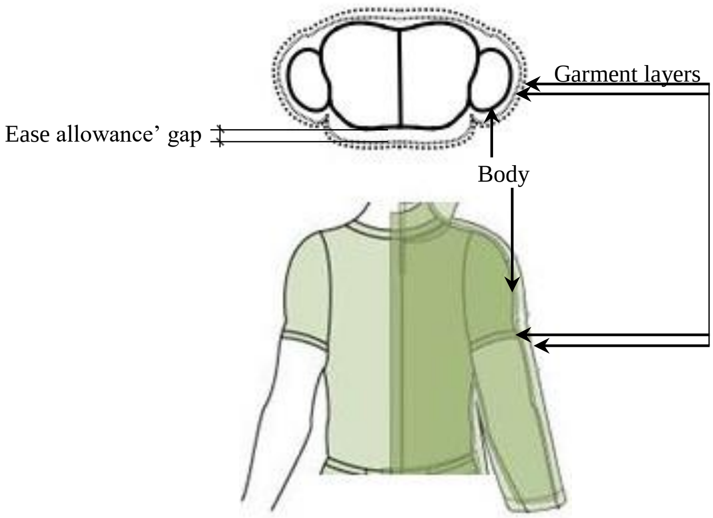


Figure 26: Graphic representation of ease allowance.

For the traditional, 2D pattern making, the ease allowance is established as a linear value added on the flat pattern. However, remembering that garment is design for a three-dimensional body, some information is missing while using just the body lengths and circumferences.

Relying on the 3D anthropometrical measurements more information about body volume and "cross-sections" of a human body can be drawn.

Ease allowance together with fabric physical features and proportions/correlations between body and garment stands for well-being and constitute the fitting of a garment.

Three types of ease allowance are recognized and described in literature and practice:

- standard ease (static ease),
- movement ease (dynamic ease),
- fabric ease.

The relation between body shape and the garment build a beauty effect. In other words, the desired value of ease allowance constitutes the style, the well –fit of a garment. This parameter is also an important comfort criterion for the consumer.

I.4.1. Ease allowance 2D

Y. Chen et al. proposed an original method to define and calculate 2D ease allowance and develop a new automatic design of 2D patterns based on fuzzy logic techniques, sensory evaluation and data aggregation [84, 85]. The fuzzy logic models developed make it possible to define and quantify the three levels of the ease allowance of a garment: standard ease, movement ease, and fabric ease.

This calculation needs the relevant body measurements related to the gluteal region and the trouser of normal size (**Figure 27.a**). Various evaluations have been realized thanks to an adaptive garment that they created to manage the different values of ease allowance by scratches (**Figure 27.b**). Although this method is only applied to jeans-type trousers (**Figure 27.c**), the authors announce that this method can be applied to the design of different garments.

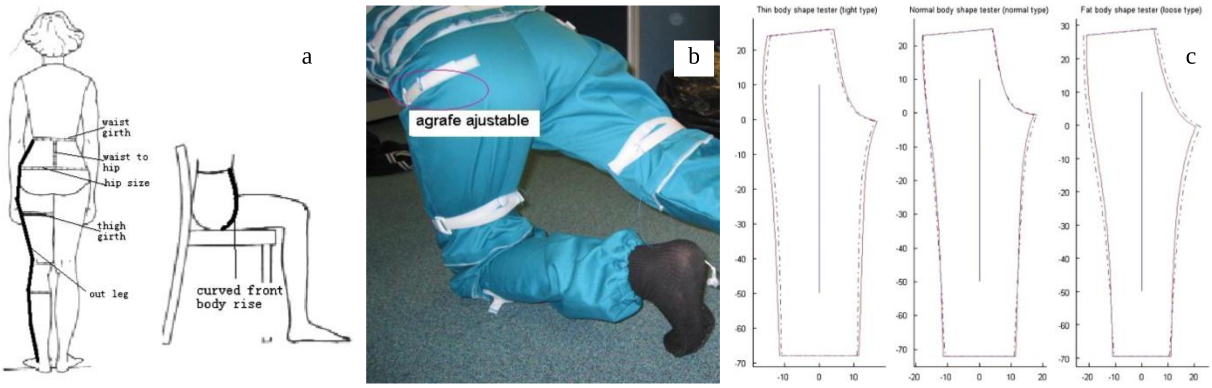


Figure 27: Evaluation of 2D Ease allowance

I.4.2. Ease allowance 3D

The first works of Wang, Ng, Newton and Zhang [86] has been to analyze the distribution of ease allowance as a function of size (**Figure 28**) and the material used. The tests were carried out with 10 jackets with variable size. The criticism that can be made is that the notion of morphotypes, especially for large sizes, has not been addressed in this concept.

These same authors [87] have then modeled the distribution of the 3D ease allowance of the garment by analyzing the difference between the shapes of the cross sections of the garment and the human body at different vertical positions (ex: bust, waist, hip ...). They use the TC^2 body scanner to scan the sections of a jacket and body at different levels. A prediction model makes it possible to improve the shape of these cross-sections by integrating the width of the horizontal section, the number of folds, the amplitude of these folds, as well as the bending stiffness of the fabric. This model is composed of 2 elementary models expressing the average morphology of the contours on which is added the effects of the folds of the cross-sections.

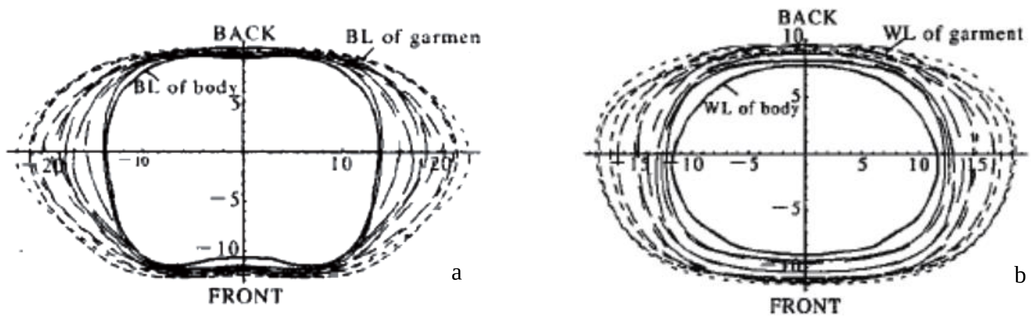


Figure 28: Chest (a) and waist (b) contours for different sizes.

The **Figure 29** shows how the first model calculates the number of folds, as well as the different amplitudes. The outline of the cross-sections was fitted by a second-order polynomial model.

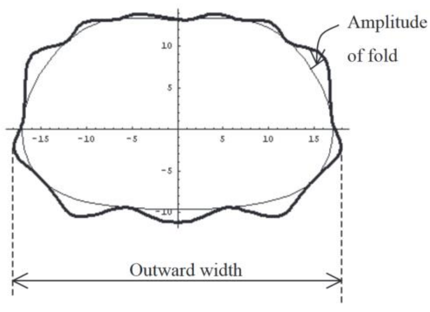


Figure 29: Measuring method of outward width and amplitude of fold

To verify their theoretical model, they compared by superposition the experimental curves and the theoretical curves (**Figure 30)**. The results show that the contours and folds of the horizontal sections were correctly represented using the theoretical model for different fabrics. However, the proposed ease allowance model is not directly applicable to the apparel because an ease allowance value on the size of 31 cm, or 20 cm for the chest contour is not conceivable. Overall, the idea of measuring the distribution of fluency by a scanner is very interesting but the garment must be perfectly fitted to the body of a person.

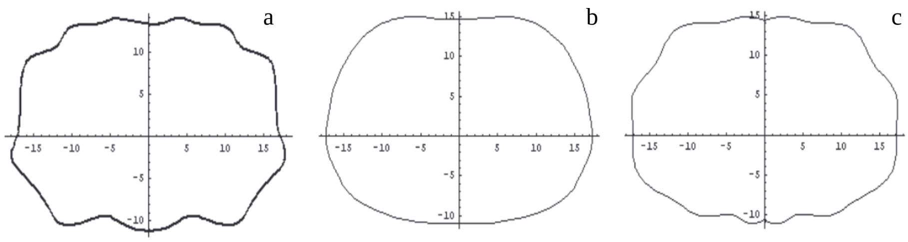


Figure 30: Prediction of the cross-sectional shape : a) experimental shape ; b) predicted shape ; without factor of fold ; c) predicted shape with factor of fold.

In the works of S. Thomassey & P.Bruniaux [75], a specific development has been realized to analyze 3D ease allowance. The schema of **Figure 31** shows the different steps to capture the gap between the garment and the body.

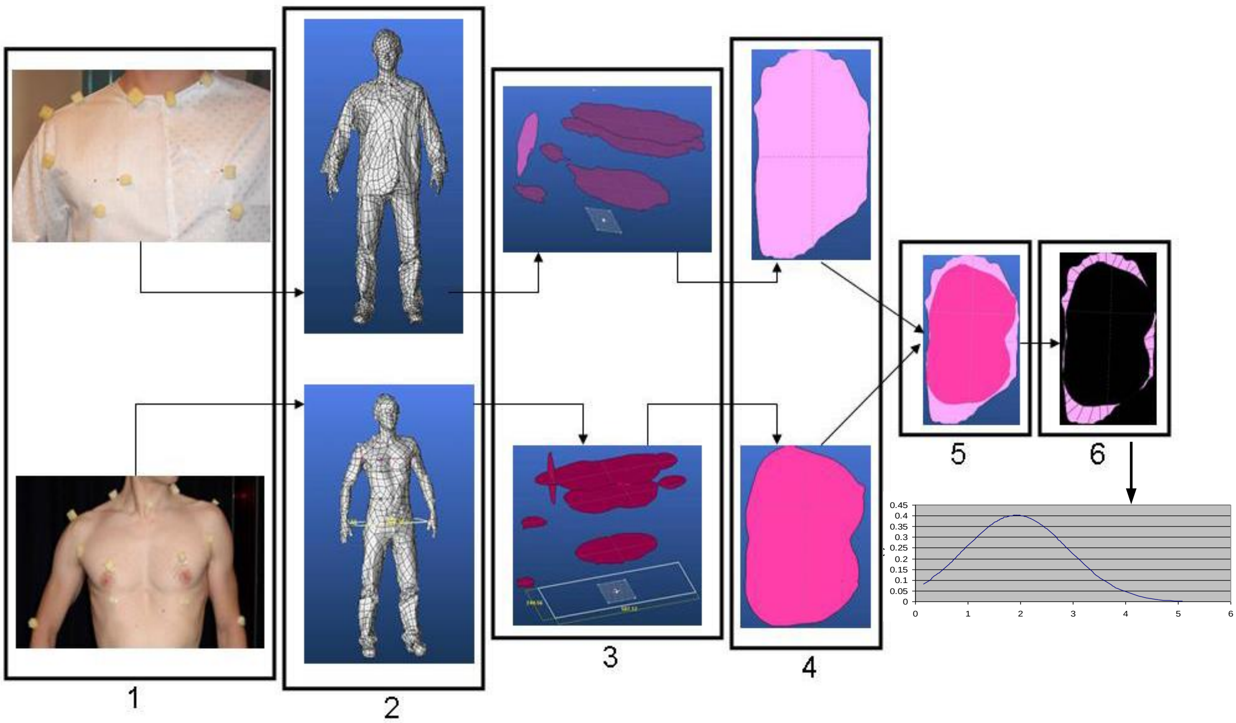


Figure 31 : Process to capture the image of the gap between the garment and the body

The evaluation of the overall 3D ease allowance is then obtained by an image processing method based on ellipses and a reverse methodology. This method has been applied to all the outlines (2D and 3D) needed for 3D garment design process and validated in this process. **Figure 32.a.b.c** explains how the gap between the body and the garment has been divided in different equidistant regions for wrist, elbow and shoulder. In **Figure 32.d**, the major axis of the ellipse method allows computing the 3D ease allowance for each region of the wrist. Similar works has been realized by Bingfei Gu et al. in order to calculate the pattern alteration of women's suits based on 3D ease distribution [88]. All of this works show a real interest to work with a 3D ease allowance and no longer a 2D ease allowance, especially if the garment design process is in 3D space.

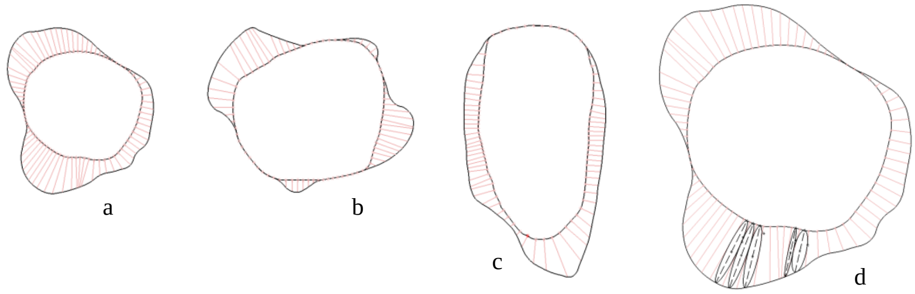


Figure 32: Division the gap between the garment and the body; Computing the 3D ease allowance par ellipse method.

I.5. GARMENT FIT EVALUATION

Garment fit is a part of a garment comfort, which is a broad phenomenon describing objective and subjective characteristics of a garment. As the garment fit is expressed by the individual and as it, it is unpredictable which factor is the most important in among others. Therefore, the definition of garment fit varies from author to author [89].

Definition of Garment fit can be applied to the population, as it is in ready-to-wear (RTW) scenario, or can have personalized approach as it is in mass customisation and made-to-measure (MTM) scenario. For the ready to wear the proper fit is related with the sizes and is acceptable when covers 80% of measured sizes [90]. This means that from the beginning it assumed the part of the population which will not be cover by the sizing system. It gives at least 20% of population without chance of finding a garment which fit them well or at all. The individual approach is impracticable from the perspective of RTW. The apparel industry challenged by the growing number of population disappointed by a lack of well-fitted garment went into mass customisation and MTM scenario. Here, fit, as a part of garment comfort, is understood from a broader perspective. There are the multiple conditions contribute the garment comfort and the same indirectly or directly the garment fit. One of the indirect factors is culture, occupation and age [91]. The direct factors influencing garment fit bound two approaches, subjective and objective. Acceptance of style, texture or printing depends on the subjective consumer's opinion. It plays a significant role in fulfilling the emotional needs, which can be different for every single person. Not without importance is the way of how fabric follows the body shape. Fabric physical and mechanical properties determine the draping and give different sensorial filling for an individual.

The objective approach is related to the procedure of pattern making thus with the anthropometrics measurements of the human body [92]. The anthropometric measurements [93] together with the method used to analyze those data [3] cover most of the fitting problems.

Basic role of clothing is to cover human body, and as the function, it has to fulfil a certain level of garment fit. Evaluation of the garment fit is made by conducting the real or virtual try-on.

I.5.1. Evaluation by real try-on

In the real try-on scenario, garment fit is evaluated on the patented mannequins represented for a range of sizes or morphotypes. In the process of evaluation on the dummies, to verify a subjective filling of the garment fit by the wearer, a value scale describing the degree of satisfaction of the result is defined. The sensory analyze is an evaluation of human senses (sight, touch,…). The sensory tests explore the subjective evaluation of consumer with a comparison of expert evaluation [89]. The judgment of experts' opinion on some technical issues can bring gradation of responses and together with subjective consumer evaluation lead to the most objective results.

For example, works in Ensait (Dhruv Saxena 2008) has been to conduct an online survey to get an overview of the actual requirement of a customized shirt among the men surveyed. In the survey they tried to investigate two key issues of a perfectly fitted shirt. The aim was to personally investigate the twin parameters; parameters of proper fit (aesthetics) and other being parameter of comfort level, which is directly related to the parameter of good fit. For the mentioned purpose they introduced the following tests to measure the satisfaction or dissatisfaction quotient among the surveyed men in relation to comfort. They answers based on the linguistics' scale (very good, good, average, bad and worst). **Figure 33** elaborates the tests in which the shirt was rated with respect to the position of the body. The region indicated in white is the area of maximum tension as figured in the relative body posture.

Figure 33: Body postures and zones of maximum discomfort indicated in white.

Similarly they conduct a fit analysis that has a direct consequence on the aesthetics of the garment. The self-indicative information of **Figure 34** formed the bases for the test.

Ease of insertion of one finger test for proper ease at the neck

Right level of the shirt until the lower hip level

Right level for fall of sleeve under both the given postures

Figure 34: Body postures and regions indicating proper fit of garment.

After the survey comprising of a sample size of 25 men of mostly Indian origin, they obtained the following statistical data which formed the basis of preliminary research of the team. The results from the surveys are given in the **Figure 35**.

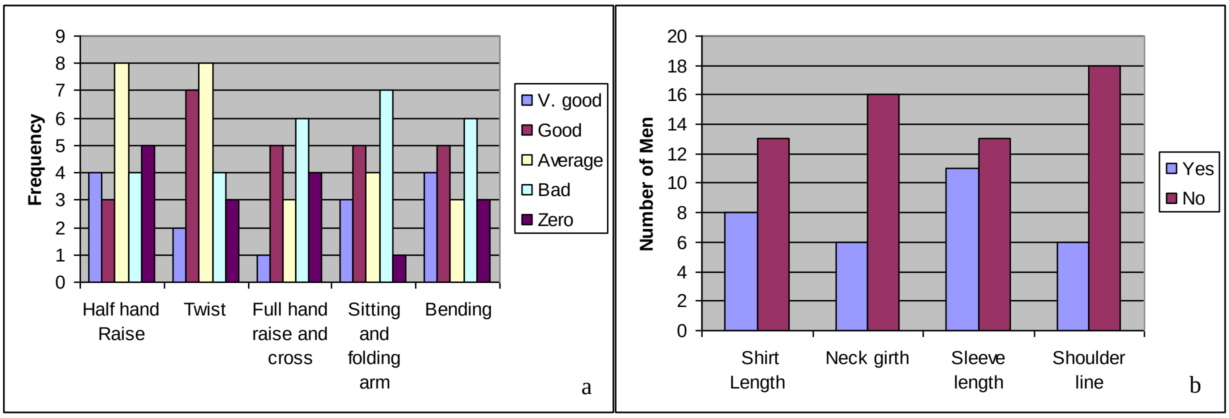


Figure 35: Results of survey: a) comforts factors in a particular posture and frequency of men suggesting the comfort level; b) number of men agreeing or disagreeing to the fit parameters of their shirt

This study is very interesting because it was a mean to design the fitted shirt of the wearer in the process of **Figure 31** [75] and the 3D ease allowance was connected with comfort of the wearer.

I.5.2. Evaluation by virtual try-on

The development of the CAD systems allowed now the 3D virtual try-on simulation of the garment. In the virtual try-on scenario the mannequins are obtained through 3D scanning. The mannequins represent certain size or morphology of target population or the individual client. The interest of this technology is to reduce the generation of real prototypes. A contrario, a wearer can't feel whether a garment is correctly fitted to his morphology like real try-on [94]. To solve this problem, different solutions have been proposed to evaluate garment fit of virtual try-on.

The first approach is to use the empirical knowledge of evaluators with different measured indicators, i.e. 3D ease allowance or air layer thickness between the garment and the human body [95, 96].

The other approaches are that the visual evaluation carried out on a 3D garment by fashion designers [97, 75]. The garment fit evaluation use pressure maps, stress maps and fit maps generated by virtual try-on software (**Figure 36**). However, the quality of the evaluation can be criticized because it strongly depends on mathematical models [66].

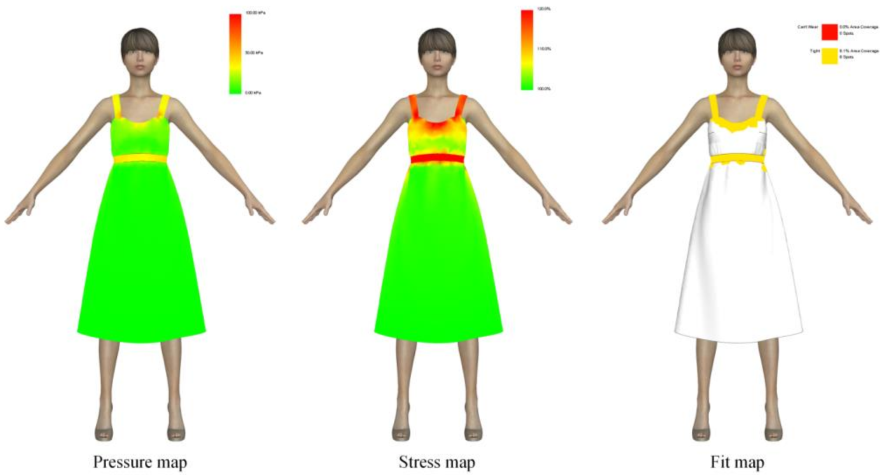
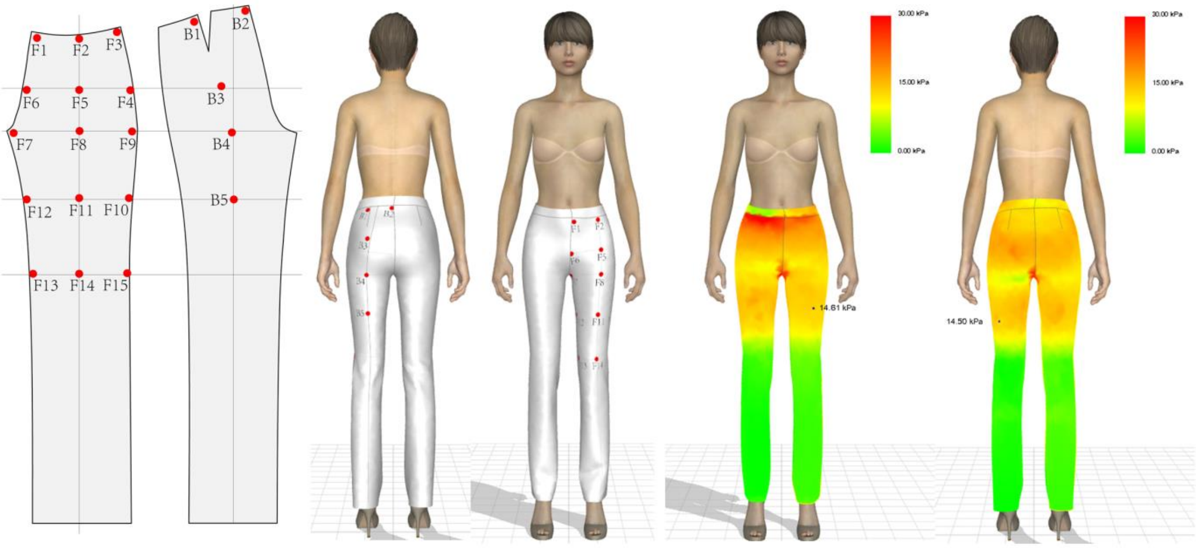


Figure 36: Garment fit evaluation with mathematical models.

K. Liu et al. have proposed a Naive Bayes-based model to evaluate garment fit [98]. Digital clothing pressures taken at different measuring points are the inputs of the model, the outputs are the predicted result of garment fit (fit or unfit) **Figure 37**. The learning model uses the real garment fit data and the digital clothing pressures. After learning procedure, their model can predict garment fit rapidly and automatically without any real try-on. The authors declare that to evaluate garment fit, it's better to use pressure than 2D ease allowance.

I.6. MASS CUSTOMISATION IN APPAREL INDUSTRY

The customer expects the garment to be fashionable, functionally acceptable and unique show his/her one of a kind visual image adapted to the body shape and reflecting the desired personality. As a result of customers' demands market has responded with the creation of initiatives, which later became the ongoing business models, one example of which is the mass customisation and this includes co-design strategy.



(a) Measuring points **(b)** Virtual try-on **(c)** Measuring clothing pressure

Figure 37: Digital clothing pressure measurement by virtual try-on.

I.6.1. Concept on mass customisation

The precursor of garment' customisation in the fashion world of the nineteenth century was an English designer and dressmaker, C.F. Worth [99]. It was under his impetus that we witnessed the birth of haute couture in the 1860s. This phenomenon originated in PARIS, called "the city of light", attracting prodigies from all over Europe. Charles Frederick Worth built a line of products (dresses) where a single dress was not the same as other. The differences were in details added or changed for the basic model according to the wish of the consumer. That time the idea of mass customisation was born [100].

Mass customisation from the last four decades constitutes a successful business model for many fashion brands, such as Nike, Adidas, Indochino.

To ‘developing, producing, marketing, and delivering affordable goods and services with enough variety and customisation that nearly everyone finds exactly what they want’ [101] the producers apply a mass customisation model to their service.

In a model of mass customisation in online retail the communication between manufacturer and consumer is carried out via the Internet. The idea behind is to build a co-design digital platform, thereby ensuring different modules so that comfortable and fashionable garments can be created.

I.6.2. Concept on co-design in garment retail

Co-design is a term used in mass customisation to describe the relationship designer-client. In contrast to the traditional approach, co-design allows a direct customer contribution in the preparation of a project or product. The consumer is supported by a vast package of tools and techniques which would enable to be a part of the experts’ panel with its own experience.

Most of the well-known fashion brands propose some form of mass-customisation. Nike introduced NikeiD custom shoes and accessories; Adidas besides shoes propose apparel customisation; customizable T-shirts, blouses or Shirts becoming more common on the market (Bow&Drape, Indochino, BlankLabel, I-Tailor).

From the spectrum of given products and modules variation, the individual customer can create his/her own garment by using co-design process. This approach gives added values to the business model by direct involvement of customers’ needs. The product is produced after it has been chosen and paid, permitting to reduce the unsold risk. According to the nature and level of customer’s participation in the co-creation process, one can determine the design solution or/and related fit level.

The concept of co-design in virtual prototyping (**Figure 38**) is crucial in consumer decision-making process. It leads to a personalization of made-to-measure garments.

From the survey [102] of 561 European respondents, it follows that a majority of online consumers wish (43%) or probably wish (39%) to obtain personalized products. 82% percent of respondents are willing to benefit from personalized products and services adapted to their expectations, constituting a high signal for mass customisation in the apparel industry.

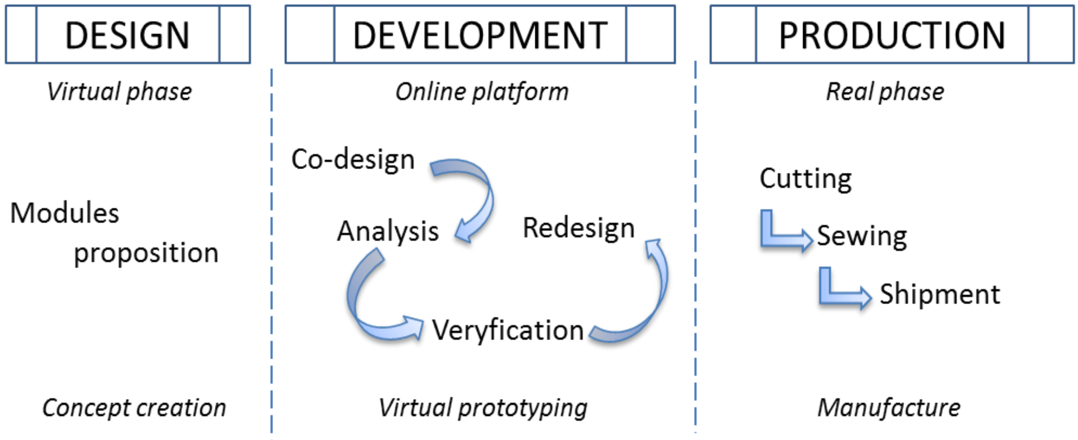


Figure 38: Concept of co-design for the online garment retail.

Thanks to the emergence of information technology, internet, and 3D scanners technology, the made-to-measure scenario in mass customisation have been made possible and grow quickly in the online fashion markets. In mass customisation, the individual consumer can personalize the design of a new product by choosing the combination of colour, style or accessories according to given variety of existing modules. Under the made-to-measure concept, the level of customisation is much higher and concerns the finished product which will be created. In garment retail it requires relevant tools, like 3D scanners, ensuring the proper measurement of the individual body. Based on the adequate measurements the personalized profile and/or personalized mannequin of the individual customer are created. Today's technology allowed the 3D garment visualization on the personalized mannequin to help the individual customer making a choice and "the patternmaking software provides the capability to adapt the standard pattern to specific design and size" [103]. As a creation of a particular garment is a complex matter itself, the whole production technology must be coherent to be cost-effective. An E-commerce sale in this scenario is more assorted, and the order size is much smaller. Therefore, the manufacturing capabilities of mass customisation must be tailored to these challenges.

I.7. CONCLUSION

In this chapter, we have introduced the state of the art of modeling the human body, modeling of the garment and dependencies between them described by elaborating of 2D/3D ease allowance. Then we have presented means to evaluate those dependencies by various methods of garment fit determination. Also, we have presented the different scenarios which are often connected with e-commerce like mass customisation and the co-design.

The whole of these works shows that CAD, 3D technology and virtual products have to strongly be integrated and used in the clothing industries. The applications of such technologies are also in the Interest of fashion brands, especially in e-commerce and mass-customisation. The technologies which have to be developed and implemented to enable digital garment design have to be applied to different sections of the manufacturing process. **Figure 39** represents sectors in which technology development is needed to enable entering a virtual design in online sales space. We clearly see the need for a global view of the process of digital clothing manufacturing.

Figure 39: Technology development sections in digital manufacturing technology.

CHAPTER II: TOOLS USED IN THE RESEARCH

The goal of this chapter is to present the various scientific and technological tools, as well as the different theories that were used in our research.

This one must answer a very complex problem which is the sale by internet of garments without real contact with the end product. The act of purchase is strongly related to the requirements of a good adjustment of the product on the customer. The question that arises is how to try-on garment on the internet without having any contact with it.

Our first contribution in this area has been to put in place a new customer's pattern recognition process (**Figure 40**). For this, we used a morphological database sufficiently complete to represent the population. This database was classified in order to extract the different morphotypes representative of each class according to a morphological criterion. Each morphotype was compared with the client by its frontal and side image in order to assign it to a morphological class. This assignment automatically creates a mannequin close to his avatar and its block pattern. It is from 3D adaptive morphotype mannequin that we have come to this result.

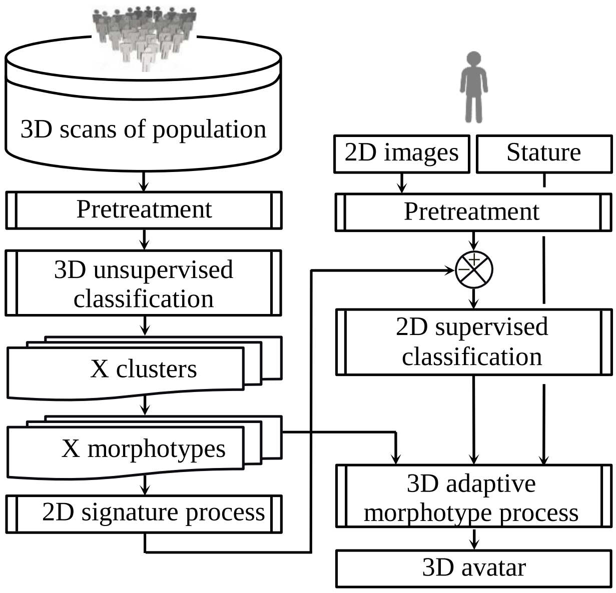


Figure 40: 3D Pattern recognition of morphology.

Another contribution was to analyze the 3D virtual try-on of the garment. The previous process requires knowing the value of the 3D ease allowance between the client and the garment because it acts on the garment fit, its comfort, thus the customer's perception. Based on the context and research plan described previously, the tools for data acquisition and related data mining used in the research will be outlined. All these tools will be used in a complementary way in order to set up a data-based model characterizing the relationship between the measured input variables (human perception on garment fit, fabric parameters, body data) and the output variable (3D ease allowance). By using this model, we wish to predict, for a specific consumer's body shape, the relevant value of ease allowance from a given fabric and desired garment style. The predicted ease allowance value will enable to generate personalized garment patterns by using a 3D garment design software in a virtual environment (seen in the first contribution).

In this contribution, the key issues include 1) data acquisition for the input and output variables, 2) setting up a fuzzy model by learning from collected data.

The stage of data acquisition concerns client's 3D body, fabric technical parameters testing, and design-related human perceptual data collection (garment fit and fabrics). Fuzzy theory has been selected for modeling due to its capacity of processing uncertain and imprecise data provided by human evaluators (**Figure 41**). For making virtual try-on with a predicted 3D ease allowance value, we first generate human body model (client's body) from a 3D scanner, introduce these data into a garment CAD software to apply our 3D ease allowance model on the morphological curves, create the garment with our graphics model from anthropometric points, and combine them with selected design parameters (fabric physical for realizing virtual garment fitting on a specific human body shape.

The next paragraphs propose chronologically the tools and theories necessary to realize these contributions.

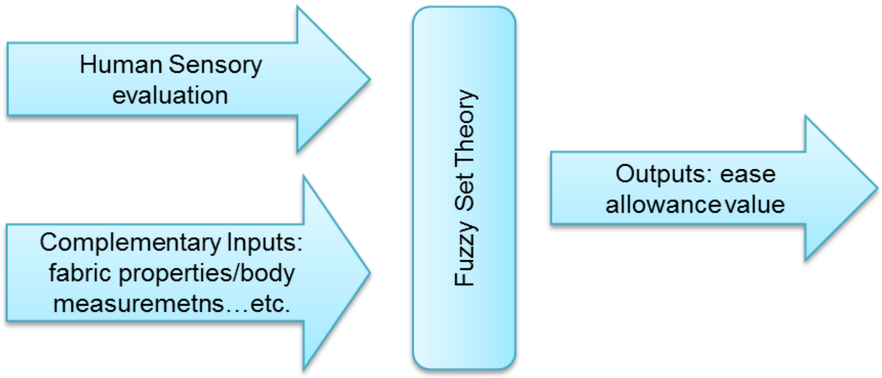


Figure 41: Predicting the ease allowance value from related input data using fuzzy theory .

II.1. PATTERN RECOGNITION TOOL FOR CUSTOMER

II.1.1. Acquisition of 3D virtual body

To obtain the 3D virtual body of the subjects we used 3D SCAN Tecmath from Human Solution. After the process of scanning the data are exported to the ScanWorX

(**Figure 42.a**). ScanWorkX [104] is a software which imports and digitizes the data from the scanner. Then in the pre-processing, the scan is purifying and smoothing. After, based on feature points positioning by AutoMeasure application the automated measurements are taken and visualized on the scan by 'virtual type measure.' The data obtained in the ScanWorX software are imported as triangular meshes (STL. file) to the RapidForm where defects and noises are removed (**Figure 42.b**). The most challenging to recover are armhole and crotch areas. They are treated carefully by using software tools for cleaning, boundary creation, and holes filling.

Once all repair processes are completed the entire mesh can be smoothed and exported in the OBJ or VRML format. The so prepared mesh can be exported in a CAD-environment to be used in a 3D manufacturing strategy (**Figure 42.c**) or in Matlab to classify the body.

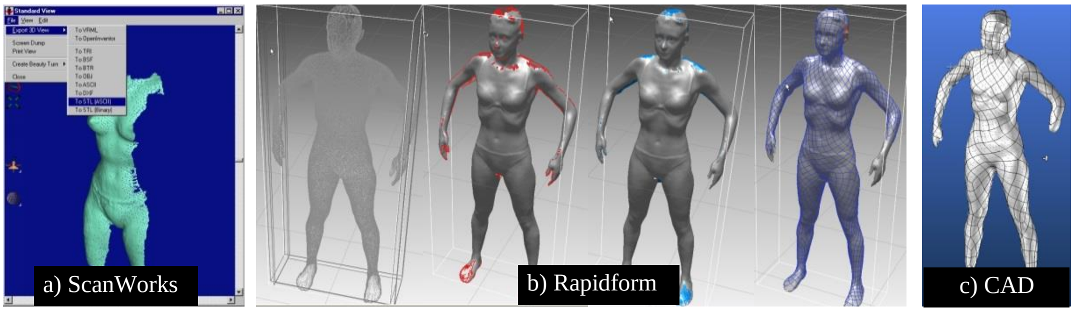


Figure 42: Acquisition and image treatment of human body.

II.1.2. 3D unsupervised classification

II.1.2.a. 3D shape preprocessing

The 3D shape preprocessing is composed of three steps: data acquisition, data segmentation, and data normalization. The goal of the first step is to obtain 3D body scan data exploitable for further processing. It consists of filling holes in the hidden zones under arms and in the crotch, removing measurement noises, smoothing and optimizing the mesh by an automatic procedure to clean the body scans. The second step is a segmentation step to create suitable torsos. Taking into account anthropometry and morphology analysis, the bodies are segmented with section planes located at anthropometric points recognized automatically by the body scanner (landmarks on the body). The compatibility between each torso, defined by the size and the number of triangles, is obtained by re-meshing the torsos. The third step represents the 3D object normalization (translating and scaling). For that, we use the minimal bounding sphere method with the algorithm of Gärtner [105] for its precision and fast processing time (**Figure 43**). The Gärtner algorithm computes the normalized vertex (x_n, y_n, z_n) from an original vertex (*x*, *y*, *z*) as follows:

$$x_n = \frac{x - c_{x,s}}{d_s}, \quad y_n = \frac{y - c_{y,s}}{d_s}, \quad z_n = \frac{z - c_{z,s}}{d_s} \tag{1}$$

with

d_s, the sphere diameter,

$c_{x,s}$, $c_{y,s}$, $c_{z,s}$, the coordinates of the sphere center.

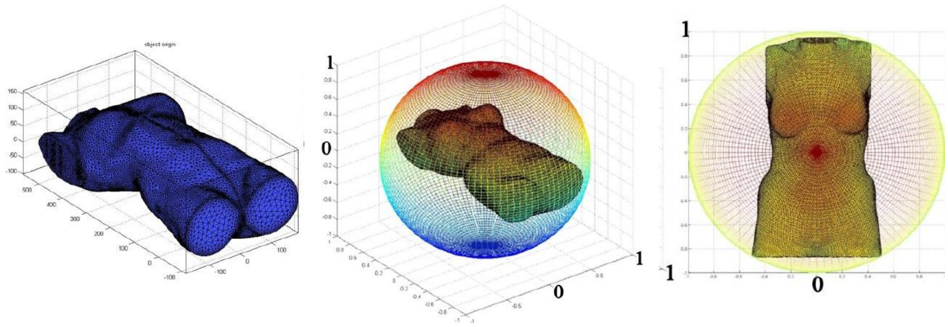


Figure 43: Normalization with the minimum bounding sphere.

II.1.2.b. 3D clustering method

The 3D shape descriptor has to be very sensitive to dissimilarities which enable it to differentiate between morphologies such as the waist, hips, and bust. Geodesic path and distribution of geodesic distances are tools especially interesting in terms of non-rigid shape description and has a low sensibility to posture variations. However, the location of reference points (or starting points) obviously impacts the results and shall be carefully performed. Thus, these reference points should be directly defined by anthropometry properties. The shape descriptor represents the statistical distribution of the geodesic distances between reference points and all points on the 3D torso mesh. The geodesic distances are computed by the well-known Dijkstra's algorithm [106], the geodesic shape distributions use the kernel density estimation [107] to calculate the probability density function of the data.

The clustering method used in this study is the straightforward k-means algorithm [108]. The k-means method splits the data set into disjoint clusters from numeric attributes. However, the random initialization of the center of classes (or centroid) and the requirements of several iterations to check the convergence of the algorithm lead to different final clusters. The goal is to find the right compromise between too many clusters (bad separability) and not enough clusters. To find the optimal number of clusters and to evaluate the quality of the obtained clustering, we compute the Davies-Bouldin (DB) criterion clustering evaluation [109]. The Davies-Bouldin criterion is based on a ratio of within-cluster and between-cluster distances, i.e.:

$$DB = \frac{1}{k}\sum_{i=1}^{k} \max_{j \neq i}\{D_{i,j}\},\ D_{i,j} = \left(\overline{d_i} + \overline{d_j}\right) / \overline{d_{i,j}} \quad (2)$$

with,

$D_{i,j}$, the within-to-between cluster distance ratio for the i^{th} and j^{th} clusters.

$\overline{d_i}$, the average distance between each point in the cluster i and the centroid of the cluster j

$\overline{d_{i,j}}$, the Euclidean distance between the centroids of the i^{th} and j^{th} clusters.

The optimal clustering solution has the smallest Davies-Bouldin index (**Figure 44**).

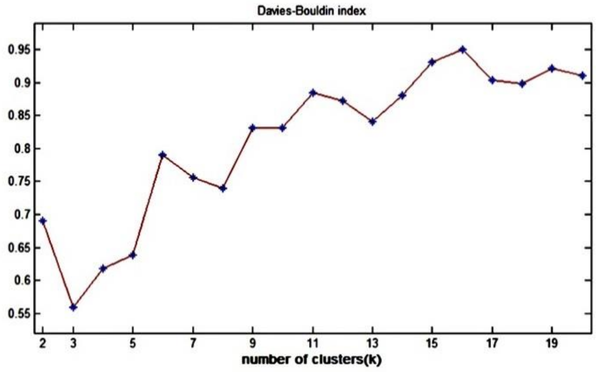


Figure 44: Quality of clustering by Davies-Bouldin index.

II.1.3. 2D supervised classification

II.1.3.a. Image capture protocol

It is considered that to build an accurate system of morphology detection; different conditions must be met. To provide normalized images the subject has to be informed about the protocol of taking the images. For our tests, the distance between the camera and subject was kept as one meter, while the target line is parallel to the ground (or focal plane is perpendicular to the ground). The experiments were carried out using a Kinect RGB camera. The images were framed between the crotch and the 7th cervical with resolution 1280x 960 pixels. Additionally, each subject's height was used as a calibration measure in the morphology reconstruction. It is imperative that the garment be worn close to the body. A black garment on a white background is strongly advised.

II.1.3.b. 2D image pre-processing

The 2D pre-processing of images is composed of four steps: data acquisition, data segmentation, data normalization and boundary detection of the silhouette. Before seeking the client's morphotype, the images need some pre-processing to be useful. The image's height is reframed between the crotch and the 7th cervical and width to 125% of the width of the hips. From this previous work, the image is converted to grayscale by eliminating hue information and saturation while retaining the luminance (**Figure 45.a**).

The binary image can now be segmented. Thereby, the image is converted by thresholding. The threshold is defined by the method of Otsu [110] which chooses the threshold to minimize the intraclass variance of black and white pixels. Let the pixels of a given picture be represented in L gray levels levels $[1, 2, \ldots, L]$. The number of pixels at level i is denoted by n_i and the total number of pixels $N = n_1 + n_2$. To simplify the discussion, the gray-level histogram (**Figure 45.b**) is normalized and regarded as a probability distribution:

$$p_i = \frac{n_i}{N},\ p_i \geq 0,\ p_1 + p_2 = 1 \qquad (3)$$

Then we dichotomize the pixels into two classes C_1 and C_2 (body and background) by a threshold at level k. C_1 denotes pixels with levels $[1, \ldots, k]$, and C_2 denotes pixels with levels $[k+1, \ldots, L]$. Then the probabilities of class occurrence and the class mean levels, respectively, are given by:

$$w_1 = \Pr(C_1) = \sum_{i=1}^{k} p_i = w(k) \qquad (4)$$

$$w_2 = \Pr(C_2) = \sum_{i=k+1}^{L} p_i = 1 - w(k) \qquad (5)$$

$$\mu_1 = \frac{\sum_{i=1}^{k} i p_i}{w_1},\ \mu_2 = \frac{\sum_{i=1+k}^{L} i p_i}{w_2}, \qquad (6)$$

The variances of class C_1 and C_2 are provided by:

$$\sigma_1^{\ 2} = \sum_{i=1}^{k} (i - \mu_1)^2 p_i / w_1 \qquad (7)$$

$$\sigma_2^{\ 2} = \sum_{i=k+1}^{L} (i - \mu_2)^2 p_i / w_2 \qquad (8)$$

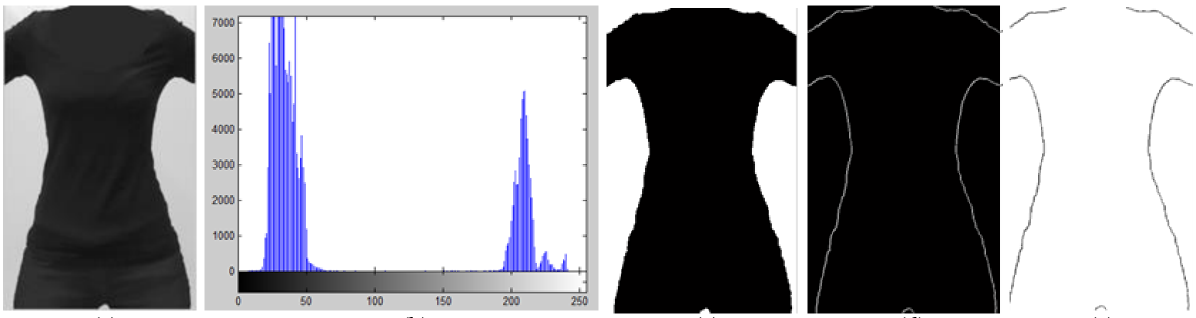
Now, the image is separated into two parts (**Figure 45.c**). To improve the comparison between images they have been normalized. In this case, all images are redefined to 600x400 for the face images and 600x250 for profile images. After this step, the silhouette can be extracted. For the step of the silhouette extraction (**Figure 45.d**, **Figure 45.e**), which amounts to a contour detection problem, the Sobel's and Prewitt's filter is simultaneously used [111, 112]. The operators calculate the gradient of the intensity of each pixel. It shows the largest change from light to dark in the different directions, corresponding to the edges. Each filter uses the matrix $[3\times3]$ which is convoluted with the image to calculate the horizontal and vertical derivative approximations. Having two images G_x and G_y, and A defined as the source image the computations are as follows:

$$G_x = \begin{bmatrix} -1 & 0 & 1 \\ -k & 0 & k \\ -1 & 0 & 1 \end{bmatrix} * A, \quad G_y = \begin{bmatrix} -1 & -k & -1 \\ 0 & 0 & 0 \\ 1 & k & 1 \end{bmatrix} * A \tag{9}$$

with $k=1$ for Prewitt's operator and $k=2$ for Sobel's operator.

At each point, the resulting gradient approximations give the gradient magnitude using:

$$G = \sqrt{{G_x}^2 + {G_y}^2} \tag{10}$$



(a) (b) (c) (d) (e)

Figure 45: Silhouette extraction process.

II.1.3.c. 2D classification method

The goal of the 2D classification is to assign the client to a cluster trough 2D shape descriptors of their torso. To measure the similarity between the client and the morphotype a similarity function has to be defined. The Dice coefficient [113] also known as Sorensen-Dice or Dice Similarity Coefficient (*DSC*) is used in this research. It is a statistic tool adapted for comparing the recovery of two samples. In other words, it defines the differences between two groups by reflecting either the presence or absence of certain characteristics. It is widely used in medical imaging [114] and studies of genetic relationships in biology [115]**.** This similarity coefficient DSC is presented in the original formula in equation (11),

$$DSC = 2\frac{|X \cap Y|}{|X| + |Y|} \tag{11}$$

where $|X|$ and $|Y|$ are the two sets of samples considered to be compared to define the value of similarity. It was adapted to meet the requirements of the experiment and will be explained later in the paper.

To weight the information coming from the two viewpoints, the *DSC* is applied to the two images of the anterior and lateral views. The expression of the final similarity τ was:

$$\tau = \frac{(\alpha \times DSC_{anterior} + \beta \times DSC_{lateral})}{\alpha + \beta} \tag{12}$$

where α and β were found empirically on a sample of the database.

II.1.3.d. Pre-processing of 3D into 2D shape descriptors

It is from the actual morphology of a client closest to the centroid of the class that we conceive the adaptive morphotype mannequin. To be consistent in our strategy of pattern recognition, we must therefore detect the silhouette of the adaptive mannequin from the morphology of the morphotype, and this for each class. The silhouette of the adaptive morphotype mannequin, seen from the front and from the side, represents our shape descriptor.

If we use the tool integrated in the software to create the silhouette on this 3D shape, the figure shows that the results are unusable (**Figure 46.a.b**). Therefore, we created our own procedure to detect the 2 silhouettes sought (face, side).

The first step is to cut the body by different planes controlled by the position of anthropometric points (**Figure 46.c**). The torso is thus extracted with the same procedure used in the classification.

Then, the detection of the frontal silhouette requires to create two section-planes parallel to the frontal plane, positioned at locations judiciously, to create two section curves (**Figure 46.d**). The foreground makes it possible to obtain the good silhouette for the side while the second plan makes it possible to improve this one for the shoulders. The fusion of these two curves in the same plane makes it possible to obtain a correct silhouette (**Figure 46.e**). This choice of two planes is necessary because of the non-symmetry or bad posture of the human body.

We use the same procedure for the side silhouette. The first section-planes parallel to the sagittal plane allows obtaining the silhouette in the axis of the chest whereas the second plan makes it possible to improve this one for the belly and in the median hollow at the level of the vertebrae. The final 2D shape descriptors are given in **Figure 46.f**.

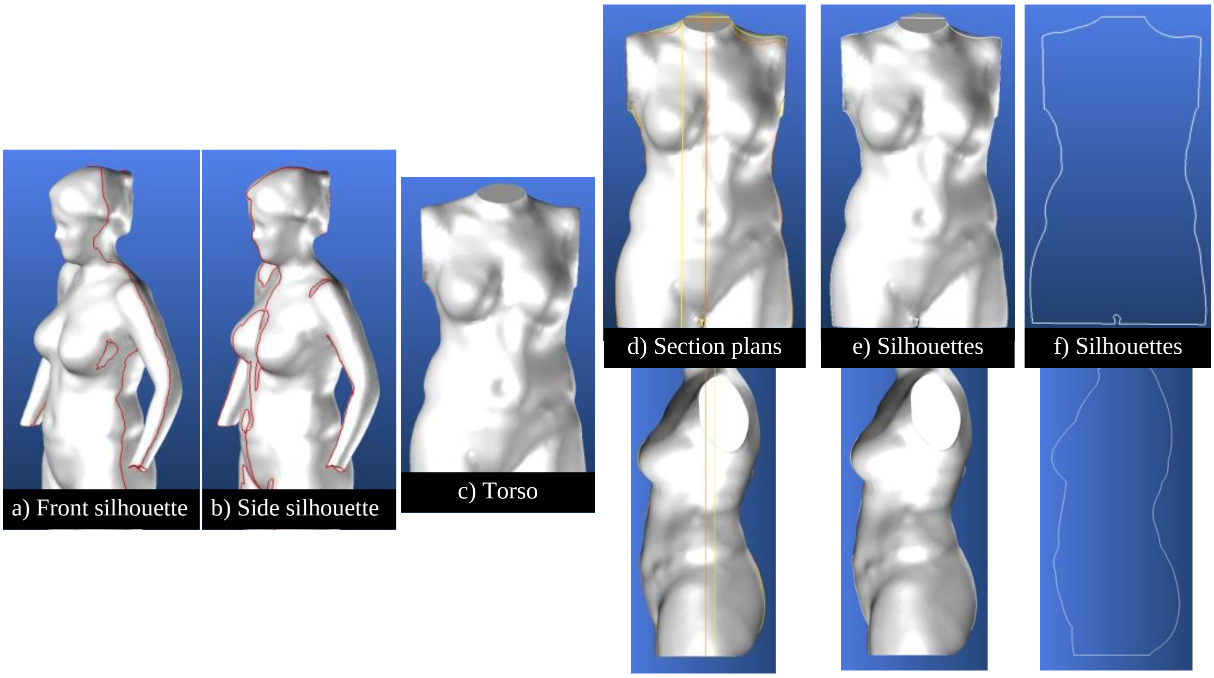


Figure 46: 2D shape descriptors process.

II.2. HUMAN BODY MODEL THEORY

Let us recall that the adaptive morphotype mannequin is used in the automatic process, while client's avatar is used during the study of 3D ease allowance. This last one has to be precise during the morphological contours recognition but requires less key position when compared with the adaptive morphotype mannequin. However these two human models have to be connected with the 3D ease allowance model, then the garment model with the same strategy.

II.2.1. Modeling relations between key body dimensions for client's avatar

In order to respect the concept of beauty found in A. Loomis (Figure 1) and Leonardo de Vinci [1], we followed the rules of the eight-headed canon to locate the main morphological contours of the client's avatar (**Figure 47**). This concept of beauty has also been applied to other contours called secondary contours with ratios proportional to the head's height (Canon).

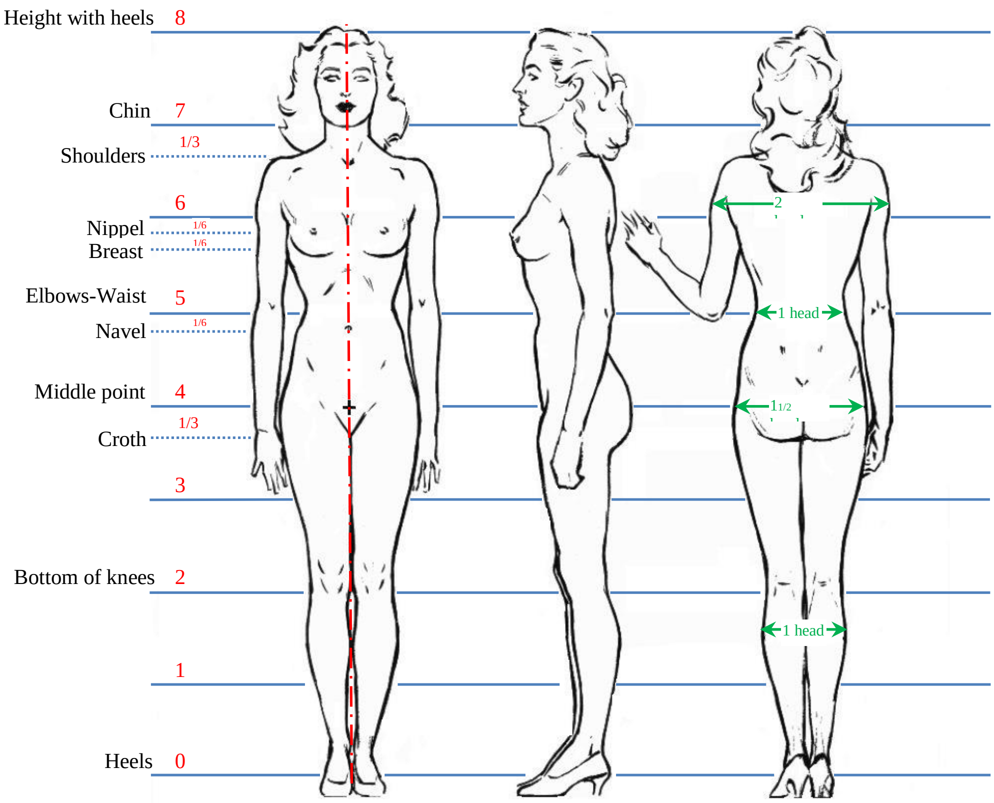


Figure 47: Ideal proportion of the body by A.Loomis.

II.2.2. Modeling relations between key body dimensions for adaptive morphotype mannequin

The modeling of the adaptive morphotype mannequin requires more morphological contours because we have to recreate a morphology similar to the morphotype. In a first step, we use the same strategy as the client's avatar to define the position of the primary contours (**Figure 48.a**). The proportions have been preserved but, in practice, the position of each contour has been calculated in relation to the height h of the morphotype to more easily control the mannequin adaptive in the vertical direction (**Figure 48.b**). Then, other secondary contours are created relative to the primary contours in order to more accurately follow the shape of each muscle (**Figure 48.c.d**). We used the same technique as A.Cichoka [116] to model the arms and control the volume of the final mannequin.

II.3. 2D/3D EASE ALLOWANCE MODEL

Most 2D/3D ease allowance models are based on the center of gravity of the morphological contours (**Figure 49**). In a first step, various points where one wishes to put a 2D/3D ease allowance are distributed on the morphological contour.

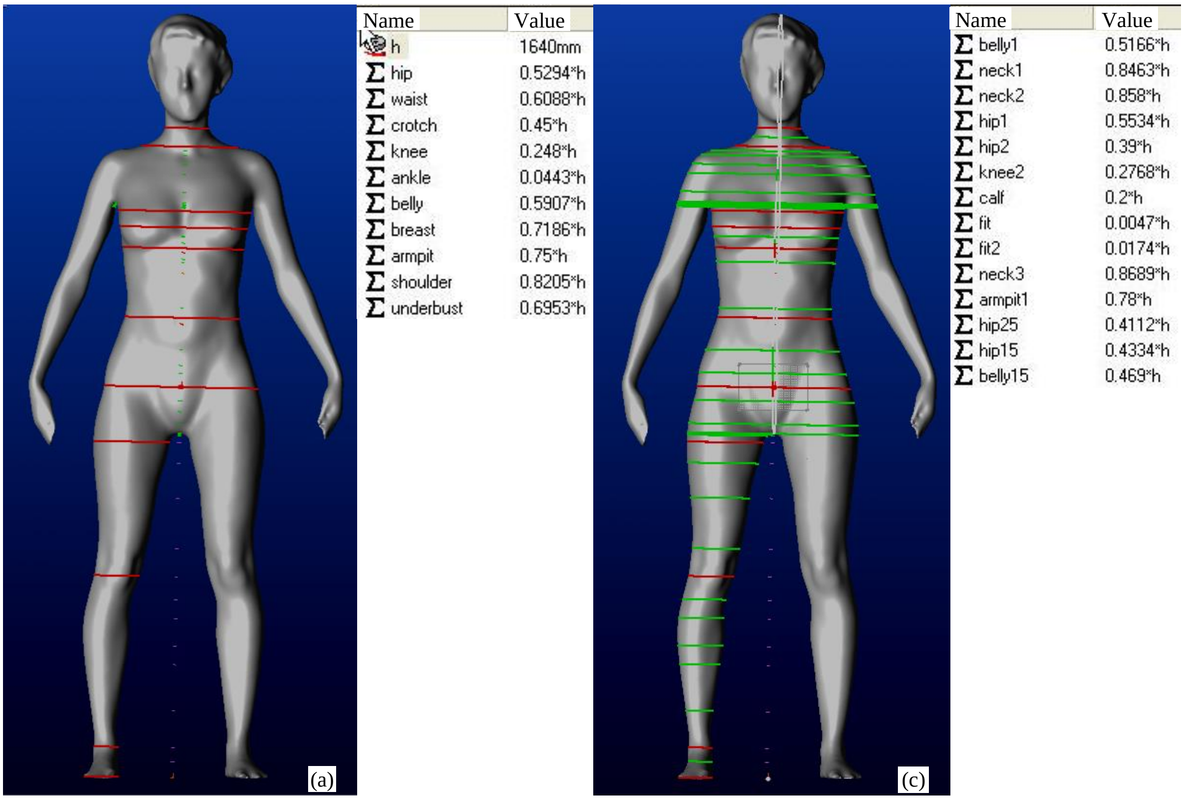


Figure 48: Proportions of the adaptive morphotype mannequin

Each point is then shifted independently in the direction of a guideline defined by itself and the gravity center of the contour. The distance between the two points represents the ease allowance value. The problem with this method is that the ease allowance value must be different from one point to another since the direction of his associated vector is imposed by this guideline. Thus, for a given contour, the authors are found on average with 20 values of ease allowance, which is huge considering the number of outlines necessary for the design of a garment.

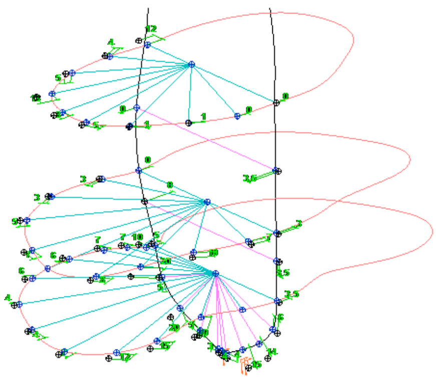


Figure 49: 2D ease allowance model by A. Cichoka [116].

Our strategy was therefore to find a 2D/3D ease allowance model connected to a reduced database. Two models have been implemented:

- 2D ease allowance model with morphological curves,
- 3D ease allowance model by zona.

II.3.1. 2D ease allowance model

The goal of our 2D ease allowance model is to be closed to the reality of measurement of the 3D ease allowance by S.Thomassey & P.Bruniaux **[75]**. The modelling starts with the division of the morphological contours into four parts to separate the front of the back, the left side of the right side (**Błąd! Nie można odnaleźć źródła odwołania.**). The lines in the middle front, middle back, left and right sides detect these points by the intersection with the morphological contours (red and green points on **Błąd! Nie można odnaleźć źródła odwołania.**). Three points can thus be distributed on each piece of curve. For all the points, we create an ease allowance line perpendicular to the contours whose length represents the value of the 2D ease allowance. Two values of ease allowance are then chosen one for the front and the other for the back.

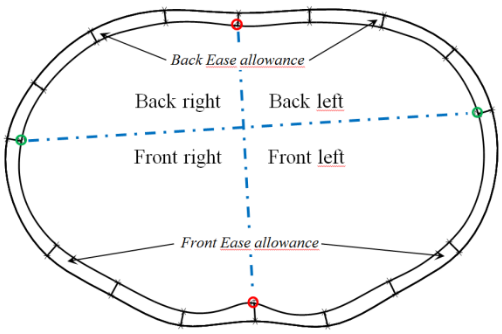


Figure 50: 2D ease allowance model.

II.3.2. 3D ease allowance model

The 3D ease allowance model is a model directly created in the 3D space in order to correctly mold the surface of the zones with strong contact, i.e. the salient parts of the body (scapula and breast) (**Figure 51**). First, we need to create the different morphological curves (red curves) that converge on the salient point (red point). A straight line (blue line) is drawn between the salient point and one of the points defined on the outside contours of the 3D pattern. This line is printed on the body in order to follow the body in a specific direction towards this external point (red curves). A sliding point (white cross mark) is created on this curve close to the contact zone. Another line (white line) is then defined between this sliding point and the same point of the outer contour of the 3D pattern. By moving the sliding point we can detect the tangency point on the morphological curve. A new curve is then created composed of the straight line (white line) connected to the sliding point and the piece of morphological curve joining the salient point.

The 3D ease allowance is given only on the salient point which constrains this curve to pivot on its other end. The set of green curves then define a surface molding the body in the area of the salient point with ease allowance value distributed and controlled by a single value.

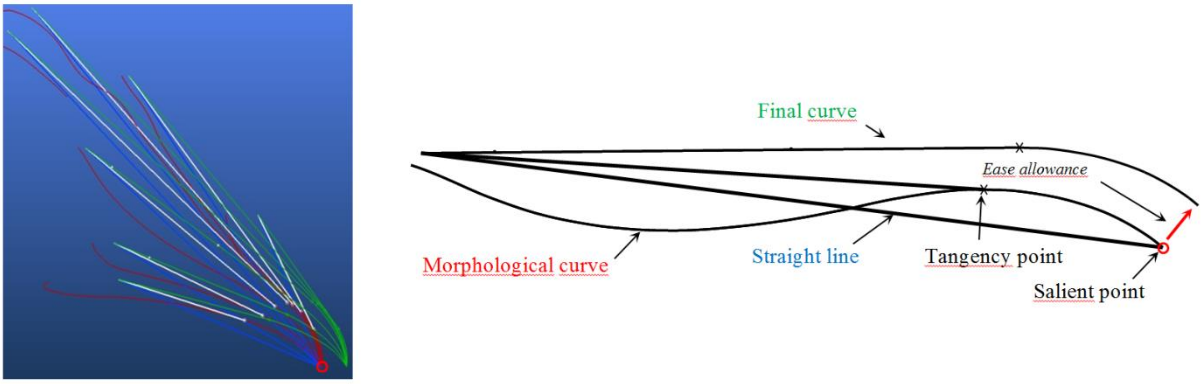


Figure 51: 3D ease allowance model

II.4. GRAPHIC MODEL OF GARMENT

The garment model is a 3D graphic model which has been developed from the conical principle of S. Efrat (**Figure 24**). The author uses different anthropometric points on the body to position his model in relation to the morphology.

Then 4 types of lines start at these different points to join on the 4 salient points (scapula, breasts). In the areas surrounding these points, the lines tend to cross the body. Our graphics model avoids this problem by improving it in these contact areas, as we explained in **Figure 51**. This modelling leads to create the block pattern of this body which is a pattern following perfectly the body without 3D ease allowance. Our garment model is connected to the 3D ease allowance model to lead to a fit garment to the body with a hierarchized management of the ease (**Błąd! Nie można odnaleźć źródła odwołania.**).

II.5. GARMENT FIT EVALUATION TOOLS

To analyze the garment fit, we need to drape the garment on the body in a 3D space. The different inputs required to simulate this operation are the client's 3D body, the garment patterns and the mechanical parameters of the fabric. This dataset associated with the fabric simulator leads to the virtual 3D virtual try-on.

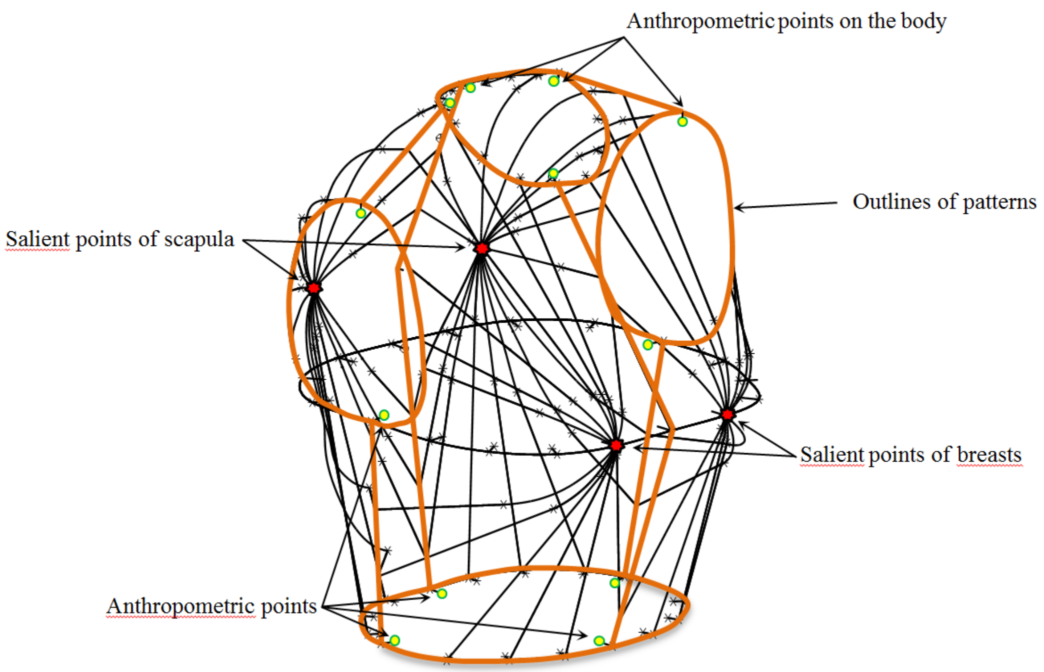


Figure 52: Graphic model of garment with 3D ease allowances.

II.5.1. Acquisition of technical parameters of fabrics

Quality is prime importance for the textile products, especially with regards to clothing. Together with visual effects, the 'hand' of fabric provides for quality of the garment.

To avoid the experts' judgments every time the development and implementation of objective measurements of fabric handle was a necessity in apparel fields. The progress in technology led to the creation of modern systems for fabric characteristics. As a result, the fabric mechanical and physical properties are measured by instruments and using equations are converted into Hand Value. The first, system, called Kawabata evaluation system (KES-F), was introduced in 1972 by S. Kawabata [117]. A few years later in Australia CSIRO introduced instruments to define wool mechanical properties called FAST (Fabric Assurance by Sampling Testing). It is much cheaper and simpler alternative to KES and as a result of which is more likely used in apparel engineering.

Those objective methods for the fabric handle evaluation are widely used in textile industry. The physical properties of the fabrics are measured while maintaining the specific laboratory and instruments conditions despite place. This process adds the value as the tools facilitating the communication between merchants, designers, and engineers at every stage from the fabric to the garment design process.

II.5.1.a. KAWABATA system

Kawabata Evaluation System, KES, consists of four mechanical modules where sixteen parameters are elaborated. First module KES-FB1 (**Figure 53.a**) measures shearing and tensile properties, second KES-FB2 (**Figure 53.b**) bending properties, third KES-FB3 (**Figure 53.c**) compression properties and fourth KES-FB4 (**Figure 53.d**) measures surface properties. Each property can be described by two or three mechanical parameters.

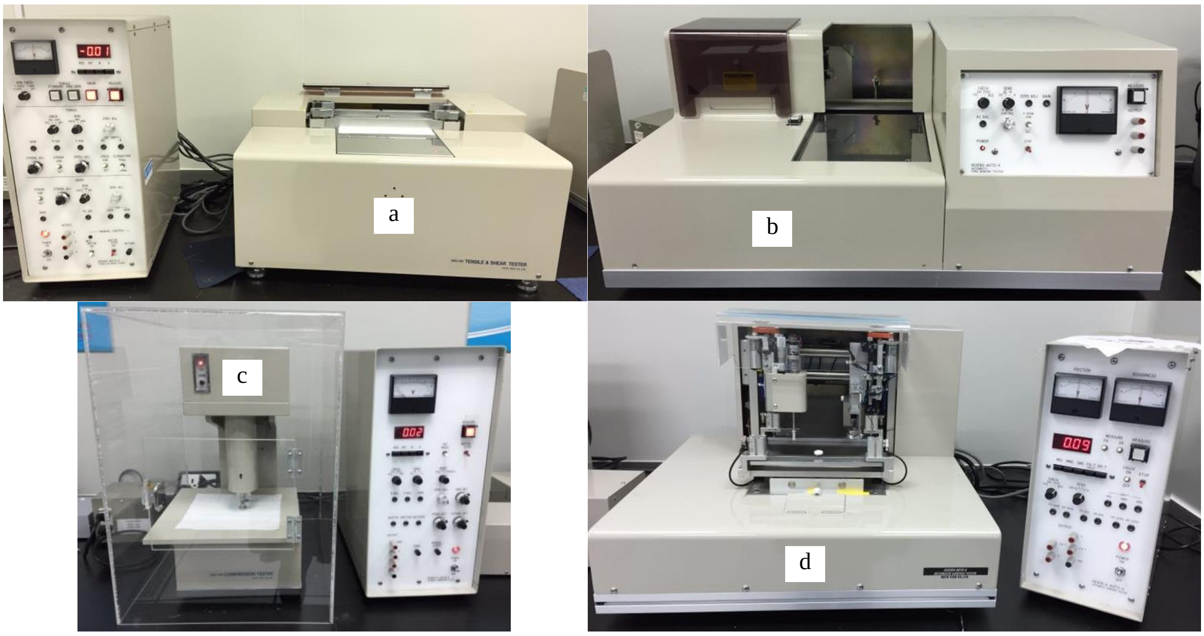


Figure 53: Different modules of KES.

II.5.1.b. FAST system

Fabric Assurance by Simple Testing, FAST, is a measuring system with three measuring devices and a test method: FAST-1 is a compression meter (**Figure 54.a**), FAST-2 is a bending meter (**Figure 54.b**), FAST-3 is an extension meter (**Figure 54.c**). Each instrument measure set of parameters describing particular measurement. Originally was dedicated to specifying the specification of the woolen fabrics.

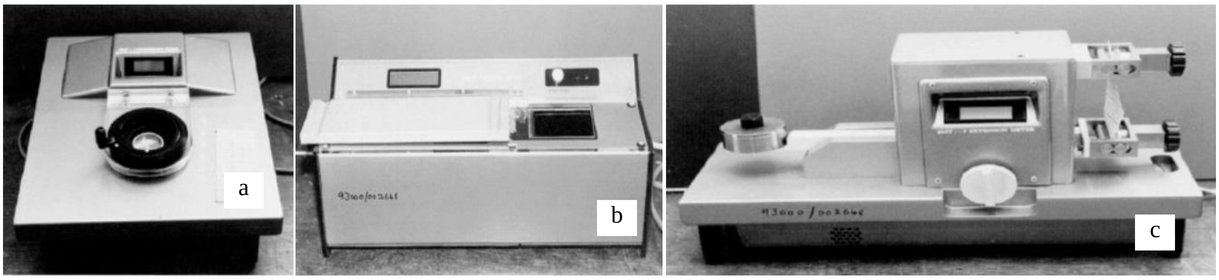


Figure 54: Different modules of FAST.

II.5.1.c. Drape measurements

Fabric drape is a deformation caused by gravitational forces and depends on the physical properties of the material. An instrument to measure is called Drape meter (**Figure 55**). The goal of this tester is to measure and calculate the coefficient of drape by tracing a shadow of the draped fabric on paper to measure and calculate the coefficient of drape by tracing a shadow of the draped fabric on paper. The interest of this type of measuring apparatus is in the comparison of the drape shape of a new fabric with respect to other fabrics; these fabrics being integrated into a database related to the mechanical parameters (KES or FAST) of each fabric (Ex: Lectra material database). The cost of the measurement would be much reduced.

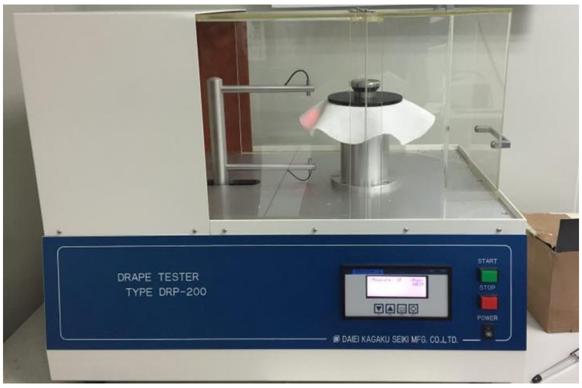


Figure 55: Drape meter.

II.5.2. 3D fit analysis during the 3D virtual try-on

In our research, for 3D virtual prototyping and garment simulation, the Lectra's software Modaris 3D Fit has been used. It's not so easy to judge the well-being because it's a mix between the 3D ease allowance, the plumb and the pieces proportion of the garment [116]. As a result, it's possible to consolidate the 3D ease allowance with other visuals feedback to move towards more objective perception.

For example, the notion of the garment proportion is perceptible by the coloring of the pieces showing in the case of a balanced distribution of the garment pieces (**Figure 56.a.b**).

The plumb of the garment can be perceived by visualizing the lengthwise grain of the fabric that has to be on a vertical axis. In our example, straight lines can be considered perfect (**Figure 56.c.d**).

According to an adjusted weighting of the color that can be perceived on the bar graph of the **Figure 56.g**, we can know the 3D ease allowance of the garment (**Figure 56.e.f**). But, one of the difficulties of the users of this software, i.e. the pattern-making designer, is the interpretation of this colorful image.

For example (**Figure 56**), the results of the analysis of the well-being that was done for this dress worn by this disabled people with a strong scoliosis was that the garment is well balanced in its proportion, the fallen is very correct because the straight lines are close to a vertical line, the 3D ease allowance is well distributed.

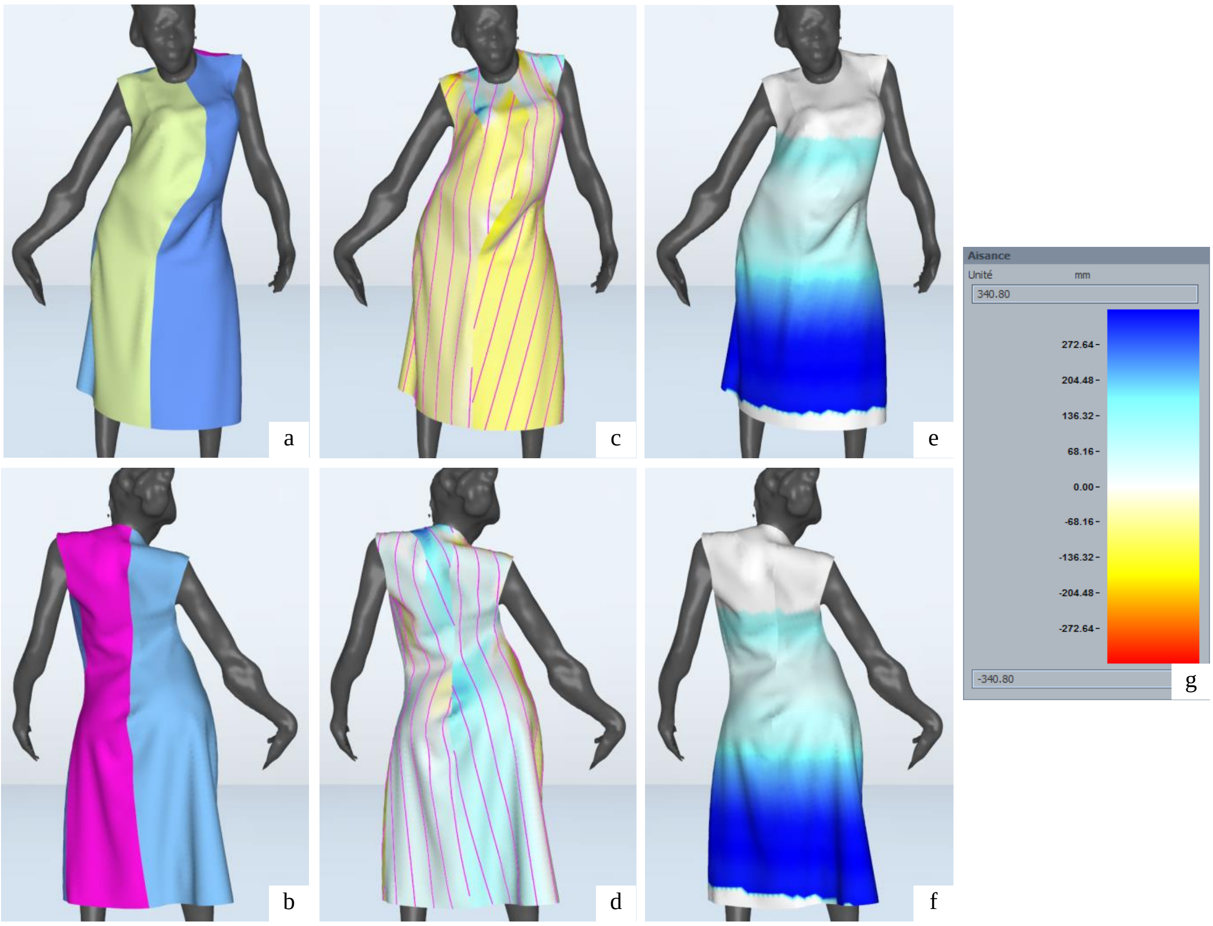


Figure 56: 3D well-being analysis.

II.6. COMPUTATIONAL TOOLS FOR MODELLING/SENSORY ANALYSIS

II.6.1. Sensory evaluation/analysis

For effectively acquiring human subjective data on various quality criteria, such as fabric hand and garment fit, sensory evaluation/analysis techniques can be used. Sensory analysis as first was introduced by the food industry in the 50's [118]. Following the definition presented in [119] the sensory evaluation *is a scientific method used to evoke, measure, analyze and interpret those responses to products as perceived through the senses of sight, smell, touch, taste and hearing.*

Sensory evaluation it is used for various purposes in the industry [120]:

- **Quality control:** it involves checking compliance of sensory properties of the product with design guidelines and specifications,
- **Impact assessment of process or recipe modifications:** sensory properties; it involves examining the impact of changing the sensory properties on the product.
- **Explain consumer preferences:** here the bases of research are some sensory properties substantially connected with the consumer assessments and thus potentially affecting consumer preferences.

Sensory attributes are determinant keys, which are indicative of the consumer acceptability of the product. Consumer testing is very important at early stage of the product creation. Therefore, one of the main areas of use is the product development process and to recognize consumers behavior. Identification of consumer perception is in interest of most companies thus, the sensory analysis started to be adapted to the need of textile industry [121].

In different application contexts, sensory evaluation is mostly conducted based on two approaches [119]:

- Product oriented evaluation, made by a selected or trained panel (expert panel) according to a number of normalized criteria,
- Consumer oriented evaluation, made by a number of untrained consumers (consumer panel).

In practice, product oriented evaluations will enable to generate more normalized data, which can be used for charactering the product quality (product profiles) while consumer oriented evaluations are relatively less normalized but can be used for understanding the market and consumer behaviors (consumer profiles). Both evaluations usually deal with linguistic expressions, which are fairly difficult to be quantified [122]. An interpretation of the evaluation results are computed by applying appropriate mathematical formulation and dedicated procedures [122].

Sensory evaluation is often combined with instrumental testing. The correlations of these two datasets have been deeply investigated. In case where there is a significant cross-compliance between them, only instrumental testing can be used without considering the use of a sensory panel [119]. In fact, instrumental testing is independent of geographical location or individual preference but cannot directly describe human perceptual criteria. The Kawabata Evaluation System (KES) or FAST are examples of quality testing for textile characterization. By using several mechanical parameters such as bending and shearing, these measuring systems can just describe fabric hand indirectly.

For the fashion industry, it is important to create the precise systems to describe the relations between sensory criteria presented by consumer's behavior and physical fabric parameters represents product quality. Human sensory evaluation has been used in our studies to estimate the 3D ease allowance values based on the fuzzy set theory.

II.6.2. Modeling with fuzzy techniques

II.6.2.a. Fuzzy logic

In the roots of Ancient Greek philosophy lays the intent of striving for perfection. This approach influenced many cultures, and it was reflected in the classical theory in particular approved by western' philosophers. One of the fundamental concepts of classical logic is *the law of the excluded middle*. This law assigns the value of 0 or 1 to certain problem. Therefore, in this approach, every decision can be either true or false. This strict classification gives a sense of the coherent system. The real or abstract phenomena are predictable and stable in the way that they are or are not in the set.

Bearing in mind that grey colour cannot be attributed either to a set of white or to set of black colours, classical theory is, in fact, an attempt to obtain an excellent response and is not itself a perfect answer. It is an attempt which may lead us to the improvement of things. The phenomenon, in reality, is much blurry than the theorem. The classical principles dealing with the issue of abstraction fail in giving a broader picture.

In many practical cases, it is necessary to take into account reasoning with uncertainty, e.g., a human evaluation with his/her perception. The judgment of experts' opinion on some technical issues can bring gradation of responses and debate leading to contradictory and vague judgments which cannot be simply answered with 0 or 1. The complexity of human perception brings the necessity of widening the scope of possible answers.

Fuzzy logic makes possible to systematize what is in the realm of empiricism, and therefore difficult to master. Its author is Prof Lofti A. Zadeh from the University of California. He introduced the theory in 1965 [123] which in 1975 have been extended by Mamdani [124] in his work on fuzzy sets. In a fuzzy set, the transition from "belonging to" and "not belonging to" is a gradual procedure. Fuzzy logic gives the possibility to deal with vague systems and describe linguistic and sensorial notions. It is 'conceptualized as a generalization of classical logic' [125]. In particular, fuzzy logic enables to provide a broader picture of the tacit knowledge evaluation. It is a useful tool in real-time applications for modeling datasets with uncertainty and complex relations, encountered in human judgements (designers, producers, consumers, etc.) on specific consumer goods and services.

The current applications of fuzzy logic are numerous both in theoretical research areas, like algebra, clustering or optimization, as well as in a real life to solve some practical issues. It has been applied mostly to operate and automatize daily systems and domestic goods e.g. washing machines, cars, hovers or in forecasting. As a branch of the artificial intelligence [126], fuzzy logic is applied in robotics, machine learning, pattern and human recognition.

Now new application areas of fuzzy logic continuously appear. In various industrial fields, it is especially applied to complex nonlinear system modeling and human operator's behaviors modeling. In our study, it can be considered as a complement to the work of fashion designer by modeling both instrumental testing data and sensory evaluations given by designers and consumers.

II.6.2.b. Theoretical concepts about fuzzy logic

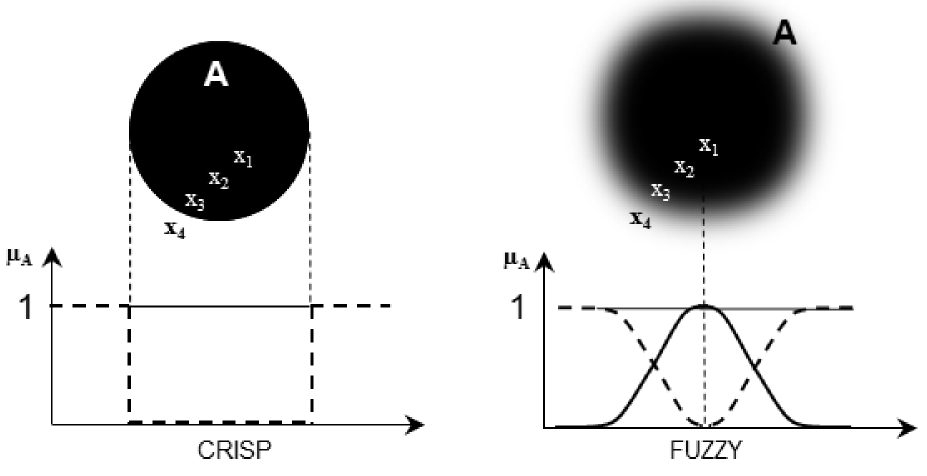
In mathematics, the use of sets to represent precise concepts is natural and is not a problem. However, that human rarely uses precise information. In everyday life, people cope perfectly with imprecise information but difficultly express a concept with precise data. In most of scenarios, we have difficulties to make a choice from two possible responses: yes or no. In this context, the concept of fuzzy set is particularly significant for human-related problem formalization, modeling and reasoning.

Fuzzy sets

The most straightforward definition of set says that set ‘is a collection of things’ [126]. Now depends on the theory it may be presented in several ways. In classic set’s (crisp set) theory an element x belongs entirely to a set A or does not belong to that set. However, to describe human behaviour, the classical set is not natural and do not give a useful notion [127] Therefore, to describe imprecise data, the gradient notions are necessary. In our example, it means that the element x may but not necessarily have to belong entirely to a set A. The definition of a fuzzy set proposed by Lotfi A. Zadeh is as follows: “A fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership (characteristic) function which assigns to each object a grade of membership range between zero and one.” [128]. By introducing the additional values to the range from 0 to 1 the interval boundaries are becoming less sharp and fuzzier. We do not have exact value but it rather based on approximation or estimation. Fuzzy logic operates on the concept of membership and degree of membership in the range from 0 to 1.

The fuzzy set in comparison with the crisp set allows a member to belong to a set to partially which is designated by a smooth boundary (**Figure 57**).

Figure 57: Graphical representation of crisp and fuzzy sets



$\boldsymbol{\mu}_A(x_1) = \boldsymbol{\mu}_A(x_2) = \boldsymbol{\mu}_A(x_3) = 1$
$\boldsymbol{\mu}_A(x_4) = 0$
x_1, x_2, x_3 *belong to A*
x_4 *does not belong to A*

$\boldsymbol{\mu}_A(x_1) > \boldsymbol{\mu}_A(x_2) > \boldsymbol{\mu}_A(x_3) > \boldsymbol{\mu}_A(x_4)$

x_1, x_2 *belong to A*
x_3, x_4 *partially belong to A*

Fuzzy sets are used to analyze the linguistic data where there are no sharply defined criteria, that is, the content of human language and others uncertain and ambiguous concepts encountered in a real world. Such approach gives a much better representation of a characteristic of an element. The bivalent condition of crisp theory, that an element belong or not belong to the set, is extended and cover by gradual assessment described with the aid of the membership function $\boldsymbol{\mu}_A$ in which A is the space of deliberation.

The value of the membership function on a given element determines its degree of belonging to the fuzzy set A.

Membership function

The fuzzy set permits to describe objects in an ambiguous way. However, to quantify the linguistic or other vague terms, a membership function, representing a fuzzy set graphically, is needed. In this way, we can describe the fuzzy set theory as ‘a class in which there may be a continuum of grades of membership’ [129]. The membership between a thing and a set is a basic and the most important concept in sets theory [126]. Membership function $\boldsymbol{\mu}_A$ associates the degree of truth of element x to the imprecise set A of elements x. The degree of truth is a precise value from the range [0, 1] or can have an imprecise character within an interval.

$$\boldsymbol{\mu}_A(x) = \begin{cases} x \in A \\ x \notin A \end{cases} \tag{13}$$

$$\begin{cases} \boldsymbol{\mu}_A(x) = 1 \quad \mathit{for}\ \ x \in A \\ \boldsymbol{\mu}_A(x) = 0 \quad \mathit{for}\ \ x \in A \end{cases} \tag{14}$$

$\boldsymbol{\mu}_A$ is a membership function of the set a membership function of the set A.

Suppose we want to describe all people who are in "middle -age" group. In classical logic, we would say for example that people of middle-age are those whose age belongs to [35; 60]. The characteristic function of the set (**Figure 58.a**) gives '0' for age outside the range [35; 60] and '1' in this interval, while the fuzzy set of 'average age' of people will be defined by a 'membership function', which differs from the characteristic function in that it can take any value in the range [0,1]. At each age x will match a "degree of belonging" $\boldsymbol{\mu}_x$ to the fuzzy set of "middle-age" (**Figure 58.b**). The membership function establishes a relationship between the numerical value and the linguistic notion (for example, membership function " middle age"). Generalizing, the characteristic function of a set x_A (crisp theory) extended to the membership function $\boldsymbol{\mu}_A$.

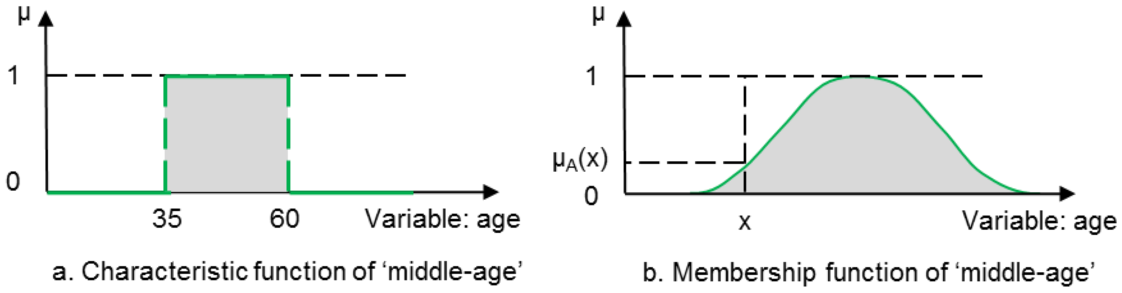


Figure 58: Characteristic and membership function of middle-age

Several fuzzy sets could be defined on the same variable, for example fuzzy sets "young-adult", "middle-age" and "old". These sets define the partitioning and gradualness of this variable (**Figure 59**). It is because in fuzzy logic, an element can belong to several fuzzy set with different degrees of belonging.

The overlap of fuzzy subsets may tell us, for example, that a 60 years old person belongs to the "middle-age" set with a degree of 0.7 and to the "old" set with a degree 0.3. This overlap of the subassemblies constitutes the robustness of the fuzzy models. It allows a gradual transition of state and consequently a progressive convergence of the decision.

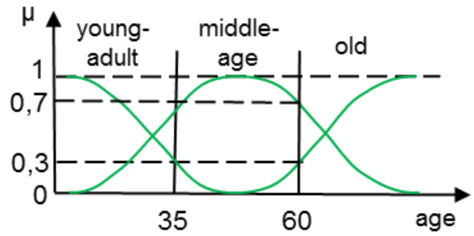


Figure 59: Membership function, variable and language.

In classical logic, a 60 years old person would be "middle-age" whereas a person of 61 would be "old", which does not correspond to our intuition. Fuzzy logic assigns the age of a person to a given group gradually. Thus, the concept of fuzzy subsets allows a nuanced membership.

The variable "size" as well as the terms "small", "medium" and "large" defined by the membership functions are referred to respectively as "linguistic variable" and "linguistic terms". These can be introduced directly into fuzzy rules and presented graphically as a linear membership function (**Figure 60**).

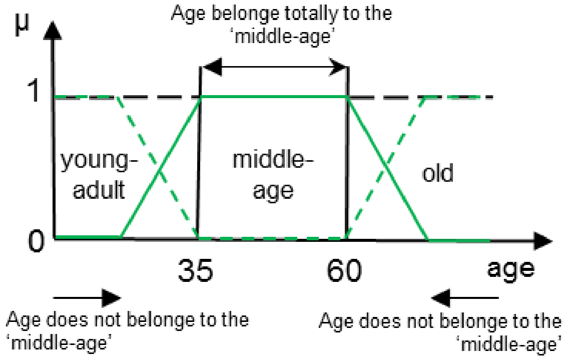
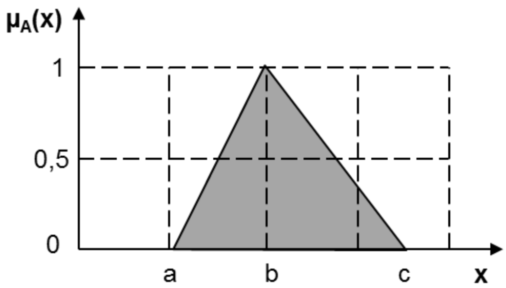
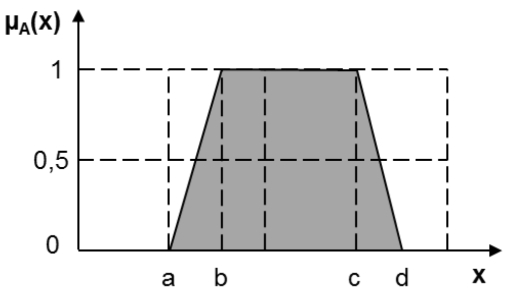


Figure 60: Linear membership function.

The process of obtaining specific linguistic values of a predefined membership function for given input data is called fuzzification **[76].**

A membership function can be expressed in many forms as long as they follow the rules of the definition of a fuzzy set. In practice, only a few of typical membership functions are used, of which the most popular are shown in Table 0.1. If a membership function only takes values from {0, 1}, it corresponds to a crisp set. In most of cases, we have fuzzy sets whose membership function values vary between 0 and 1.

The basic fuzzy set operations are named the same as for classical set operations, union, intersection and complement. These operations are defined by computations of the corresponding membership functions.

Triangular membership function	
$\boldsymbol{\mu}_A(x) = \begin{cases} 0 & if\ x \leq a \\ \dfrac{x-a}{b-a} & if\ a \leq x \leq b \\ \dfrac{c-x}{c-b} & if\ b \leq x \leq c \\ 0 & if\ x \geq c \end{cases}$	
Trapezoidal membership function	
$\boldsymbol{\mu}_A(x) = \begin{cases} 0 & if\ x \leq a \\ \dfrac{x-a}{b-a} & if\ a \leq x \leq b \\ 1 & if\ b \leq x \leq c \\ \dfrac{d-x}{d-c} & if\ c \leq x \leq d \\ 0 & if\ x \geq d \end{cases}$	
Gaussian membership function	

$$\boldsymbol{\mu}_A(x,a,b) = e^{\frac{-(x-b)^2}{2a^2}}$$

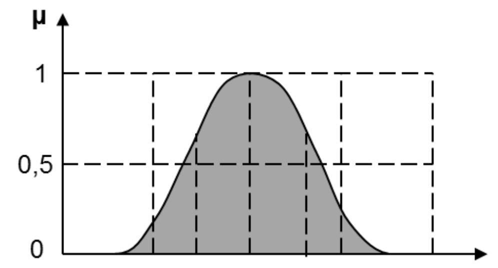


Figure 61: Main types of a membership function.

Fuzzy rules

Fuzzy Set Theory has a practical application as a fuzzy system which is represented in the form of fuzzy rules. The base of fuzzy rules is a set of n fuzzy rules in the general notation as follow:

$$\boldsymbol{IF}\ \ x\ is\ A_i\ \ \boldsymbol{THEN}\ \ y\ is\ B_i\ i = 1, \ldots\ldots, n$$

where the fuzzy set $A_i \in F(X)$ and $B_i \in F(Y)$, represent some properties **[76]**.

The fuzzy $\boldsymbol{IF-THEN}$ rule is called control rules and can be used by the fuzzy inference system to compute the degree to which the input data match the condition of a rule [130].

The reasoning with $\boldsymbol{IF-THEN}$ fuzzy rules can be applied to a variety of applications. They can be obtained by learning from a dataset on inputs (x) and output (y). Fuzzy rules are usually used for modeling the relation between the inputs and output or predicting the output value from given input data.

Next, we show an example of air conditioner, proposed by [130] for illustrating the process of reasoning with fuzzy rules.

The air conditioner is a control system in which Temperature (input) is used for controlling Motor Speed (output). The first step of the process is the fuzzification of the input and output data, namely transformation of the intervals of Temperature and Motor Speed into fuzzy values (linguistic values) (**Table 1**).

Table 1: Air conditioner example using fuzzy logic.

The normal temperature range		Linguistic variables
Low temperature	20°F~40°F 30°F is center	LOW
Medium temperature	30°F~80°F 55°F is center	MEDIUM
High temperature	60°F~90°F 75°F is center	HIGH

According to the distributions of these intervals, we define a trapezoidal membership function for Temperature (**Figure 62.a**). The same principle is also applied to More Speed for defining its membership function (**Figure 62.b**).

After fuzzification of the inputs and output, we will elaborate the fuzzy control rule according to the corresponding membership functions. In the example of air conditioner, we propose a fuzzy rule as follows:

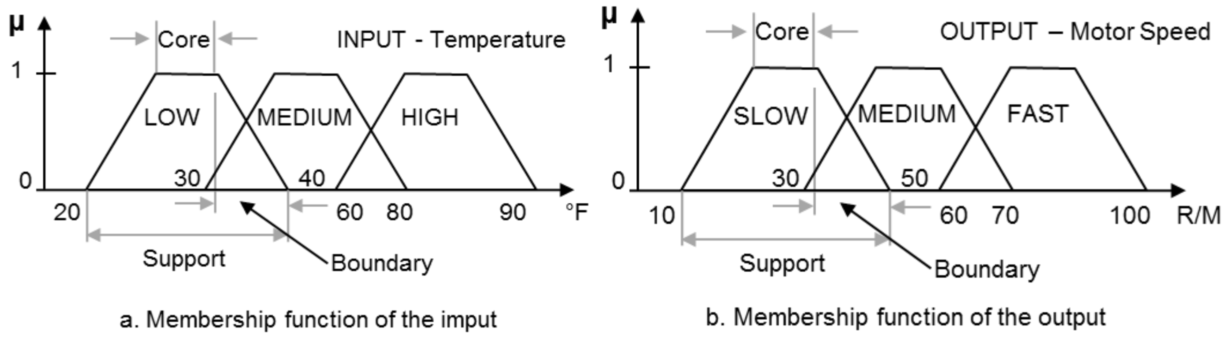


Figure 62: Membership function of air conditioner process.

After fuzzification of the inputs and output, we will elaborate the fuzzy control rule according to the corresponding membership functions. In the example of air conditioner, we propose a fuzzy rule as follows:
Rule 1: IF Temperature is Low, THEN More Speed is Slow.

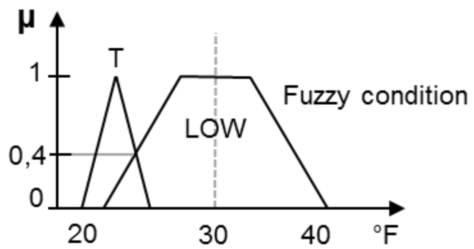


Figure 63: Matching fuzzy inputs with fuzzy condition.

Following the air conditioner as an example the **Figure 63** is a graphical representation of the way to calculate the degree between a fuzzy input T (temperature, around 20°C) and fuzzy condition LOW. This condition can be represented by the function:

$$M(T, LOW) = Support \min\,(\boldsymbol{\mu}_T(x), \boldsymbol{\mu}_{LOW}(x)) \quad (15)$$

Predicates

A predicate (also called premise or condition) is a combination of prepositions by ***AND***, ***OR***, ***NOT*** operators [131].

- ***AND*** is an intersection of fuzzy set, indicated by the minimum of the membership function
- ***OR*** is the union fuzzy sets, which is a maximum of the membership function
- ***NOT*** complement the fuzzy set.

II.6.2.c. Fuzzy modeling

Fuzzy modeling is a procedure integrating the previous concepts. It is a basic fuzzy inference process which takes place in three stages (**Figure 64**): Fuzzyfication, Fuzzy reasoning (Interface engine. Application of fuzzy operation and application of fuzzy implications) and Defuzzyfication.

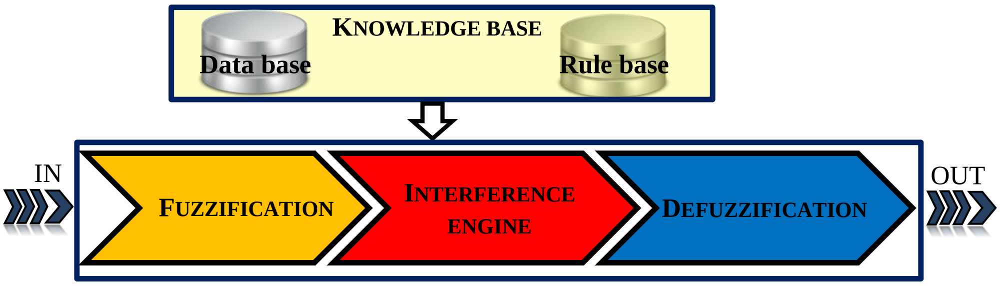


Figure 64: Schema of fuzzy system.

Fuzzyfication

As previously discussed in the part of fuzy rules, a specific numerical value will be transformed into a vector asociated with a number of lingustic variables by means of assumed membership functions and their parameters.

Knowledge Base

It's the creation of a set of **IF/THEN** fuzzy rules (fuzzy inference mechanism) by learning from human knowledge or measured data. At the learning stage, the input and output learning data are transformed into linguistic values by means of their associated membership degrees and the **IF/ THEN** rules can be established by exploiting relations between input and output linguistic learning data. The structure of Knowledge Base is shown more precisely on **Figure 65** [132].

Fuzzy Inference System – Fuzzy reasoning

In this stage, for any new input data already transformed into a fuzzy value (fuzzy set) in the stage of Fuzzification, each rule of the knowledge base is applied in order to obtain their matching degree. The matching degrees for all the rules are then aggregated to form the final output fuzzy value. It is the process which turns input fuzzy sets into output fuzzy sets by manipulating the whole rules of the knowledge base.

The most commonly used fuzzy inference mechanism is the so-called "Mamdani" [133]. A fuzzy rule base of Mamdani includes linguistic rules only (from linguistic inputs to linguistic output) using membership functions to describe the concepts used (**Figure 65**).

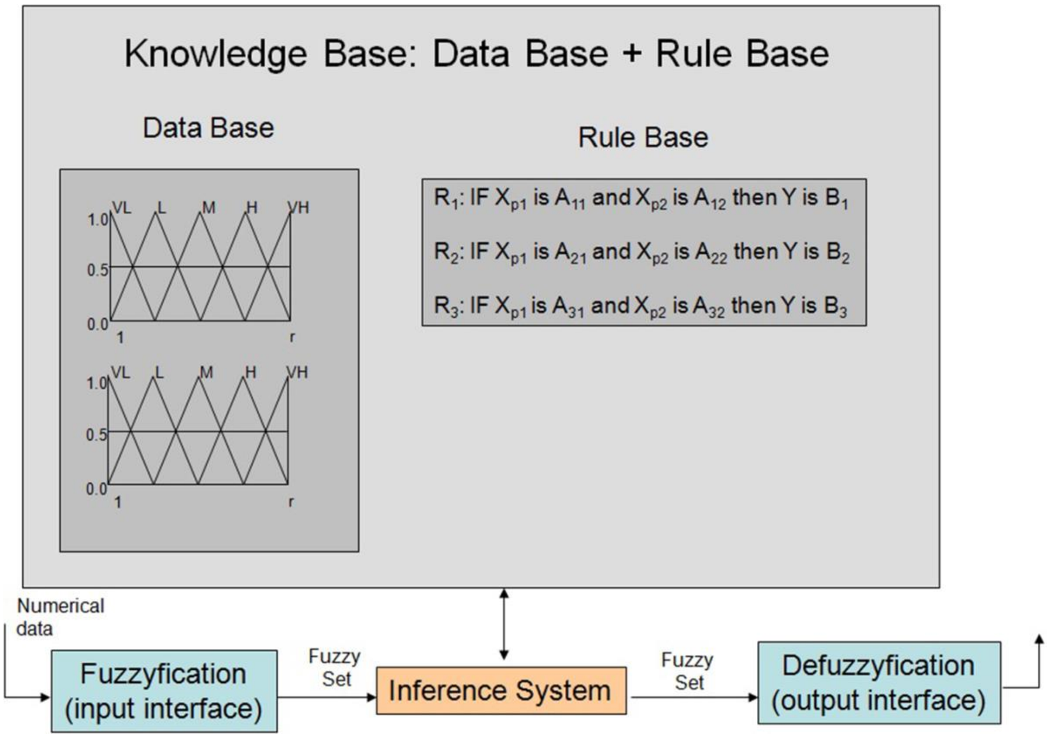


Figure 65: Structure of Fuzzy Rule System.

In this thesis, we apply the Mamdani fuzzy inference mechanism because our rules deal with relations between linguistic values only. Another fuzzy inference mechanism is Sugeno type, whose rules are used to characterize relations between linguistic inputs and numerical output.

The complete Mamdani inference process (including fuzzification and defuzzification) comprises from three basic steps: fuzzification, implication process, defuzzification [132]. We suppose that there are n fuzzy rules in the knowledge base under the form:

$$\boldsymbol{IF}\ \ x\ is\ A_i\ \ \boldsymbol{THEN}\ \ y\ is\ B_i\ i = 1, \ldots\ldots, n$$

where $x = (x_1, x_2, \ldots, x_m)$ and y are the inputs and outputs respectively. $A_i = (A_{i1}, A_{i1}, \ldots, A_{im})$ and B_i are the linguistic values corresponding to x and y respectively.

For each new input (crisp value) $x_p = (x_{p1,} x_{p2,} \ldots, x_{pm})$, we perform the following operations:

1. **Fuzzification.** At this stage, the computation of the Matching Degree is realized. The degree of membership of inputs to each input fuzzy set is determined. To compute the matching degree of the previously established input fuzzy set to comply the requirements of each rule, a conjunction operator ***C*** is applied. The minimum t-norm is advised by the Mamdani method.

$$\mu_{A_j}(x_p) = \boldsymbol{C}\left(\mu_{A_{j1}}(x_{p1}), \mu_{A_{j2}}(x_{p2}), \dots, \mu_{A_{jm}}(x_{pm})\right) \quad (16)$$

This operation enables to evaluate the membership functions used in predicates of the rules.

2. **Implication process** in which we apply an **Indication Operator**. The input fuzzy set x_p and output fuzzy set *y* are combined by using an intersection operation. The implication operator ***I*** can be a t-norm operation (we take the minimum in most of cases).

$$\mu_{B_j'}(y) = \boldsymbol{I}\left(\mu_{A_j}(x_p), \mu_{B_j}(y)\right) \quad (17)$$

3. **Defuzzification process.** The resulting fuzzy output set $\mu_{B_j'}(y)$ is transformed into a crisp value y_0. To obtain the output value two approaches can be applied: "aggregation first, defuzzification after" or "defuzzification first, aggregation after". The Mamdani method suggests to apply the first approach by computing the center of gravity of the fuzzy set $\mu_{B_j'}(y)$.

$$\mu_B(y) = Y_j \mu_{B_j'}(y) \quad (18)$$

$$y_0 = \frac{\int_y y.\mu_B(y)dy}{\int_y \mu_B(y)} \quad (19)$$

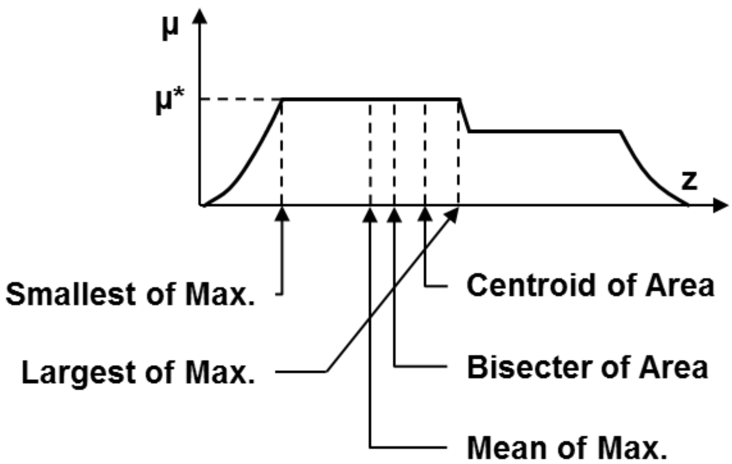


Figure 66: Different method of defuzzification.

II.7. PRINCIPLE COMPONENT ANALYSIS

In practice, the fuzzy rules extracted from data are less efficient and difficult to be interpreted when the number of input variables is too great with respect to the quantity of available data. It is the case in many industrial applications. For solving this problem, we use PCA [134] to reduce the number of input variables to 2 or 3 before starting the procedure of fuzzy rules extraction. By using this technique, a lower dimensional input space is obtained from the projection of the original high dimensional space. Its principle is given below.

PCA performs a linear transformation of an input variable vector for representing all original data in a lower-dimensional space with minimal information lost. The q observations in the original n-dimensional space, corresponding to n input variables, constitute a data distribution characterized by the eigenvectors and the eigenvalues which can be easily calculated from the variable covariance matrix. PCA aims at searching for the smallest subspace in the n-dimensional space maintaining the shape of this distribution. The first component of the transformed variable vector represents the original variable vector in the direction of its largest eigenvector of the variable covariance matrix, the second component of the transformed variable vector in the direction of the second largest, and so on. In our approach, the two first components are taken as input variables. Therefore, we obtain a fewer dimensional input/one output system for each model. This system can be easily modeled from a small set of learning data.

II.8. CONCLUSION

In this chapter, the various scientific and technological tools are presented, as well, the useful theories which were used in my research. A large number of tools used in the study show how a wide and complex area is the design of clothes in 3D.

The basic data which were used for building database classified in order to extract the different morphotypes were Measuring Campaigns described in the Chapter I. Obtained in these way morphotypes are helpful to define customer's virtual mannequin, ease allowance and the graphic model of garment. All of these three means are useful for making virtual try-on with predicted 3D ease allowance value.

Data acquisition for obtaining 3D virtual body of the subjects was made with use the software 3D SCAN Tecmath from Human Solution and the programm ScanWorkX which imports and digitizes the data from the scanner. These data were imported as triangular meshes and then repaired, smoothed and exported in the OBJ format useful for CAD environment for use in 3D manufacturing strategy. These shape pre-processing is helpful to define specific consumer's body shape and to assign him to specific morphotype and morphology. In our research we develop the 3D garment design modelling on five different body scans. In our research, for 3D virtual prototyping and garment simulation, the Lectra's software Modaris 3D Fit has been used.

The next step is to analyse the garment fit. To drape the garment on the body in a 3D space we need the fabric physical properties. The progress in technology led to the creation of modern systems for fabric characteristics, eg. Kawabata evaluation system (KESF) or instruments to define wool mechanical properties (FAST). The values obtain from above tools has been input into 3D Prototyping database to further use in the simulation.

The fit and comfort analysis are obtained from human perception including wearers and expert knowledge, which is often inconclusive and intuitive.

In practice, product oriented evaluations will enable to generate more normalized data, which can be used to characterize the product quality (product profiles) while consumer oriented evaluations are relatively less normalized but can be used for understanding the market and consumer behaviors (consumer profiles). Both evaluations usually deal with linguistic expressions, which are fairly difficult to be quantified. Therefore, to measure quantitatively such ambiguous phenomenon we need to use tools which manage the uncertain problems. In this context we use the modelling based on fuzzy set theory. Fuzzy logic gives the possibility to deal with vague systems and describe linguistic and sensorial notions. In this thesis, we apply the Mamdani fuzzy inference mechanism because our rules deal with relations between linguistic values only.

Moreover, during the modelling procedure, in order to reduce the complexity of the extracted fuzzy rules, we use PCA to project the original multidimensional input space into a fewer dimensional subspace. The combination of PCA and fuzzy modelling from learning data constitutes the main tool for predicting ease allowance for a specific wearer's morphology and desired fit and comfort requirements.

CHAPTER III: MODELING OF THE HUMAN BODY

This chapter is dedicated to the customer's pattern recognition and the creation of his avatar in an e-commerce context. The architecture of the customer's pattern recognition is first presented in its entirety in order to put into appearance the different sub-processes that have been implemented. Then, a morphological analysis of different people was carried out in order to show the impact of a bad posture, of the shape of the spine on anthropometry. Their adverse effects are presented at different stages of our study, i.e. 3D adaptive morphotype mannequin creation, 3D ease allowance analysis, 2D supervised classification when taking side view image. The interest of positioning oneself in relation to a 3D unsupervised classification to recognize a new customer is then demonstrated. It is from a 2D shape descriptor representing the client's silhouette in front and side view that the link will be created with the 2D supervised classification.

III.1. GLOBAL PROCESS FOR THE PATTERN RECOGNITION OF MORPHOLOGY

III.1.1. Introduction

To improve similarity between the individual client and his virtual counterpart (avatar), the process of morphology recognition has to rely on the database of the representative morphological population types. From this perspective, an automatization of morphology recognition process provokes great interest in an online garment retail segment.

The avatar of the client can be obtained directly from the scanner, but it will involve the necessary computer processing, for example, elimination of noise, holes and other imperfections by using RapidForm [135] or other software to process 3D scans and by this the expert's' intervention is necessary.

Creation of an avatar of the customer by comparing its data from the scanner with a wide database of morphological dimensions is presented in other works [136, 137] and the similar project CAESAR [138].

The results are impressive, however, stays in contrary to the principles of online sales. The main reason for this is that to deploy scanner on different stores, distributed wisely to be close to the client, is expensive, time-consuming and obliges the client to be present in the warehouse while scanning.

Therefore, inspired by the desire to develop a superior, more cost-effective model, we have created a conceptual schema of our model, which is formulated around two axes of research: 3D unsupervised classification [41] and 2D supervised classification (**Figure 67**).

III.1.2. Architecture of the process

The objective of the first axis is to classify a set of characteristic 3D morphologies of the population. It starts by pretreatment based on Hamad's [139, 140] automatic preprocessing of 3D scans data to extract and standardize the torsos from a group of different morphologies (**Figure 67.a**), consistent with the needs of the clothing industry. The torsos have been normalized and strictly compared with the stature constraints. The 3D geodesic curves allowed him to describe each 3D torso according to their signature (**Figure 67.b**). Then, X clusters are detected by the criteria of the unsupervised 3D classification Davies-Bouldin index [41]. Exploitation of the results of the classification led to the determination of X morphotypes (**Figure 67.c**: in grey), each of them representing the morphology of a scanned person, the closest to the centroids of each cluster. A process of 3D adaptive morphotype creation was then applied on each morphotype to make them adjustable in function depending on a stature parameter (**Figure 67.c**: in black). The adjustment of the volume is controlled by the stature following rules extracted from a statistical analysis of each cluster.

The objective of the second axis is the pattern recognition of a new customer by the 2D supervised classification. Working on a 2D scale has a double benefit. The first is economical because it avoids the expensive scanning procedure among retailers. The second is human oriented because the end user can quickly take a picture using a Kinect Microsoft camera, computer camera, smart phone or other accessible tools, which may provide RGB or grayscale images.

Our purpose is to achieve the situation in which the client using the means, as mentioned above, can send by the Internet the lateral and anterior views and a value of stature (**Figure 67.e**). The stature is necessary as a reference to establish parametric dimensions of a 3D adaptive morphotype. In our work, we focus on torso silhouettes to be coherent with the unsupervised 3D classification data.

A pre-treatment converts different information of silhouettes into standardized torso information (**Figure 67.f**). To assign the client to one of the 3D morphotypes required a change of physical space via a 2D signature process (**Figure 67.g**).

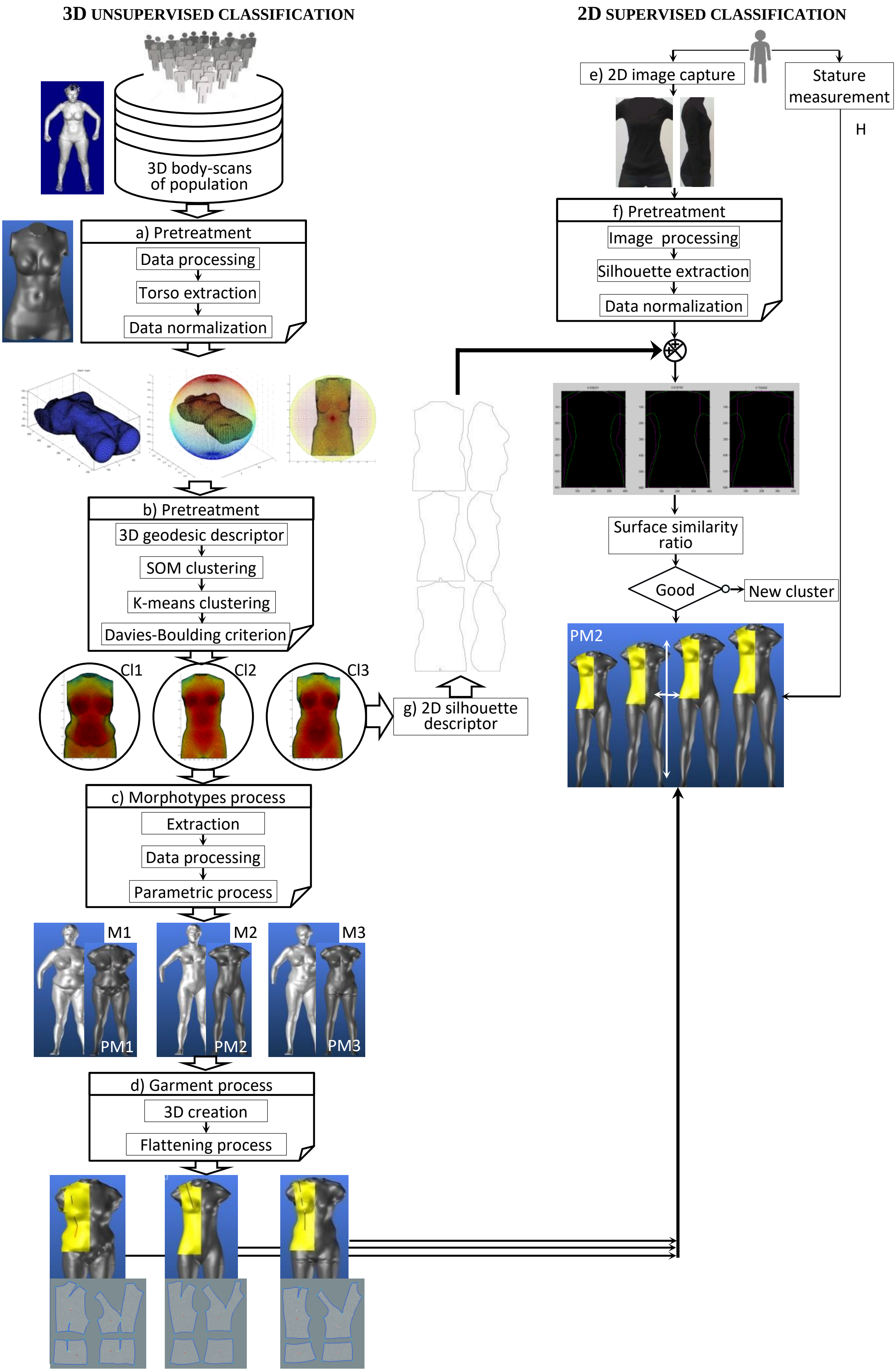


Figure 67: Pattern recognition of morphology.

Then, the client is assigned to his specific morphotype by supervised 2D classification. This morphological assignment provides an appropriate choice of the 3D adaptive morphotype and manages the client's avatar by the stature. But before explaining these two major axes, we will explain the morphology problems of a particular customer.

III.2. ANALYSIS OF THE HUMAN BODY MORPHOLOGY

III.2.1. Posture analysis of the human body

The skeleton of an adult consists of 206 separate bones. This number varies depending on the age: for children is bigger (up to 356 bones) and for seniors is smaller. The spine (backbone) plays a significant role to support the body. It consists of the 33-34 vertebrae, which connect to each other by creating flexible sloop that is the axis of the trunk [141]. The muscles surround the backbone serve to stable the position of all vertebrae and to twist and bend the trunk. It gives the motility and toughness to the whole body.

The natural shape of the backbone is constituted by curves (lordosis and kyphosis), which from the lateral side form a letter ‘S’ (**Figure 68**). The natural curve lordosis is a backward bending cure of the spine in the cervical and lumbar regions. The natural curve kyphosis is a forward bending curve of the spine in the thoracic spine and sacrum [142]. From the posterior position backbone should be vertically straight (**Figure 68**).The overall posture of the trunk is determined by the orientation of the individual lumbar and thoracic vertebrae. [143].

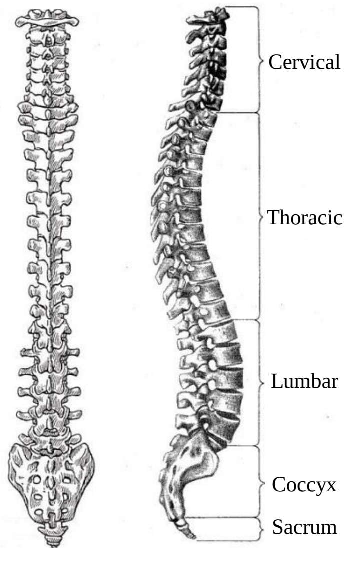


Figure 68: Natural curvature of spine.

Usually, the types of normal figures are defined on the basis of anthropometric studies [144]. Industry describes the morphology by dividing the body based on figure types or shape categories. This categorization serves in particular for matching the client to the appropriate group and finding right size or style of garment. What is important here is to be aware, that to design a well fitted garment for an individual any deviations from the normal posture should be taken into account because it requires changes to the pattern construction.

If there is no congenital anomalies humans are born with the perfect spine with its natural curvatures. However, during the growth and adolescence the body development can be influenced by wrong body postures, which in turns, is reflected in backbone disorders in adults. It is necessary to pay attention to these factors, because these situations affect the majority of the population. And that is one of the reasons why most individuals deviate from the ideal model on which garment are design. Therefore, if classification to a certain group is based on matching to the averaged and idealized model it exists huge probability that the individual will not find the garment which fits his posture. It is rare that all models fit all silhouettes, even if a selection is made in relation to a fashion or style.

Figure 69 presents the different woman's figures. We see that the same person can develop different posture. The individuals which postures deviate from the normal is mostly due to the faulty posture (defects due to spinal distortions) or due to the genetic determination [144] (too high, too small, prominent bust or bottom). These are not clinical symptoms considered as a disability. It is rather a manifestation of a lifestyle and occupation. However, any changes in posture should have its implication in pattern construction.

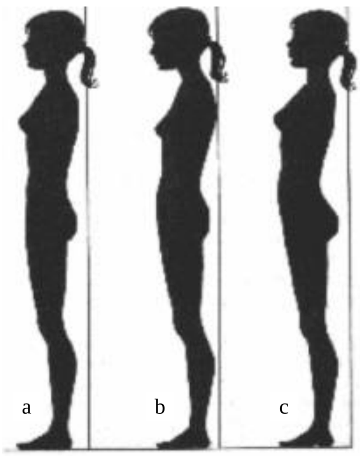


Figure 69: body posture types: a) normal, b) slooping c) flexible.

Very often to ensure proper fit according to size some retouch is needed. The most common retouches are those that change the length of the garment or part of the garment (such as sleeves) [145]. Another often performed retouching is when a prominent bust requires darts manipulation to shape the fabric around the bust's curves. On the other hand, back tilting can affect the material drapability on the shoulders and armpits, which also can be changed during retouching.

The method to be used to retouch will be different according to the manufacture of the articles, but also according to the materials and the style. The ready-to-wear manufacturer can only try to best adapt his clothing to the majority of individuals in a certain market, for example by using average measurements of the human body for a given population. However, this procedure does not ensure that the clothing is adjusted to the individual figure. For online stores, there is only a check through a virtual try-on.

Another more and more frequent, resulting out of necessity solution is to offer the client the opportunity to use external tailoring services. This solution is proposed, for example, by Zara in relation to more expensive outfits and is just dedicated to brick-and-mortal store. Some adaptations, like shortening the part of a garment, are ease to make. However, some adaptations, like deeper undercut of an armhole, are difficult or even not possible to make when the garment is already produced. The best solution is when all adaptations are made before the fabric is cut. Respectively, the virtual reality, CAD software with the virtual try-on gives the possibility to verify all parameters.

We focused on understanding the issue of the individual figure recognition and fitting the cloth in context of the online sales in the mass customisation scenario. The model of mass customisation fit the requirements of human-centered design which should be achieved without excessively increasing the purchase price. The goal is to design well-fitting garments for individuals.

III.2.2. Posture description of the five subjects body

For the experimental part to analyze the 3D ease allowance, we have chosen five subjects. Those Subjects have been chosen due to specific body features, which will be discussed in the further part of the chapter. The women are in age between 34 and 42 years. They are scanned by using 3D SCAN Tecmath from Human Solution. The subjects are dressed in their underwear. They stand in a predefined position adjusted in the area of accessibility of the lasers. Raw data are corrected by the Rapidform software in order to convert the point cloud into a surface directly exploitable to 3D CAD tools (Design Concept 3D). In the process of garment creation the first step was to understand the body curvature and proportion. It is important to analyze the body figure from different views and recognize the location of characteristic points for garment construction. The figure analysis was made by using tools available in DesignConcept. For each subject the process of making an individual garment have been covered and described in the following Chapter 4. All adaptations are made directly on the virtual body models.

Five Subjects were selected as examples of individuals with characteristic features such as prominent hips (Subject 3), slightly abdomen forward (Subject 5), slightly bent forward (Subject 1), prominent breasts (Subject 4), small breasts (Subject 2). Any of those features are not classified as disfigurements.

Lateral and Posterior views has been the means to analyze the posture of each subject (**Figure 70**). The subjects are not diagnosed with any severe problems of the spine. However, they present different posture body types. The heights of subject are presented in **Table 2**.

Table 2: Subject's heights.

Subject	1	2	3	4	5
Height (cm)	160.0	165.5	162.9	156.5	161.0

First Subject has a bit rounded shoulders with the balance of the body moved on the back side. The abdomen is flat but the curvature of the spine makes it slightly bent forward. The buttocks are rounded but not prominent, hips are bit larger than the bust.

Second Subject is the highest in the studied group. He has a correct posture, which appears in straight back from lateral view, chest is up and forward. The bust is small and the hips not prominent.

Third Subject has a bit prominent belly, sloping shoulders and slightly rounded back. The buttocks and hips are prominent and well-marked in relation to small bust. The difference between bust and hips circumference is 21.7 cm.

Fourth Subject is the lowest in the studied group. He has slightly rounded back which can be a result of a prominent chest.

Fifth Subject posture is bent forward on the lumbar spine, which made an abdomen forward and, as will be explain further, strongly influence the body proportion.

For each of the subjects the waist line is well marked.

As was mentioned above: the body of people is a reflection of his lifestyle. Of all subjects, only Subject 2 performed dance during his childhood and adolescence period. Therefore, her attitude, despite the sedentary profession she is currently performing, is most strongly outlined as the right one.

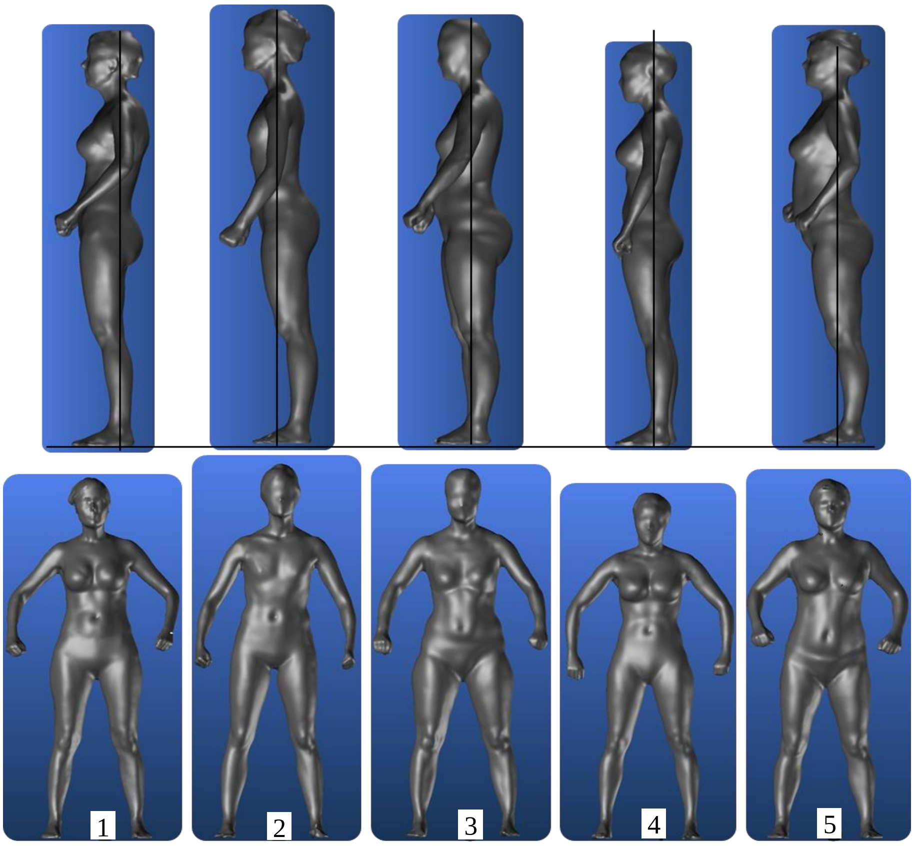


Figure 70: Lateral and Front view of the virtual models.

III.2.3. Body ratio of the five subjects body

In the posterior view, we observe that any of subjects are symmetrical (**Figure 71**). Those are not warped figures therefore the figure asymmetry does not influence the balance between left and right side of the garment. However, we aim to work on the perfectly vertical bodies therefore we need to make a first adjustment of the symmetrical line. To create the symmetry line we had to rotate each torso at a certain angle (**Table 3**). The angle of subject 2 and 5 has a negative value due to reverse direction compared to the Subject 1, 3 and 4.

Table 3: Value of the rotation angle of the torso.

Subject	1	2	3	4	5
Angle (°)	0.8	-2.6	0.4	0.5	-2.0

The morphological contours to positioning the garment respectively to the body shape were identified on the basis of woman's ideal proportion. The ideal proportion presented by Leonardo Da Vinci and Loomis [1], and used nowadays in instructional art books propose 8 Head Units. We have applied this ratio for our Subjects. Most Subjects (1, 2, 4 and 5) follow almost perfectly this division. However, for the Subject 3 the ratio of eight heads were not satisfactory. We checked other ratio proposed by Greek sculptor Polykleitos which is seven heads. The ratio of 7 Head Units was most suitable for the body proportion of the Subject 3.

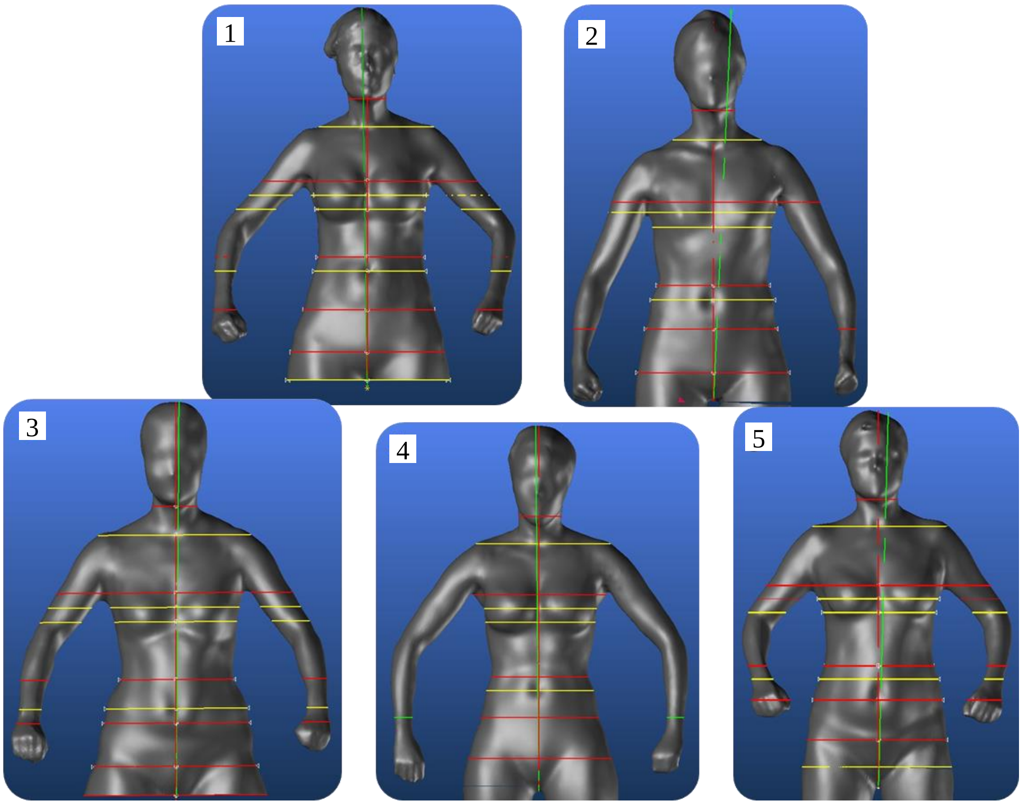


Figure 71: Anthropometric ratios of the subjects.

For the fifth Subject the lower back bends forward which change the proportion ratio. The division was consistent with the eight-head ratio in the lower and upper part above the bust. Only the trunk part did not designate correctly the waistline and bust line (**Figure 72**: dash lines).

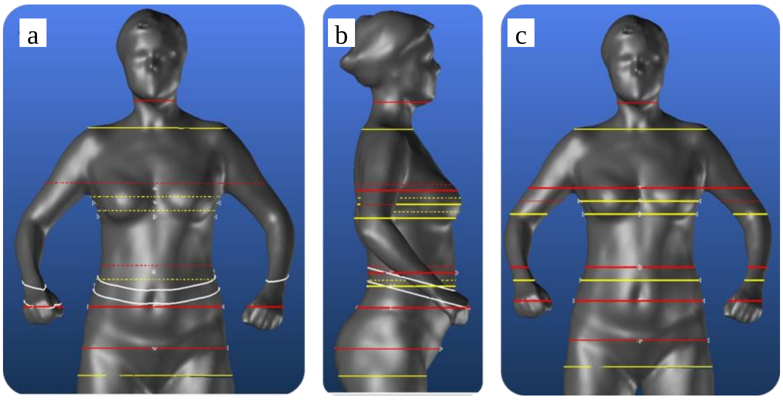


Figure 72: Correction of the waist and bust lines for the fifth subject.

We have researched about how the spine curvature in the lower part causes a deflection from the normal position. We recognize the angle to be fixed to achieve straight position (**Figure 72.a.b**: white lines). Then, we have changed the position of the initial dividing lines by this angle. Thanks to this procedure the new waist and bust lines were indicated at the right position (**Figure 72.c**).

In our research, we focus on the five Subjects which are examples of an average consumer. These subjects have been chosen to define the good value of the 3D ease allowance on these different morphological curves and in specific zones associated with some of these curves.

Experience tells us that classifying based on a size or silhouette group may not be enough to obtain well-fitting clothes. We need to know the structure of the body with its curvature. So the 3D body structure. Looking at five subjects we may imagine the diversity of body postures and the challenge to classify them into an adequate morphology.

For fashion brands at industrial level is very important to classify people into similar morphological or sizes groups. The sizing system which covers a variety of body figures needs to have a strict procedures to assign individuals in certain group. For this reason the human body shape clustering plays vital role in fashion industry. The body shapes information is changing for all population after years. It is therefore very important to update and correctly analyze the existing sizes and morphological groups. Consequently this in turns allow finding a garment that provides a reasonable fit for potential consumer,

On the foundation of previous research on unsupervised 3D morphology clustering [140] we build the 2D supervised client's morphology classification.

III.3. CONCEPTUAL PROCESS OF MORPHOLOGY CLASSIFICATIONS

III.3.1.3D unsupervised classification

The foundation of present research is the robustness classification of a target population. Therefore, we have employed the 3D clustering method of the individual morphotypes, which has been developed in Matlab and validated by Hamad [41]. The morphological database is composed of 500 females from the French national measurement campaign conducted in 2006 by IFTH (Institut Français du Textile Habillement).

The implementation of a non-supervised classification of morphologies from 3D scans is a complex task. Robustness and precision are two criteria that define the quality of the final results. The diagram in the figure shows the 3 major steps that must be implemented to achieve this quality objective:

- **pretreatment of data:** The goal of this step is to mesh the cloud of points resulting from the scanned body, to filter the noisy data, to fill up the holes corresponding to the zones of shade and to smooth the mesh. This step presented manually in Figure 41 is performed automatically. The position of specific anthropometric points allows extracting torsos from the body,
- **3D shape descriptor for human bodies:** The 3D torsos are then standardized in order to respect the dimensional proportionality and mass distribution of the treated torso. This standardization makes it possible to compare body morphology and not individual measurements. The morphology of each 3D torso is then represented by a 3D shape descriptor. It is defined from the distribution of geodetic distances with respect to a set of reference points.
- **unsupervised classification:** An unsupervised classification used two methods is applied to 3D torso descriptors, the K-means algorithm and a two-step procedure based on an SOM and the K-means algorithm.

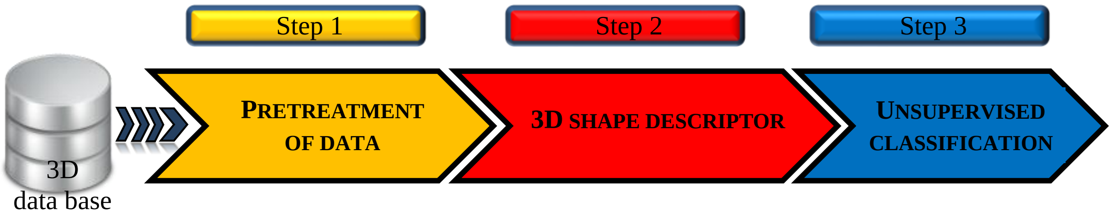


Figure 73: 3D unsupervised classification of morphologies.

Our raw data are taken from the French anthropometric survey. The 500 females were measured using the Vitus Smart 3D body scanner from Human Solutions. The Davies-Boulding index curve shows that the optimum number of clusters is defined for a value of $k=3$.

The results of the 3D unsupervised classification are given in **Figure 74.** The three torsos and the associated morphotypes are represented.

III.3.2.2D supervised classification

The goal of this section is to recognize the client online by relying on precedents classified in the morphologies database. For that, 2D supervised classification [146] was used. However, the difficulty is finding a shape descriptor or a similarity function that creates the bridge between the 3D environment of the database and the 2D space of the client in front of its screen.

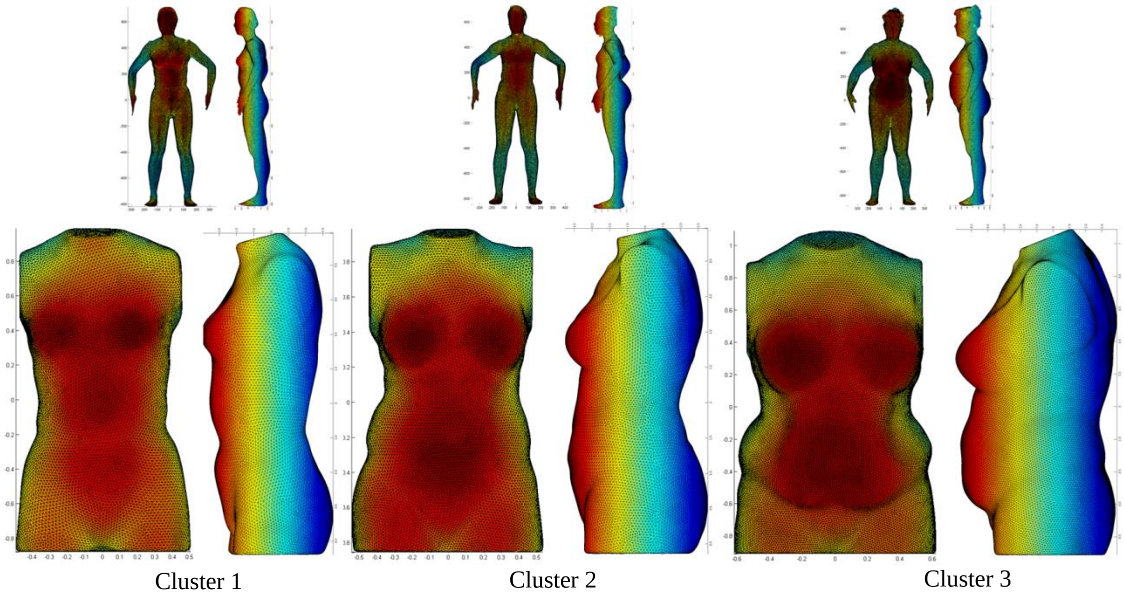


Figure 74: Morphotypes and normalized torsos of the 3 clusters.

Identifying one shape from another can be solved by analyzing the client's silhouette in relation to that of each morphotype of the database. In this case, to deal with the problem related to the switching from 2D to 3D space, we chose to work in 2.5D, i.e. by relying on two images of the client to get closer to the 3D data of the database. As it was already specified, the stature will be used, in the next step of research, for the parametrization of the 3D adaptive morphotype mannequin to create the client's avatar.

III.3.2.a. 2D Image processing of client’s pictures

Based on the previous unsupervised classification, the supervised classification of a new customer is in 2.5D, using two images taken by the client, a face and a profile. These images were taken with a definition 1280x960 in American shot. The process is deterministic, so it makes perfect reproducibility.

The steps between the native image (**Figure 75.a**) and the final image (**Figure 75.b**) representing the silhouette of the person comes down to:

- reframe the image’s height
- convert the image it in grayscale
- segment the binary image with gray-level histogram
- re-adjust the definition to 600x400 for the face image and 600x250 for profile image
- detect the contour by Sobel’s and Prewitt’s filter

Figure 75: Silhouette extraction result.

III.3.2.b. Pre-processing of 3D into 2D shape descriptors

As aforementioned, the 3D clustering method of morphology shape detection [139, 140] has provided three morphological clusters presented in **Figure 74**. The morphotypes are assigned to the closest 3D morphology of the centroid of each cluster **Figure 76**.

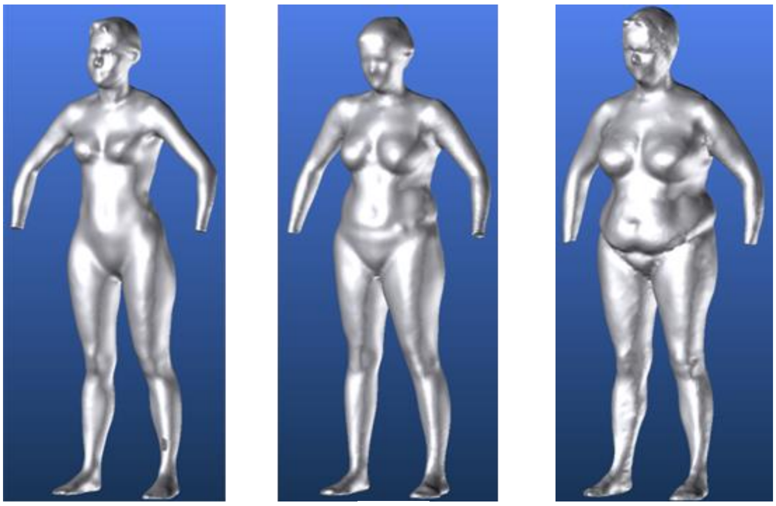


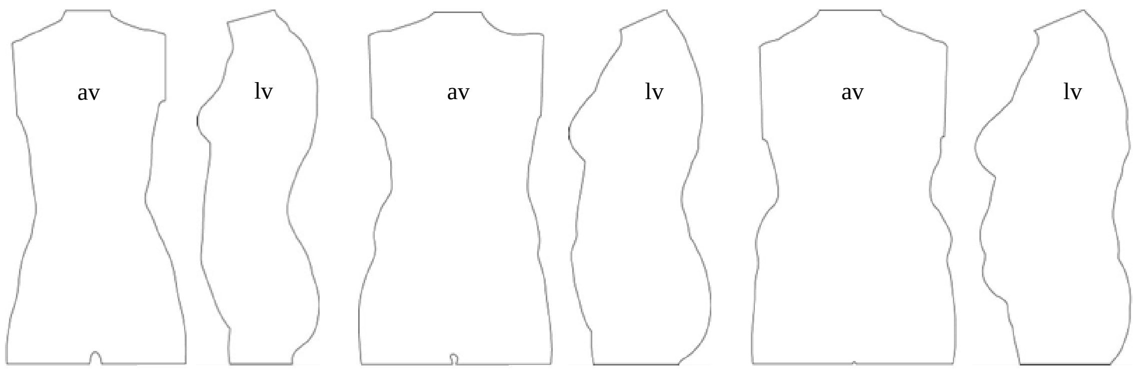
Figure 76: 3D morphotypes for the cluster 1:(a), 2:(b), 3:(c)

Subsequently, the 2D shape descriptors of 3D morphotypes are obtained. The 2D shape descriptors of anterior (av) and lateral (lv) view are shown in **Figure 77**.

III.3.3. Results and discussion

III.3.3.a. Classification evaluation

The quality of our classification is evaluated based on the results of Hamad's 3D morphology classification [139, 140]. It is particularly relevant since we are interested here in morphology classification within the context of assignment to the 3D morphotypes database. Therefore, fifteen women subjects have been scanned and classified into one of three morphotypes, five for each morphology, with the 3D method [41]. The 2D shape descriptors to each of the images, both for the anterior and the lateral profile, have been determined and correspond to a balanced distribution of the fifteen morphologies in the clusters C1, C2 or C3. Morphology 1 is assigned to cluster C1, morphology 2 to cluster C2 and morphology 3 to cluster C3.



(a) (b) (c)

Figure 77: 2D shape descriptors of the 3D morphotypes for the cluster 1:(a), 2:(b), 3:(c).

Table 4 presents the values of *DSC* between the fifteen women subjects compared to the morphotypes of each class for anterior and frontal views. The global index of similarity τ is an indicator defining the quality of the classification. The expression τ , $\alpha = 1.0$ and $\beta = 0.7$ has been calculated empirically.

Table 4: Similarity index of 15 women's subjects with the three morphotypes.

Morphology	Anterior profile			Lateral profile			τ		
	C 1	C 2	C 3	C 1	C 2	C 3	C 1	C 2	C 3
Morphology 1	0,77690	0,79746	0,81692	0,88488	0,91821	0,83471	0,82136	0,84718	0,82425
	0,90680	0,84062	0,81458	0,80267	0,83784	0,78138	0,86392	0,83947	0,80091
	0,85113	0,79177	0,84981	0,79941	0,81781	0,73962	0,82983	0,80249	0,80443
	0,88105	0,85350	0,82548	0,84582	0,84266	0,73876	0,86654	0,84904	0,78977
	0,88725	0,86419	0,82702	0,88566	0,90592	0,81302	0,88660	0,88137	0,82125
Morphology 2	0,81126	0,86623	0,83597	0,81220	0,86314	0,82447	0,81165	0,86496	0,83123
	0,86973	0,80115	0,82725	0,82205	0,88086	0,82321	0,85009	0,83397	0,82558
	0,79913	0,88822	0,87163	0,77418	0,83082	0,77180	0,78886	0,86458	0,83052
	0,66054	0,72490	0,81870	0,78210	0,82293	0,86272	0,71059	0,76526	0,83683
	0,84645	0,88373	0,88386	0,79736	0,83827	0,70955	0,82624	0,86501	0,81209
Morphology 3	0,71150	0,83493	0,88419	0,80397	0,86473	0,83405	0,74957	0,84720	0,86354
	0,67176	0,76497	0,84186	0,78819	0,82292	0,86819	0,71970	0,78883	0,85270
	0,67753	0,76507	0,84398	0,78338	0,82161	0,91168	0,72112	0,78835	0,87186
	0,78544	0,88166	0,89886	0,77635	0,83444	0,86785	0,78170	0,86222	0,88609
	0,73002	0,87017	0,87984	0,82321	0,88705	0,80768	0,76839	0,87712	0,85013

From top to bottom, the classes are determined by the 3D classification, each line represents a subject. The columns represent the comparison value between the morphology of the subject and the representative of the classes C1 to C3. The last columns presents the final results, in green the right decisions in relation to the ground truth, and in red the bad ones. Green and red colors in this table represent the best level of similarity between consumer’s measurements and a certain morphology. The green color reflects the good matching, and the red color shows a defect matching. The yellow color represents the subject which is given in **Figure 78**. In this figure, we compare the silhouettes of the previous yellow subject (violet color) with the silhouettes of the different morphotypes (green color).

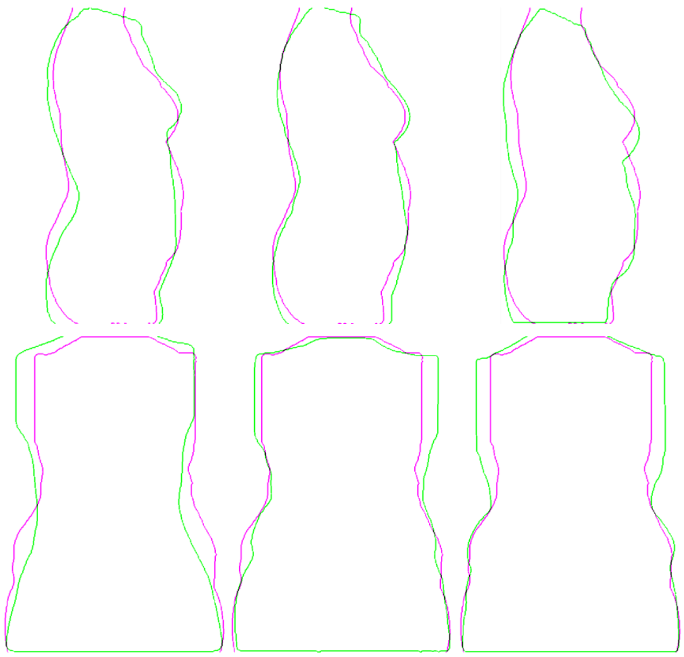


Figure 78: Comparison between one morphology in the anterior and lateral view with the morphotypes for the cluster 1:(a), 2:(b), 3:(c).

III.3.3.b. New client classification

The method was tested with a new client following the measurement protocol. The client's comparison results are presented in **Figure 79** and give us as the value of similarity index τ the following values: 0.83648 for the morphotype 1, 0.77016 for the morphotype 2, 0.67738 for the morphotype 3. Thus, the morphotype 1 can be assigned to this new client.

The estimation of the client's shape can be defined by superimposing two 2D shape descriptors at once. This operation has to be executed between the different morphotype’s 2D shape descriptors and subject’s 2D shape descriptors. The discrimination of the 2D shape descriptors is solid if it is used with τ representing the *DSC* weighted between the lateral and anterior views. Depending on the garment, it may be beneficial to give more value to the lateral view than to the anterior view.

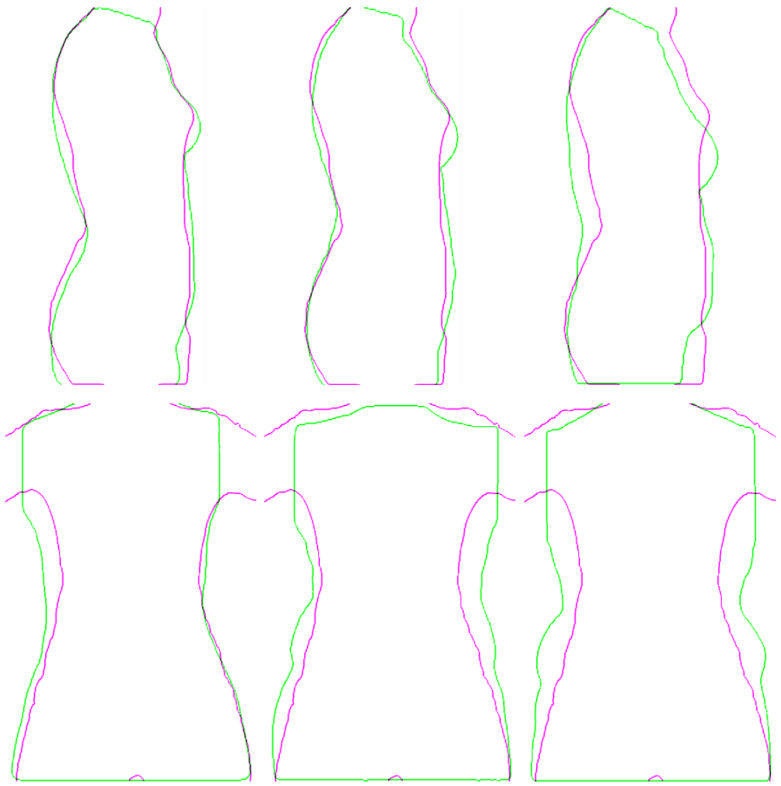


Figure 79: Comparison between new client in the anterior and lateral view with the morphotypes for the cluster 1:(a), 2:(b), 3:(c).

The 2D descriptor classification method was evaluated through results of 3D clustering classification. **Table 4** shows the overall results; the client's morphotype recognition is 75% correct, and the value of τ to validate is close to 0.865. This recognition rate is right because the classification does not use the same descriptor. It can be noted that even when there is an error, there is no confusion in transferring the subject from morphology 1 to morphology 3, which are the two extremes of the morphotypes.

The classification of the new client gives satisfactory results with τ (= 0.836) slightly inferior to 0.865. The others values of τ are distant enough, i.e. 0,86654 for Morphology 1/ example C1 for τ

III.4. Discussion

Many factors could influence a client's shape. The ambiguity may occur mostly owing to the posture. On the anterior view, we observed the tendency of a subject to tilt the shoulders more on one side. Bad posture on the lateral side can cause even more serious inaccuracy. Likewise, the breasts are prone to adapt to the bra shape. Therefore, if the subject has a bra which deforms the breasts, the chest line may overlap with under chest segment of the body. As a result, the contour which is extracted from the lateral view can lead to an inaccurate data reading.

Based on the outcomes two decisions are possible: First, if the new client does not match with any of morphological clusters, the new cluster can be created. Second, if the new customer matches one of the morphological class (e.g. Cluster 2), the adaptive morphotype PM2 (**Figure 67**) is adjusted for the stature of the customer thereby creating an avatar with body dimensions. Thanks to the basic garment pattern of the adaptive morphotype PM2, the basic garment for a particular client can be obtained.

Nevertheless, for an e-commerce, there is an existing need for the pattern recognition of client's body. The knowledge of the clients' measurements can be globally obtained by the clustering of a morphology database on which we can define the measurement charts. Additionally, by using the 3D database the client's shape can be identified. Our method makes possible to recognize the client's shape and in next step to create the avatar, which is a demand in the tailor-made sector.

Without recognition of an individual client to a particular target population represented by size or morphotype, the fashion industry would not be able to fit the garment on the client. To obtain the perfect match of the garment to the body is essential in consideration of the client's 3D posture and the stature. Matching the characteristic client morphology to the morphology cluster of a target population is a crucial step for effectiveness and profitability of fashion industry. A designing garment for the correct morphology improves the percentage of the well-fitted garment and decrease the number of returns.

III.5. CONCLUSION

In this chapter is presented our first research area which is the pattern recognition of customers who would like to buy garment on an e-commerce site.

For this, we expanded the work of Hamad who worked on 3D unsupervised classification of bodies. The interest of connecting to this work was to benefit from the results of this research, in particular, the 3 representative morphotypes of a female population. Given the constraints, we had set ourselves, i.e. to have only 2D images of the client from the front and side view, we therefore created our own shape descriptor to compare these 3 morphotypes to this lambda client. Following this, a supervised classification method was implemented to recognize his morphology among these 3 morphotypes and assign it to the cluster of the recognized morphotype. This method has been tested on typical morphology in order to test its robustness.

Among other things, the measurement of client's stature allowed us to dynamically control the adaptive mannequin of his associated morphotype and finally create his avatar.

A small anthropometric study was also carried out in order to show the complexity of positioning the morphological curves on a 3D avatar, this step is crucial because it intervenes at the same time in the creation of the garment and thus the 3D ease allowance.

CHAPTER IV: MODELING OF THE GARMENT CREATION PROCESS

This chapter is devoted to the implementation of a new design process of the garment fit the body in a 3D digital environment. Nowadays, the design of a new garment is carried out directly on a wooden dummy or fashion model with many precise and repetitive adjustments. This step commonly called drape technique requires expert manual know-how. Other design methods such as 2D pattern-making methods exist and are widely used as they are strongly practiced today in a digital environment. On the other hand, what can be criticized is that they do not take into account the morphological and anthropometric data of the client because they are based only on its measurements.

Looking back at the needs of the apparel industry, it is imperative to reduce the time of design step following an increasingly strong demand to quickly change the collection imposed by Fast fashion. Also, the complete digitization of the garment design process is a possible solution, even cost-effective if implemented in a 3D environment.

To achieve this goal, a lot of CAD software already on the market can become the miracle solution. But the apparel industry uses only the final part of this digital design chain, i.e. the 3D virtual try-on tool that makes it possible to verify the well-being of the garment on the mannequin. To reduce the design time, it is imperative to act upstream of the process by digitizing this manual step of 3d design which is much more respectful of the morphology of the client than the digital methods of the 2D pattern-making. Moreover, a completely numerical process leads to fluidity in the design, avoids errors that would be perceived and corrected almost instantaneously at the end of the process. Another key point of this method is to safeguard the know-how of creators in a digital form.

The goal of this chapter is to demonstrate that it is possible to create directly a garment fit to the client's morphology. For this, we have implemented a digital design method in a 3D environment. This method is based on the analysis of 2D pattern-making methods used by model makers. These methods highlight the morphological and anthropometric links that we have used to develop a similar method in 3D. The difference is that we work directly on the 3D wearer's morphology as in the manual 3D drape techniques, which avoids morphological interpretation errors. Among other things, we integrate a 3D zoning technique that improves 3D molding, not integrated into the previous work of the team. For that, we developed a new concept of 3D ease allowance management which is a perception means of the proximity between the garment and the body by with or without contact zones if the fabric is stretched. This last aspect is very important because it imposes on the creator to imagine what will become this digital garment when it falls during the 3D virtual try-on.

IV.1. ANALYSIS OF THE CREATION PROCESS OF THE WOMEN'S BLOCK PATTERN

IV.1.1. 2D process analysis

Different pattern-making methods to realize the women's block pattern exists. These methods depend both on the country or the author who develop the method. For a given country, different methods can also be proposed. But it turns out that after analysis, the results are relatively close because they all follow a common drape strategy nearest body. These methods generally start with a basic frame limited in X by the largest morphological contour and in Y by the greatest height (Figure 80: ½ chest girth +10, full front length). This frame can be replaced by two perpendicular lines having the same objective of limiting the working environment while giving a 2D reference frame.

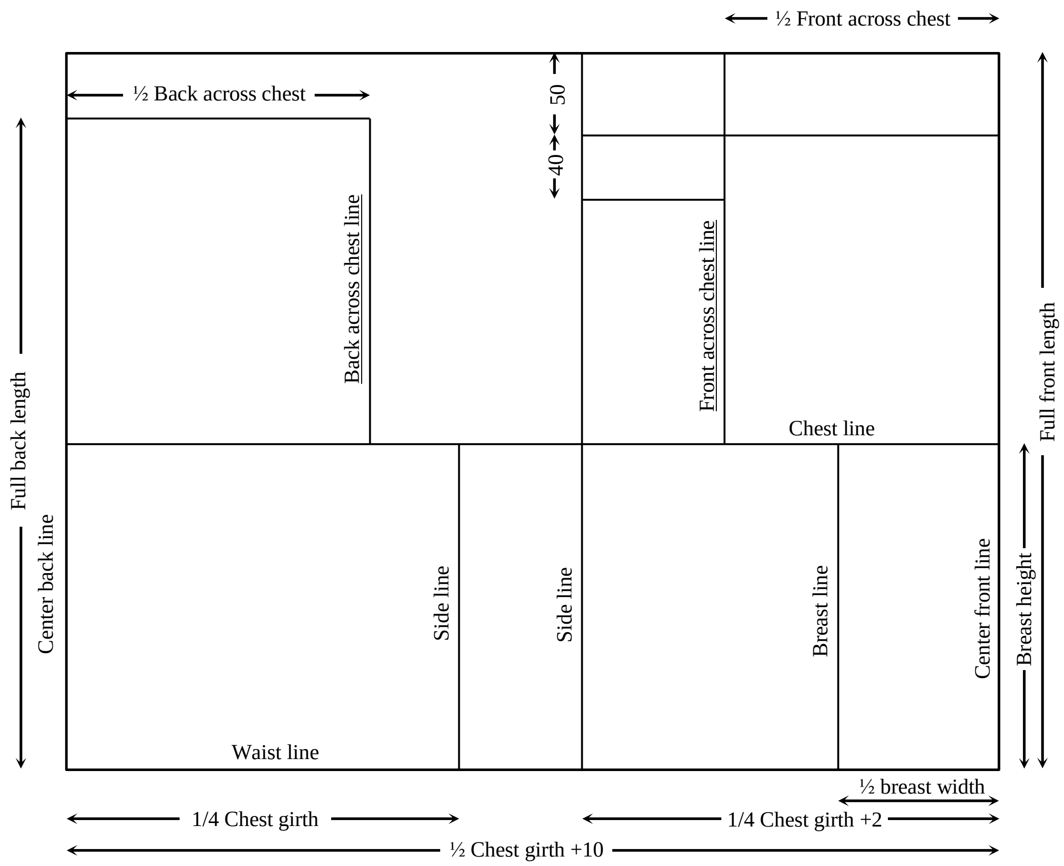


Figure 80: Morphological lines creation.

Then, different lines parallel to the low edge (**Figure 80**: waist line) of the frame are created to define the position the morphological lines relative to each other in the vertical direction (**Figure 80**: chest, breast height, full back length, shoulder slopes by the values 50-40). In the horizontal direction, a similar operation is performed according to the center front and back line to define the other morphological lines (**Figure 80**: back across chest, front across chest, breast, side).

Some anthropometric points such as the acromion, the 7th cervical, the manubrium, the front across chest, the back across chest, the underarm, the neck side (**Figure 81**: star points) are then located to create other lines or complementary curves (**Figure 81**: shoulder lines, Neckline) as a support to define the contour of the block pattern.

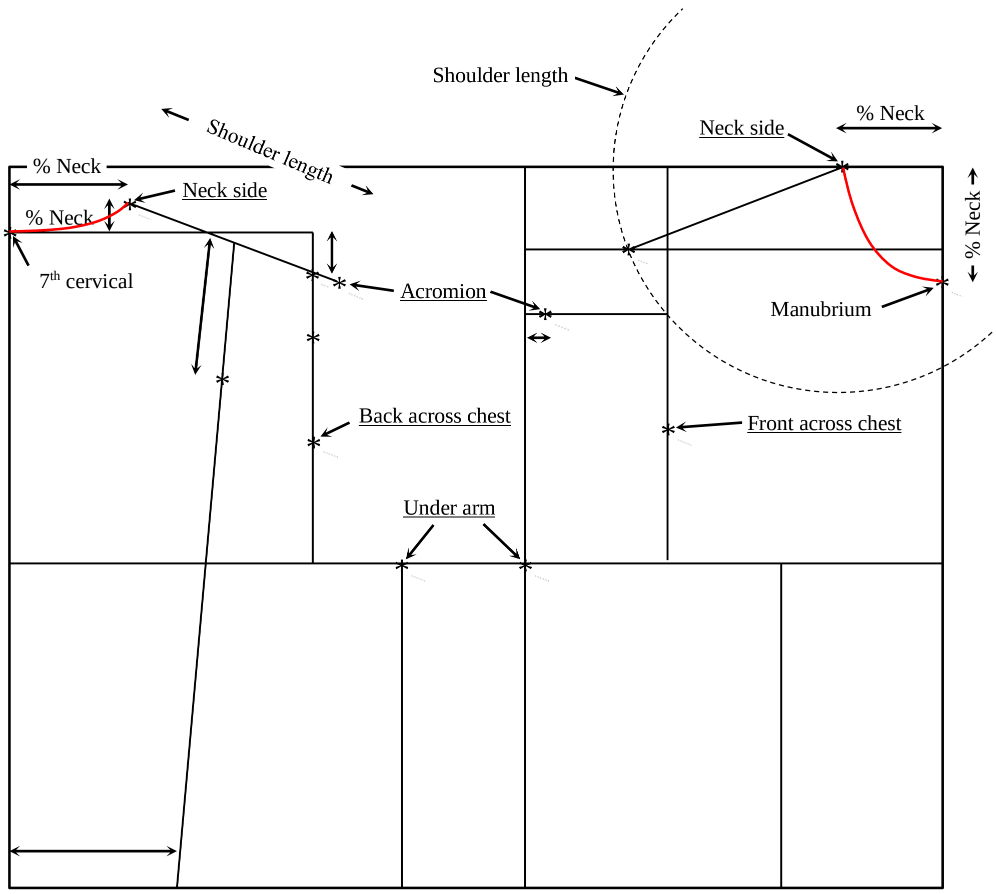


Figure 81: Anthropometric points creation.

At this stage, the 2D front and back block patterns (**Figure 82**: red) can be drawn using the lines characterizing the morphology, going through the previous anthropometric points and integrating the chest, shoulder and waist darts to allow the flattening of the 3D patterns in 2D.

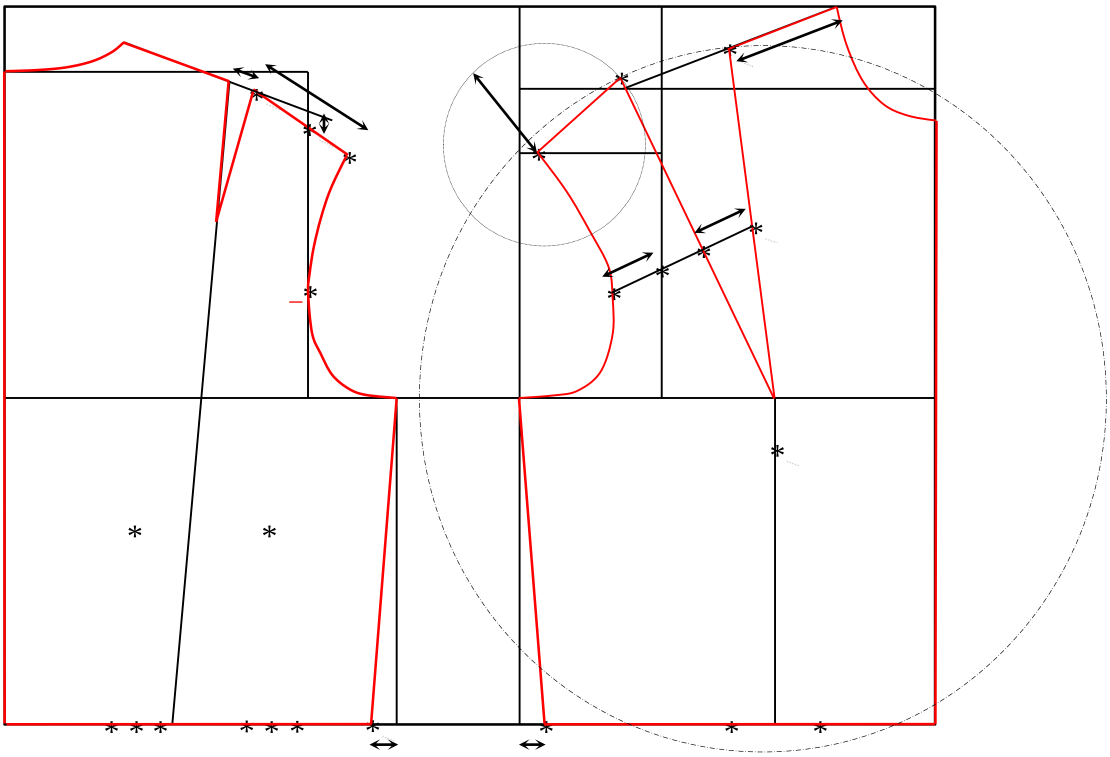


Figure 82: Final pattern drawing.

IV.1.2. Difference between the 3D & 2D process

The creation method of the 3D garment block that we implemented perfectly follows this design logic because it first identifies the morphological contours, locates the anthropometric points and defines a contour of garment that uses these points. Among other things, it follows different constraints of design such as the tangency respect of the armhole curves on the chest contour, the tangency continuity of these curves between the front and back. These constraints are not always expressed in 2D pattern-making methods.

The difference between the 2D and 3D methods is that a 2D morphological line becomes a 3D morphological contour, an anthropometric point defined in 2D must be localized 3D and the notion of 2D ease allowance (addition of the value of ease allowance on the measurement of contour) have to be replaced by a zoned management of the ease in 3D in order to better distributed it on the body. By this difference, the position of the garment relative to the body of the wearer is perfectly controlled and takes into account the morphological deformations which are not always integrated by simple measurements. Among other things, contact and non-contact areas (with ease allowance) are more easily manageable to anticipate the garment fallen implicitly integrated into the draping method on a real body.

IV.2. 3D CREATION PROCESS

IV.2.1. Posture analysis

The first step in the garment creation process starts by the acquisition of the wearer's scan and checking his posture. To create a symmetrical garment, the torso of the body must be perfectly vertical and aligned with the middle axis of both legs. To do this, we have to create a symmetrical plane perpendicular to the ground (**Figure 83**.**a**: red line) and check if it corresponds to the sagittal plane of the scanned body. This analysis should be realized from the torso. The sagittal section plane is defined with respect to a coordinate system in the crotch middle; the origin of this coordinate system is a pivot point for realigning the torso if necessary. The sagittal plane of the scanned body (**Figure 83**.**a**: green line) which we must verify is another section plane orientable controlled by an angle α leading to the global alignment of feature points such as the nose, the middle point of the breast lines, the navel, the manubrium. Of course, depending on the wearer's morphology, the angle α must represent the best compromise on the alignment of these different points.

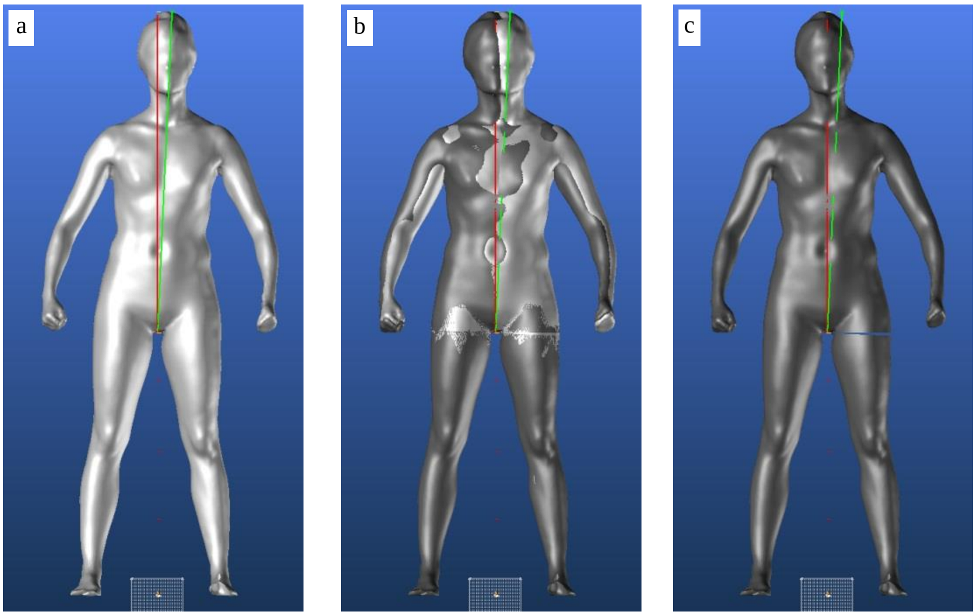
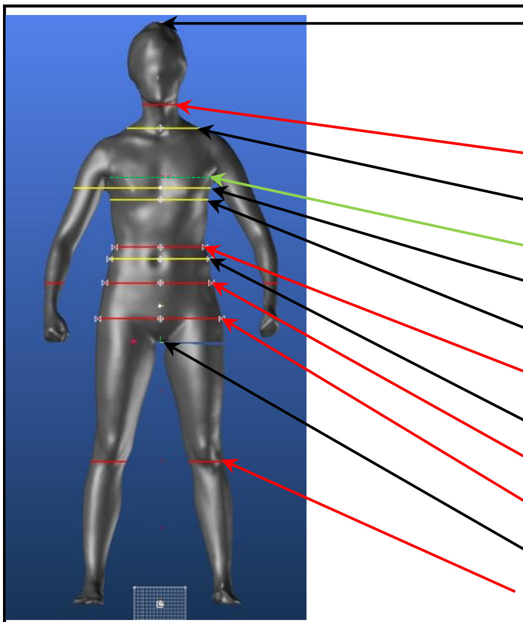


Figure 83: Posture analysis.

Thus, the analysis of **Figure 83**.**a** shows that the person leans his body towards the left side, hence the need to vertically realign his bust. This operation requires cutting the body at the level of the crotch and straightening the upper part of the body with an angle opposite to the one that has been previously detected (**Figure 83**.**b**). **Figure 83**.**c** shows that the new sagittal plane of the scanned body (red line) is now aligned with the feature points.

IV.2.2. Morphological contours respecting the beauty criterion

The goal of the next step is to locate the position of the morphological contours which will allow positioning the garment relatively to the wearer's body. The anthropometric ratios that have been applied to this wearer are those that follow the rules of woman's ideal proportion described by Loomis [1]. This wearer has the particularity of following these rules perfectly, which is not always the case, as we have explained in Chapter III. Some primary contours follow rules directly proportional to the stature (Figure 84: red and green contours), other secondary contours are defined relative to the primary contours (Figure 84: yellow contours). The table of Figure 84 shows that the stature manages the set of rules making it possible to position the morphological contours along the vertical axis. However, the value of the parameter h that localizes the top point of the head called bregma must be very accurate. We used the value of the stature resulting from the scanner measurement to initialize the anthropometric rules and obtain a first version of the morphological contours. This value was then adjusted so that all the curves are correctly positioned without changing the proportion ratios, knowing that our visual reference curves are mainly the curves of the chin and the waist.



Stature	h	1655
H8	h/8	206
Chin	7*H8	1448
Shoulder	Chin-H8/3	1379
Under arm	6*H8	1241
Chest	Under arm-H8/6	1206
Under chest	Under arm-H8/3	1172
Waist/elbow	5*H8	1034
Navel	Waist-H8/6	999
Low waist	4.5*H8	930
Middle point	4*H8	827
Crotch	Middle point-H8/3	758
Low knee	2*H8	413

Figure 84: Anthropometric ratios of the human body

IV.2.3. Anthropometric points detection

Still in the same spirit to create morphological contours for the positioning of the garment in 3D, some of them require detecting specific anthropometric points such as the armpits, the neck sides, the acromions and the 7th cervical.

The technique we used to detect right and left armpit points (**Figure 85**: points 1, 1') is based on the algorithm of Wang and Lu [147, 148]. From a morphological contour parallel to the ground and slightly below the desired position (armpit contours is represented by 3 contours showing a clear separation between the cutting of the 2 arms and that of the torso), that one goes up slowly step by step so that these three contours may touch slightly. The cut used is the one that was created just before the contact between these 3 contours. The two anthropometric points are then positioned in 3D on this contour at the intersection of the tendons of the pectoralis major attached to the arms.

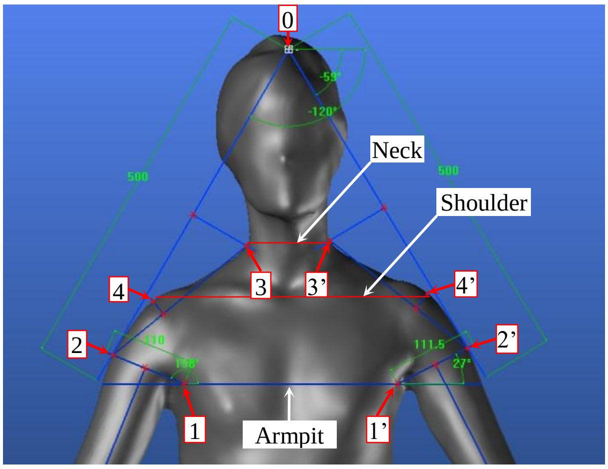


Figure 85: Anthropometric points detection.

The detection of the neck side points (**Figure 85**: points 3, 3') follows a strategy similar to that defined in Han [149]. To do this, we have to draw on each side a straight line passing through the bregma (**Figure 85**: points 0) and point (**Figure 85**: points 2, 2') located at the intersection between the arm silhouette and perpendicular line to the arm axis started on the armpit point. Then another perpendicular line to this line slide over it to find the greatest distance between the neck side point and the sliding point of the first line.

According to Han [149] and Dekker [150]**,** the acromion's (**Figure 85**: points 4, 4') are located at the end of a line perpendicular to the line defined by the neck point (**Figure 85**: points 3, 3 ') and the point on the deltoid silhouette (**Figure 85**: points 2, 2'). According to the method of detection of the neck side point, we seek the greatest distance from this line whose the extremity follows the shoulder silhouette by sliding it on the line 2-3 or 2'-3'.

From the position of these anthropometric points defined on the silhouette, we were able to vertically position the morphological contour of the neck between 3-3' (**Figure 85**), the shoulder contour between 4-4' (**Figure 85**). These two contours make it possible to locate definitively in 3D the neck side points taken at the intersection between the contour of the neck and the axis of the clavicle, the acromion's defined at the right and left extremums of the new shoulder contour.

The 7th cervical should be located at the intersection of the neck contour and the sagittal section plane.

IV.2.4. Contours and morphological lines - 2D/3D Ease allowance

The network of characteristic curves connected to the garment is based to a large extent on the previous morphological contours, i.e.: the neck, the chest, the waist, the navel, the low waist, the hips/middle point. It is at this stage of the design process that we integrate the notion of 2D ease allowance. The 2D ease allowance is represented by parametric lines attached to ease points distributed strategically on each morphological contour. At the end of these lines, new contours are created that are assigned the appropriate contour ease allowance value (**Figure 86.a**: brown outline). This 2D ease allowance is controlled independently between the front and back to control the garment balance and plumb. Certain points like the navel require increasing the value of ease allowance with respect to that defined on the half-outline in order to avoid the excavations. The objective is to find a stretched canvas (flat fabric) in these particular zones, that is to say, to create a curve not necessarily following this excavation.

The neck is processed differently because it must pass through the following four anthropometric points: the 7th cervical, the 2 neck side, the manubrium. It is thus represented by a 3D curve which is based on two half-contours connected by the two neck side points 3 and 3' (**Figure 86**). The half-contour of the back is none other than the back part of the initial morphological contour of the neck (**Figure 86**.**b**: red contour). The half-contour of the front is the front part of a contour defined by a cutting plane pivoting along axis 3-3' (**Figure 86**.**b**: white contour). The angle of the pivot is fixed when the lower end of this contour passes through the upper point of the manubrium (junction of the sternum/clavicles). The neck ease allowance points, as well as the lines of ease, are then defined in a balanced way on these 3D curves. The new 3D contour of the neck (**Figure 86**.**b**: brown contour) is obtained as above from the ends of these ease lines. The 3D ease allowance is also independently managed between the front and back to control the neck opening that is given by the designer. **Figure 86.b** shows the 3D positioning of the acromion's defined at the right and left extremums of the shoulder contour in red.

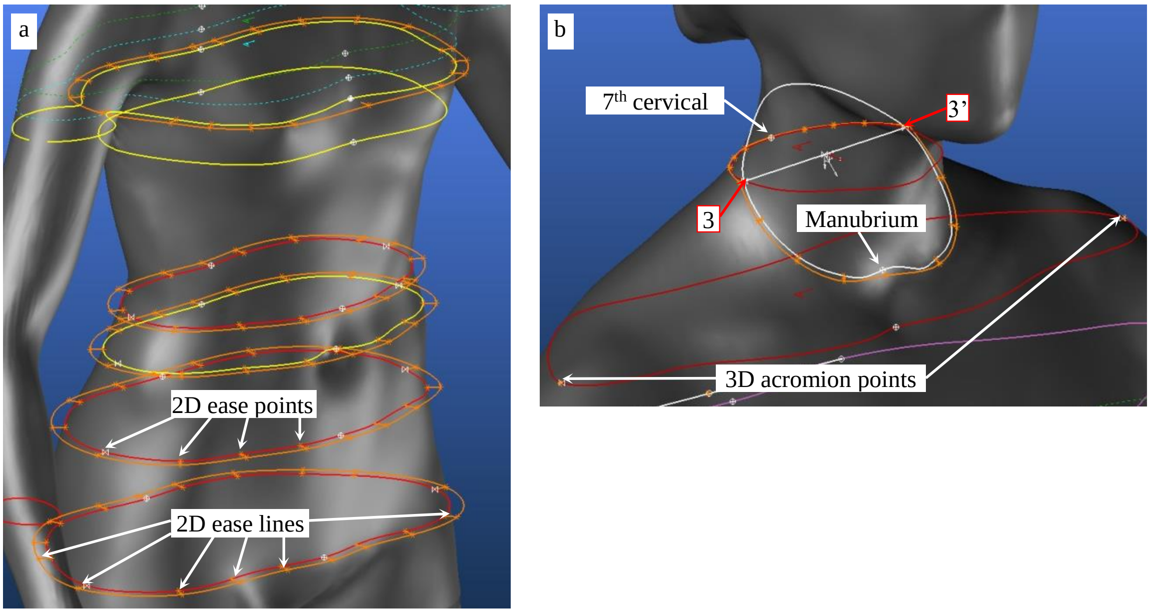


Figure 86: Morphological contours with 2D ease allowance.

The armhole curves have their own design specificity because they are also to be defined in 3D with feature anthropometric points, that is to say: acromions, underarms and front and back across chest. These strategic points control the 3D curve spatially, hence the interest to start the design process by these points. **Figure 87** shows that we have imposed their own ease allowance in the plane of section of their respective contour. The ease allowance on the acromion manages the contact with the wearer's body in this zone. The ease allowance of the underarm has the goal of assuming the continuity of ease allowance between the front and the back on the chest contour. On this contour, the gap between the front and back can be very different. Also, it is very important to specify that the 3D underarm point, positioned by the chest contour, slips on this contour in order to manage the inclination of the side line according to the wearer's morphology (side view). A line joining 3D acromion and underarm points with their 3D ease allowance localize the central point CE (**Figure 87**) distributing the external points of the armhole half-contours. This point is vertically located in the plane of the front across chest. In the **Figure 87**, the green dashed line represents the contour of the front across chest. The turquoise dotted line represents the contour of the back across chest, her vertical position is relative to the contour of the front across chest. At the lower extremity of this previous line are created two coordinate systems orientable along its axis in order to obtain two design plans for the front and back of the armhole. This technique allows us to control more easily the width of the front and back across chests, and this independently. Thus, on each plane are created different adjustable lines centered on CE on which are created at their extremity the front and back points of the armhole. The 3D shape of the armhole is then managed by the polar coordinates of these points with respect to CE and associated planes (front or back). Two points representing the front and back across chest points are then created at the intersection of their respective planes and the armhole contour.

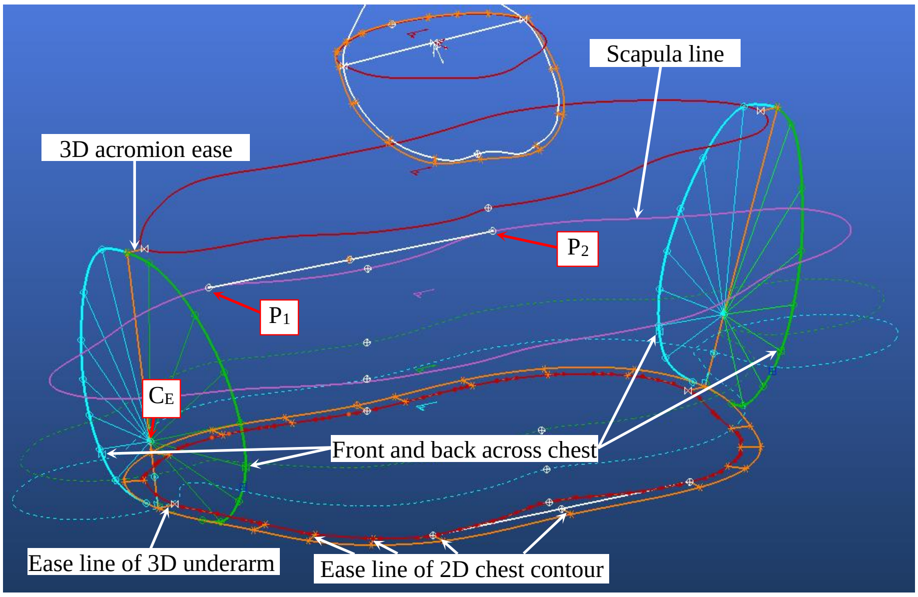


Figure 87: 3D feature points and contours of armhole.

The prominence of the shoulder leads to a contact area which must be managed because it has a significant impact on the wearer's morphology and therefore on the pattern final shape. This area is located on a curve (**Figure 87**: pink curve) defines in the mean plane of the most prominent points of the shoulders. Two points of prominence P1, P2 are assigned to this curve by searching for the maximum of the length of the line joining these points, which corresponds to the tangency points.

IV.2.5. 3D garment block modelling

Until now, we have started to set up the 3D wire frame model of the garment which is connected to the wearer by its morphological contours and anthropometric points. This point of view has been precedently detailed in the 2D creation process with a connection being made with the own wearer's measurements (**Figure 80**, **Figure 81**). However, this 3D wire frame model has to integrate the concept of 3D ease allowance. But this starting model is not sufficient to represent the 3D garment. The set of curves and lines defining the contour of the garment (**Figure 82**: red line) are not yet created. It remains to link a few strategic points to achieve this objective. **Figure 88** shows that the shoulder lines are a linear connection between the acromion points and the neck side points. The center front line is a broken line connecting the manubrium, the midpoint of the line between breasts and the midpoint on the front waist curve. The center back line is a broken line connecting the 7th cervical, the midpoint of the prominence points P1, P2 line and the midpoint on the back waist curve. The side lines connect the under arm points and its counterpart to the waist. These waist side points are located on the waist contour and slide on it like the underarm points on the chest contour. Due to the mobility of these two kinds of point, side lines are orientable in order to manage their inclination according to the morphology of the patient.

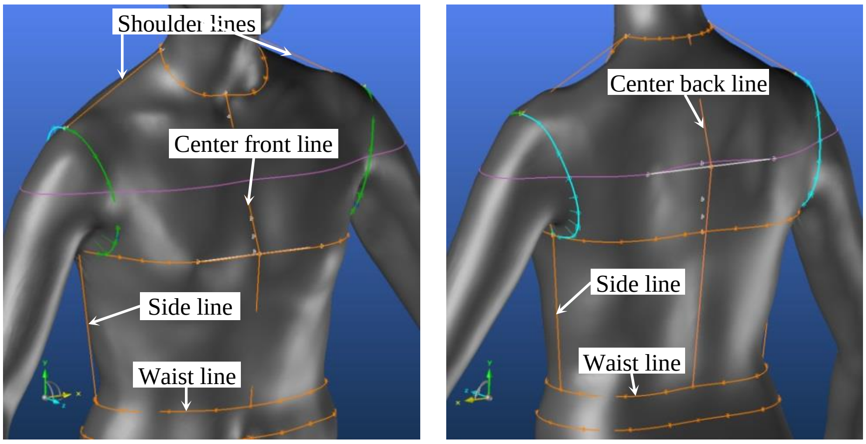


Figure 88: 3D design of the contour defining the shape of the garment.

At this stage of the garment creation process, it is impossible for us to use in the state this network of curves and lines to create a surface representing the garment. The surface model leaning against this strategic network would yield results that do not take into account the notion of moldability; Fundamental notion in 3D drape techniques to obtain a perfect fit. The example of the **Figure 89:** Unmanaged contact area. shows clearly that the surfaces cross the body regardless of the contact areas between the garment and the body.

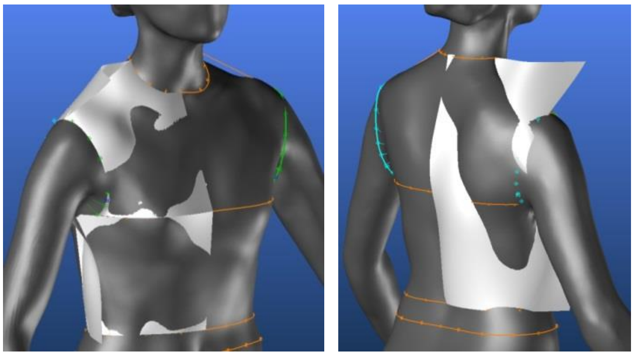


Figure 89: Unmanaged contact area.

To solve the previous problem, a moldability technique has been implemented in order to localize in a first step the contact zones. A first network of curves hooking to the 3D outer edge of the patterns (**Figure 82**: red line) has been created. This curves network is like of 4 cobwebs whose the center points are the prominent points of the breast (nipples) and the scapulas P1, P2 (**Figure 90**: blue curves). The first goal of this crossing lines network is to detect the intersection between its straight lines and the body which is the departure of the contact zone.

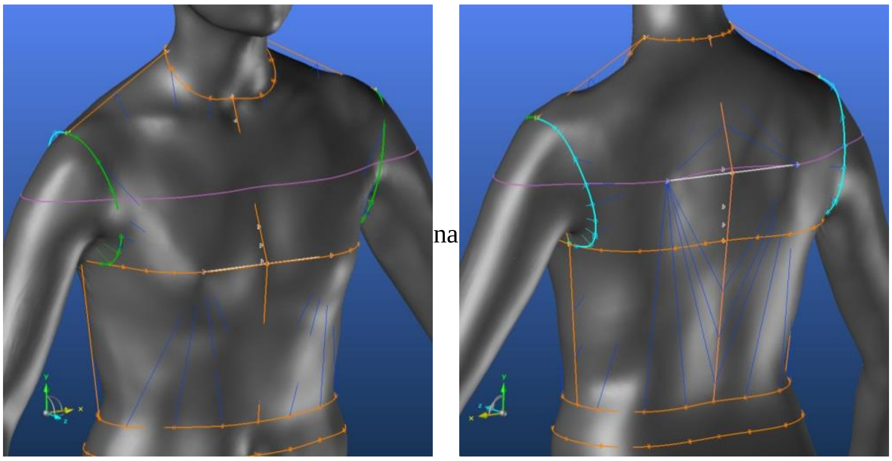


Figure 90: Detection of the contact zone by crossing lines.

Now, we can use the 3D ease allowance model explained in the chapter II. The goal of this network is to capture the 3D wire shape of the contact zone by the projection of each line on the body. Of course, the projection of these gives a curve network following the body's morphology but much greater than the contact zone (**Figure 92**: red curves).

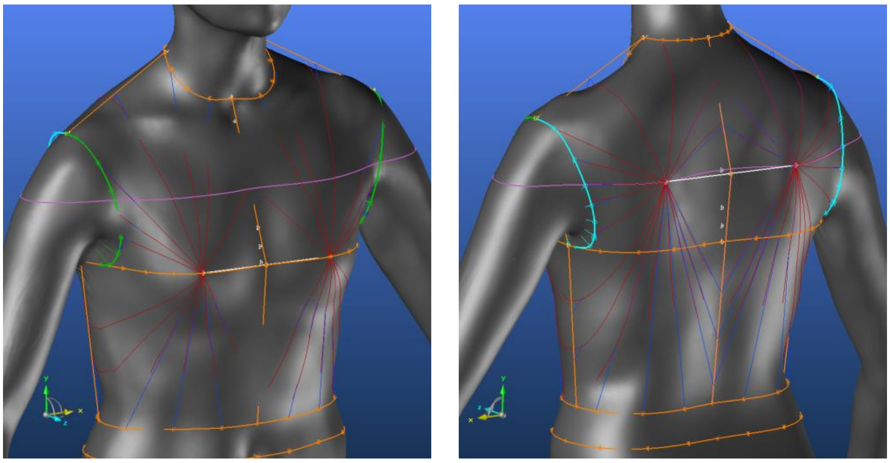


Figure 92: Printing of the contact area.

To limit the contact area, we have to search for its starting points. To do this, we have to create a slippery point on each of these curves which will mark their limit (**Figure 93**).

These points will then be connected to straight lines to extend the curves representing the contact area to the outer edge of the patterns. This extension is none other than the shape recognition of the garment stretched areas (**Figure 93**: white lines). It should be noted that the points at the end of the straight lines attached to the outer edge of the patterns are the same points that made it possible to create the blue crossing lines. The optimal position of the sliding points (contact limit) is given by a continuity of tangency and alignment between the white and red lines.

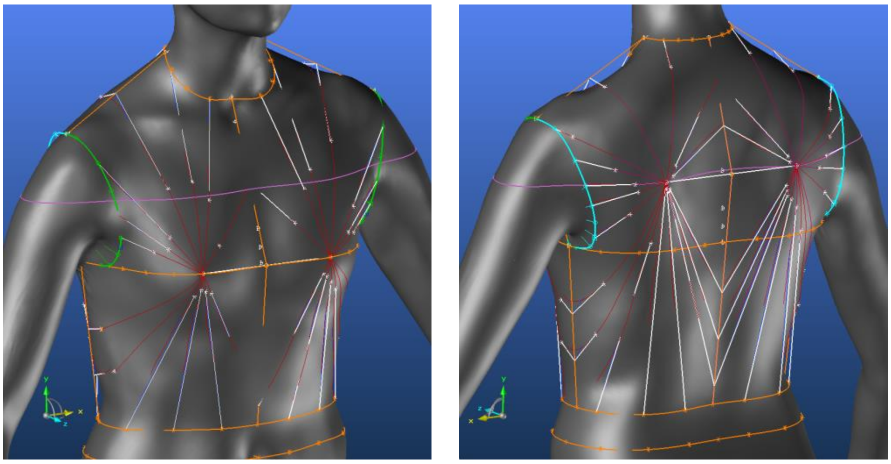


Figure 93: Limitation of the contact area, creation of the stretched canvas.

The goal of this final step is to create an internal curve network attached to the outer edge of the patterns. This network consists of merging the contact lines limited by their respective sliding contact points (**Figure 93**: red lines) and the expanded straight lines (**Figure 93**: white lines). The result is a network of perfectly connected curves (**Figure 94**: brown lines).

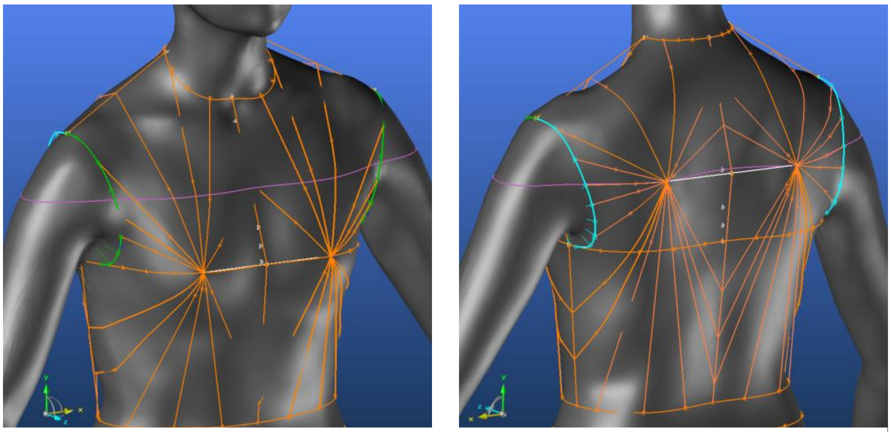


Figure 94: Curves network modeling the wire structure of the garment.

From these 4 networks of internal curves and their associated outer edge, a specific surface modeling tool allows us to create the 4 surfaces representing the right front pattern, the left front pattern, the right back pattern and the left back pattern (**Figure 95**: Blue surfaces). The flattening of these 3D patterns in 2D requires placing different darts at locations defined in **Figure 82**, i.e.: 2 chest darts in the front armholes, 2 front waist darts, 2 back waist darts and 2 shoulder darts (**Figure 95**: white curves). Their strategic locations will be dealt with in the next chapter.

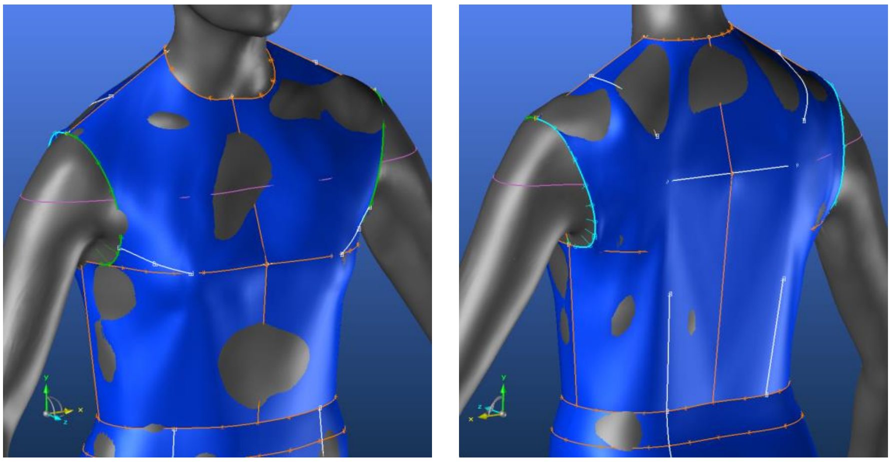


Figure 95: 3D garment surfaces.

IV.2.6. 2D block pattern from 3D garment block

In order to obtain the 2D pattern of the garment, we have to discretize these 4 surfaces by a meshing step. Depending on the surface area and the results quality desired, the size of the mesh has to be optimized; the optimum value we obtained is 10mm (**Figure 96**).
In this flattening step of the 3D surfaces, it is time to choose and validate the optimal position of the dart.

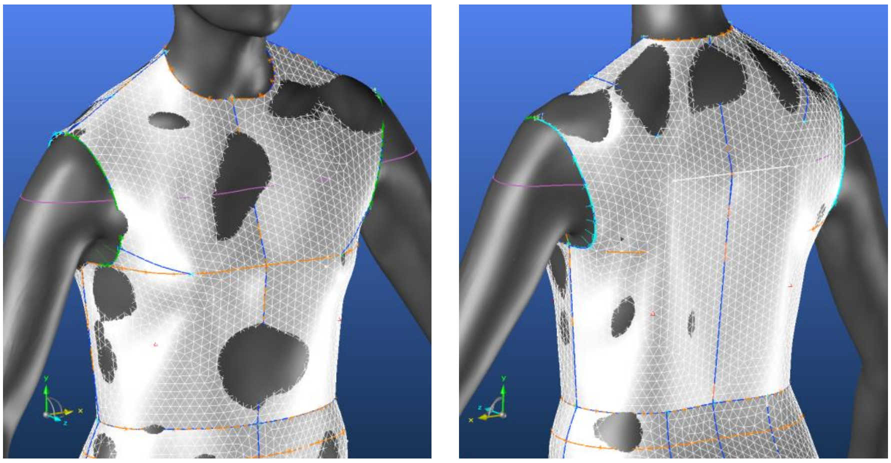


Figure 96: Garment surface meshed.

A post-treatment allows us to check if the flattening causes important deformation in 2D, which is not the case as shown by the turquoise color representing a deformation threshold close to 0 (**Figure 97.a**). The final result of the flattening (**Figure 97.b**) shows that each pattern is different, that is to say are not symmetrical with each other. The reason is that the garment was customized in 3D on the wearer. This result also shows that the rules imposed by pattern-making designers that instinctively integrate darts on the front waist do not always have to be followed. The wearer's morphology may thwart these rules. For example, for our case, there is no dart on the front waist.

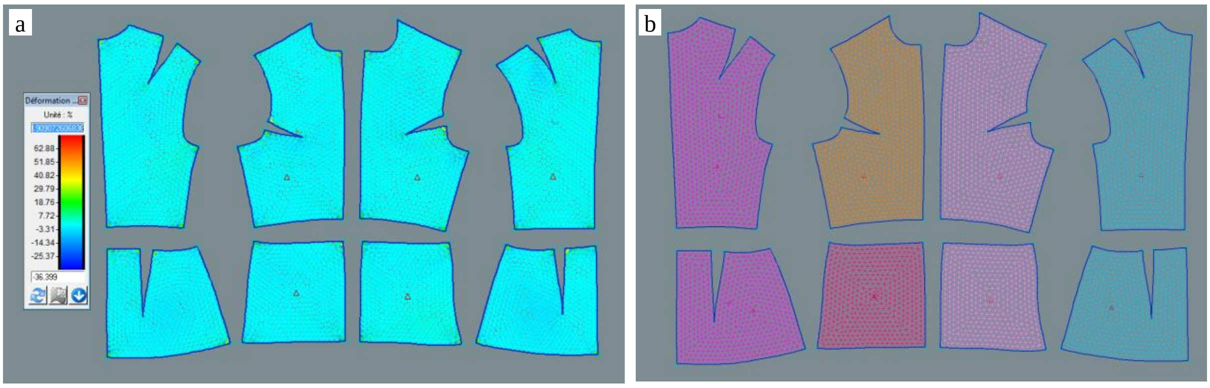


Figure 97: 3D/2D deformation analysis and flattening.

IV.3. CONTROL OF THE WELL-BEING AND THE 3D GARMENT FIT

IV.3.1. 2D virtual try-on

The computer tool we use to analyze the garment fit is 2D/3D Modaris software from LECTRA. To do this, each part of the garment has to be imported into the 2D pattern environment which we then sewed according to the assembly order of the block pattern (**Figure 98.a**).

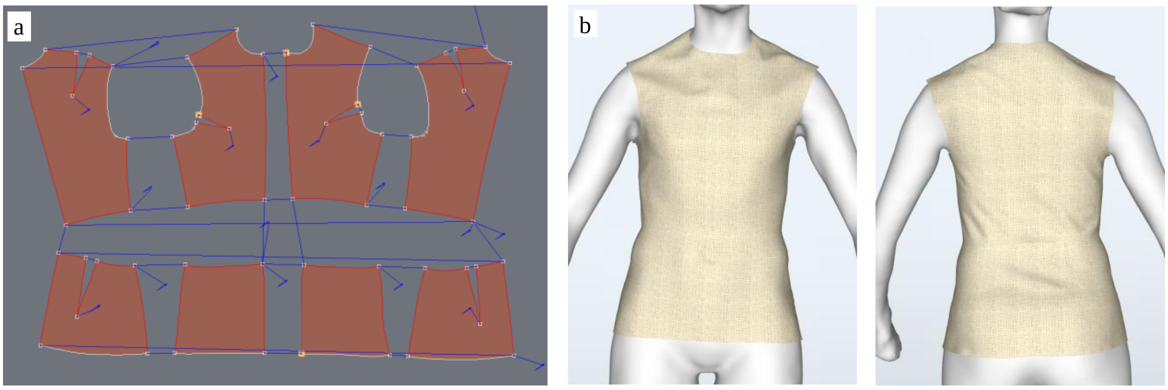


Figure 98: 2D sewing and 3D virtual try-on.

Then, we used the 3D tool to simulate the virtual try-on of this garment on the wearer's body. The result shown in **Figure 98.b** shows that the garment is very close to the body but this visual has only a subjective perception of the proximity, especially if one wishes to compare different visuals of this garment with different values of 3D ease allowance and kind of fabric.

IV.3.2. 2D/3D ease allowance by area

The ease allowance we have defined previously in the creation process is a 2D/3D ease allowance per zone as shown in **Figure 99**. Two techniques of ease allowance management are proposed, i.e.: by contact, by anthropometric curves. The ease allowance by contact appears in a level of the chest and scapula's. It is a 3D ease allowance which is widely distributed on these two zones because it uses the limited red curves of **Figure 92** in order to move the garment wire structure around to the nipple and scapula points P1, P2 (**Figure 93**). The ease allowance by anthropometric curves can be assimilated to a 2D ease allowance because it is defined in the contour plane concerned (**Figure 86**). At the level of the neck, we can consider that the ease allowance is in 3D since this contour is defined in 3D by two non-aligned 2D morphological contours. Note that on the front part of the neck contour was designed so that the designer can handle the neckline opening by a specific value. Let us also recall that we have defined in certain mini-zones a specific ease allowance on the following anthropometric points: acromion, underarm.

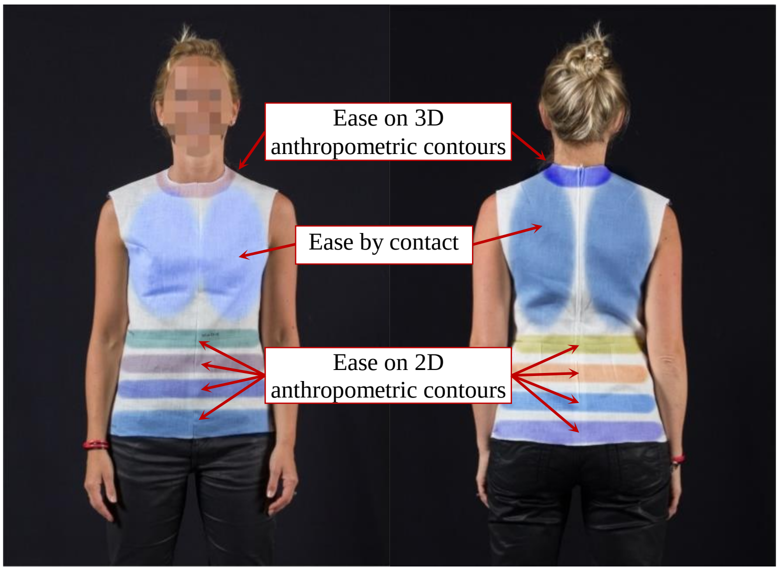


Figure 99: Ease allowance managed by zone.

IV.3.3. Perfect fit calibration

The goal of this empirical test is to find the ease allowance values of each zone which brings us to a perfect fit of the garment on the wearer's body. The fit evaluation in the 3D virtual world can be perceptible by a bar graph translating the ease allowance values in different colors. The ease allowance value close to zero is represented by the white color. Since the overall ease allowance does not necessarily correspond to a value equal to zero at each comfort point (stretched zone), it has been necessary to set up a method for managing the 3D ease allowance with a reduced number of tests. In the initial state, the comfort values are taken so that the garment can fall without any discomfort at the chest. Then, starting from the upper body, the ease allowance value was reduced until a white zone was obtained in this zone when the garment is at the equilibrium position. This assignment process evolves from top to bottom to take account of the natural direction of the fallen of the garment. **Figure 100** shows the end result of the ease allowance assignment in function of the bar graph values.

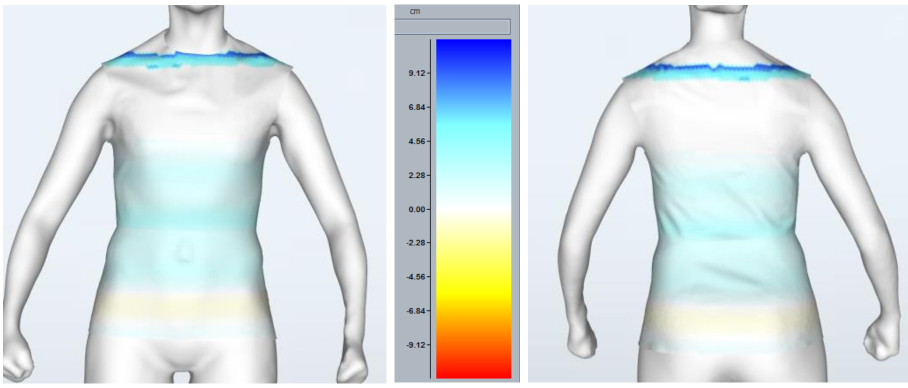


Figure 100: Objective perception of ease allowance during the fall of the garment.

IV.3.4. Impact of ease allowance on visual evaluation

Since we wish to know the values of the 3D ease allowance in order to obtain a garment perfectly adjusted to the wearer's morphology, it is important to check the computer tool that allows us to evaluate this type of data. Since the 3D ease allowance is defined by zone, the tool has to be sensitive to the gap between the garment and the body in the case of contours detected in a plane parallel to the ground. It has to also be sensitive when evaluating in the vertical direction, i.e. between two close contours.

Figure 101 shows different cases of the 3D ease allowance distribution perceived by these color gradations. The evaluation process shows that, based on the chosen values defined in the **Table 5**, the evaluation of ease allowance modification between these three cases is very perceptible. This test was very important to check since our modifications are very low which means that they are not always perceptible in the real garment wearing.

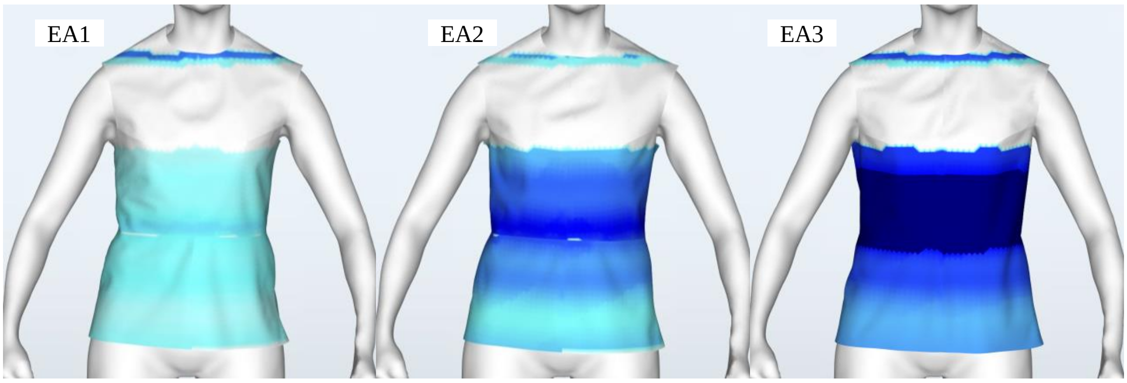


Figure 101: Different cases of the 3D ease allowance distribution.

Table 5: Values of 3D ease allowance distribution.

Ease allowance	Side	Perfect fit	Fit EA1	Fit EA2	Fit EA3
Neck	Front	3	6	6.8	7.6
	Back	1	4	4.8	5.66
Chest	Front	5	10.4	15	20
	Back	5	10.4	15	20
Waist	Front	1	8	12.7	17.5
	Back	4	11	15.7	20.5
Hip	Front	1	8	9.5	11
	Back	6	13	14.5	16
Navel	Front	1	8	11.1	14.25
	Back	2	9	12.1	15.25
Low waist	Front	4	11	14.1	17.25
	Back	6	13	16.1	19.25
Scapula		1	4	4	4
Acromion		1	1	1	1

IV.4. CONCLUSION

This chapter introduced a new technique of designing and modelling clothing directly on a client's virtual counterpart which is set in a remote environment. At first, we analyzed the 2D pattern-making methods. Despite same logic in developing the basic garment block, between the 2D and 3D method, there are essential differences mainly in the environment in which the design follows. In our solution to position the contours we use an anthropometric ratio and not the vertical length dimensions as it is in 2D solution. Virtual space gives the possibility to see the human body in 3D for what it really is. In contrast, the 2D methods perceive the three-dimensional body as the two-dimensional measurements. It is due to the way the patterns are made.

In the 3D creation process, we design the block pattern starting from the choice of the most relevant points and contours of the human body model. This approach can also be used for other basic models.

The method is a 3D-to-2D solution where we may control the 3D garment fit by determination of the ease allowance. We have extended the approach on the 3D zoning techniques to assure the best possible draping on the wearer's body.

CHAPTER V: 3D EASE ALLOWANCE BY USING DATA-BASED MODELING APPROACH

This chapter aims at setting up a series of mathematical models characterizing the relationship between garment design parameters (fabric properties, garment styles), wearers' morphologies and postures, as well as ease allowance values, in order to control and adjust garment patterns according to designer and consumer's perceptions. By using these models, the concept of 3D ease allowance optimization will be integrated into the 3D garment CAD approach for obtaining an appropriate garment surface on a specific virtual human model and delivering customized finished garments in the context of remote design.

The relationship between the design parameters, human morphology, posture, and ease allowance is complex and uncertain due to the existence of human factors related to designers' and consumers' perception. Therefore, according to the analysis in Chapter 2, we propose to use fuzzy modeling techniques for extracting fuzzy rules by learning from experimental data, measured or evaluated on the inputs and output of the models. In this context, we propose to develop Chapter 5 by using the following sections. First, we give the general principle of the proposed modelling procedure as well as related concepts. Next, the fabric and garment samples collected for acquiring learning data are described. These samples are then characterized using instrumental measurements and sensory evaluations to form the input and output data for modeling. Based on the acquired input and output learning data, we describe the modeling procedure for extracting relevant fuzzy rules permitting to predict 3D ease allowance values from desired human perception on fit and comfort and other design parameters. For a new fabric and new consumer morphology, we compute the relevancy degree of the input data related to all the fuzzy rules in order to find the most appropriate ease allowance value.

V.1. GENERAL PRINCIPLE OF THE PROPOSED MODELING

We consider that the best strategy of remote customized garment design with Internet and virtual reality tools is to optimally manage and control interactions between real and virtual design environments. In the real design environment, we use a number of representative real fabrics, real garment samples and real wearers' body shapes for identifying the relation of ease allowance with the influencing factors: desired real garment fit and comfort, human morphologies, and material properties (Model 1). With this model and related learning database obtained from the reals samples, real garment try-on can be used for validating any proposed design solutions in terms of comfort and garment fit. In the context of remote garment design, any real samples are not available and the consumer and designer have no physical contact between them. Therefore, the 3D CAD tools in a virtual environment can be used for generating virtual 3D garments. Virtual garment try-on should be developed for validating any proposed design solutions related to a specific body shape in term of virtual garment fit. Therefore, the relation between 3D ease allowance, virtual garment fit and other concerned elements should be quantitatively identified. However, in the virtual environment, wearer's comfort cannot be visualized and virtual garment fit does not necessarily conform that in the real environment. In this situation, we need to quantitatively identify the relation of real garment fit and comfort with virtual garment fit and other influencing factors (Model 2). From these models controlling interactions of garment design elements in the real and virtual environments, we can effectively predict 3D ease allowance values for any specific wearer, fabric material and other design parameters. In fact, we wish to know the values of the 3D ease allowance in order to obtain a garment perfectly fitted to the wearer's morphology with different postures. The general principle on this modeling procedure is given in **Figure 102**.

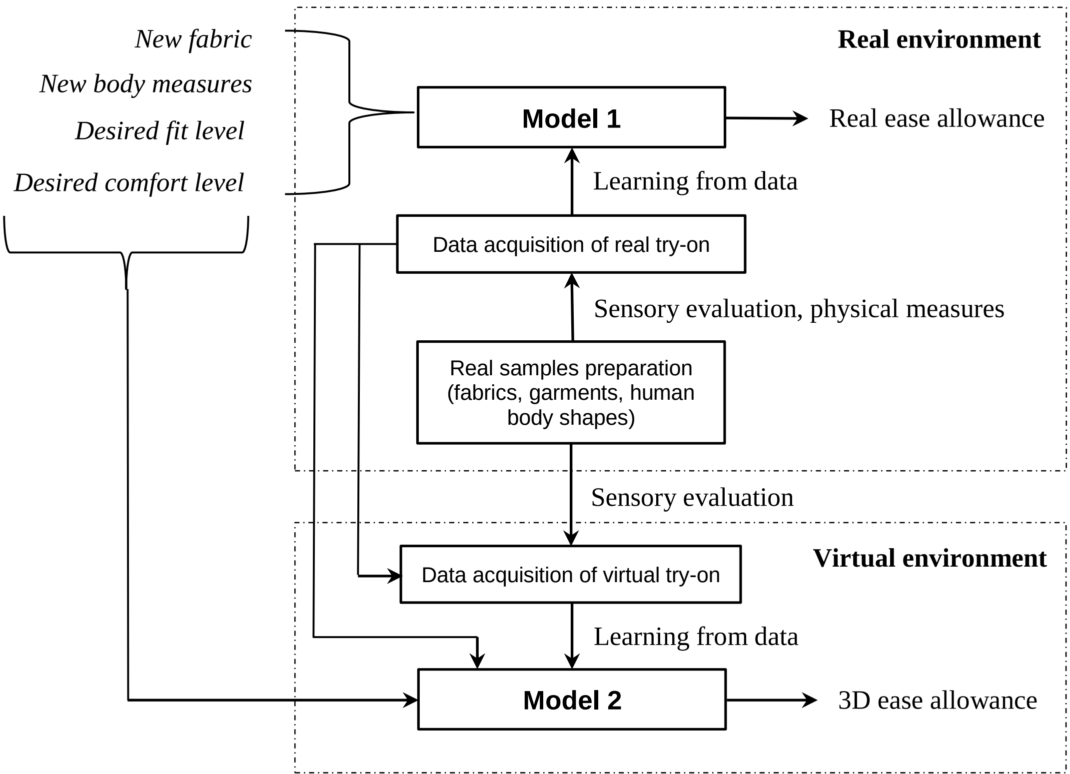


Figure 102: General principle for predicting 3D ease allowance by using data-based modeling approach.

According to **Figure 102**, the modeling procedure is based on data collected from a set of real samples (selected wearers/subjects, fabrics and garments). The data acquisition is realized by using physical measures for fabrics and sensory evaluations for garment fit and comfort. Model 1 permits to characterize the relation of real ease allowance with perceived real garment fit and comfort, fabric properties and human body measures, i.e. Real ease allowance = Model 1 (garment fit perception, comfort perception, body measures, fabric properties). By using Model 1, we can find, for any specific body shape and selected fabric and garment style, the most relevant ease allowance value corresponding to the comfort and garment fit desired by the consumer and designers. Model 2 permits to characterize the relation of 3D ease allowance with real garment fit and comfort, perceived virtual garment fit, ease allowance, fabric properties and body measures, .i.e. 3D ease allowance = Model 2 (real garment fit, comfort, virtual garment fit, ease allowance, body measures, fabric properties). Compared with Model 1, virtual garment fit has been introduced as a new input variable to Model 2 for controlling the interaction between the real and virtual environments and predicting 3D ease allowance from both real learning data and desired real garment fit and comfort.

V.2. DATA ACQUISITION

V.2.1. Formalization and preparation of samples

In our study, the learning dataset constitutes the foundation for setting ups the proposed model. In a general sense, it is composed of the following issues:

- {W1, …, Wn}: the set of n selected wearers with different morphologies covering the whole target population.
- {F1, …, Fm}: the set of m selected representative fabrics for the garment to be designed.
- {EA1, …, EAp}: the set of p ease allowance values selected for different sizes of the garment.
- {P1, …, Pq}: the set of q postures with which the designed garment is evaluated.

The previous formalization can be adapted to all garment design cases. However, in our study, we just focus on the specific case of designing a customized upper blouse without sleeves for five types of female body shapes (n=5). The selected subjects are white women between 35 and 42 years. Their body measurements are shown in **Table 6**.

Table 6: Body measurements of the five selected wearers/subjects.

Body measurements (cm)	Height	Chest girth	Waist girth	Hip girth	Chest width	Under-bust circumference	Shoulder width (left)	Shoulder width (right)
W_1	162.0	92.0	70.1	101.0	38.1	73.7	13.8	13.8
W_2	165.5	83.2	67.5	95.8	36.9	75.2	12.4	14.6
W_3	162.9	87.5	73.3	109.2	35.5	77.0	12.4	14.0
W_4	156.5	88.3	63.3	96.0	37.9	70.8	14.9	14.7
W_5	161.0	95.8	77.5	101.0	44.9	80.0	13.1	14.4

From direct observation on the data of **Table 6**, we can find that these body measurements are not proportional between them and can represent various body shapes of the target population.

The selected fabric materials include F1 (100% cotton), F2 (100% PES), F3 (100% Linen) and F4 (65% PES and 35% Cotton) (m=4). These four fabrics are frequently used in block pattern design and their physical properties are quite different between them. Also, according to the designer's experience, we propose, for each selected wearer/subject, three ease allowance values EA1, EA2, EA3 for developing three garment styles (loose, normal and tight). For each EA, its ease values at different body positions are different (**Table 7**).

Table 7: 3D ease allowance values for different body positions.

3D EA (mm)	Chest	Waist	Hip	Collar
EA1	6.4	8	8	4
EA2	11	12.7	9.5	4.8
EA3	16	17.5	11	5.6

For each selected wearer/subject, during the garment evaluation session, she is visualized with four postures: straight standing, standing with raising two arms, leaning forward, and sitting down (q=4). The fitting effects of a linen upper blouse on the body shape of W1 with the ease allowance EA1 are shown in **Figure 103**.

Considering all the previous combinations of subjects, fabrics and ease allowance values, we have produced 5×4×3 = 60 different garments, which will be used for learning data generation. During the evaluation session, each wearer/subject realized one try-on with each of the 12 concerned garments (combinations of 4 fabrics and 3 styles), which is evaluated by herself and a number of design experts for all the 4 postures. Therefore, the total number of evaluations for each expert is 12×5×4=240 (**Figure 104**). The number of evaluations for each subject is 48.

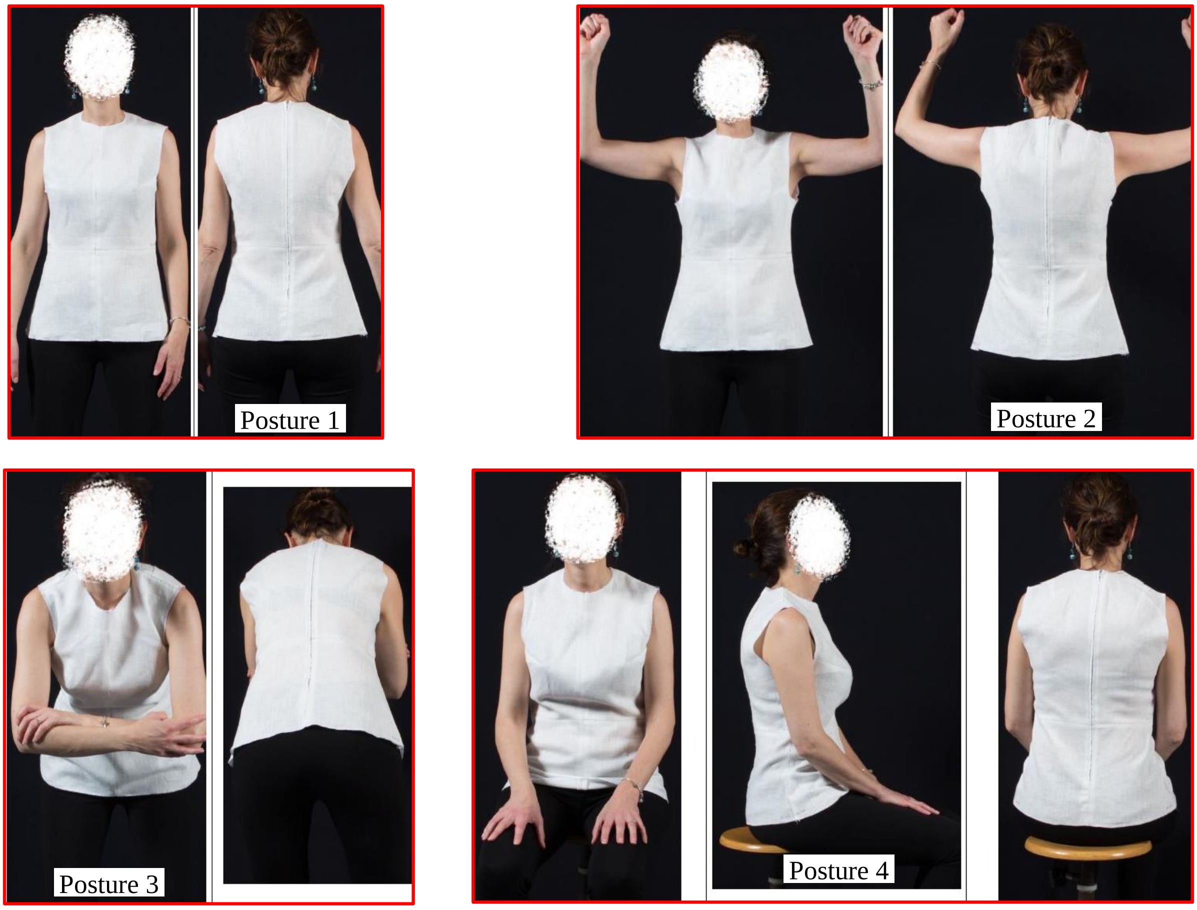


Figure 103: Fitting effects of a linen upper blouse on a wearer W1 with a fixed ease allowance EA1.

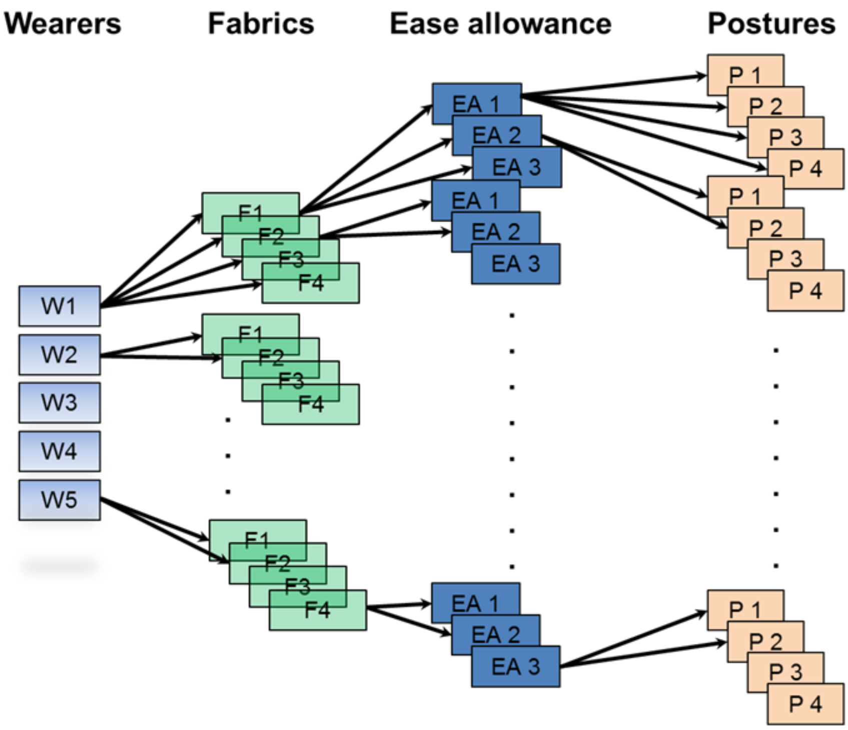


Figure 104: The total combinations of subjects, garments and postures.

According to the previous real garment design parameters (measured fabric physical parameters and allowance values) and morphologies of the selected subjects, we generate the corresponding 60 virtual garments and 60 virtual fitting effects with 4 postures by using the Modaris 3D software, commercialized by French Lectra Company. **Figure 105** gives one example of virtual garment fitting effects (front, back and side) on the wearer W_1 with cotton material and different ease allowance values. We can find that the effects of ease allowance and fabric properties can be clearly visualized. The data collected from these samples (real and virtual garments, fabric parameters, human perception on garment fitting and comfort) will be presented in the following two sections and used for setting up the model using fuzzy techniques.

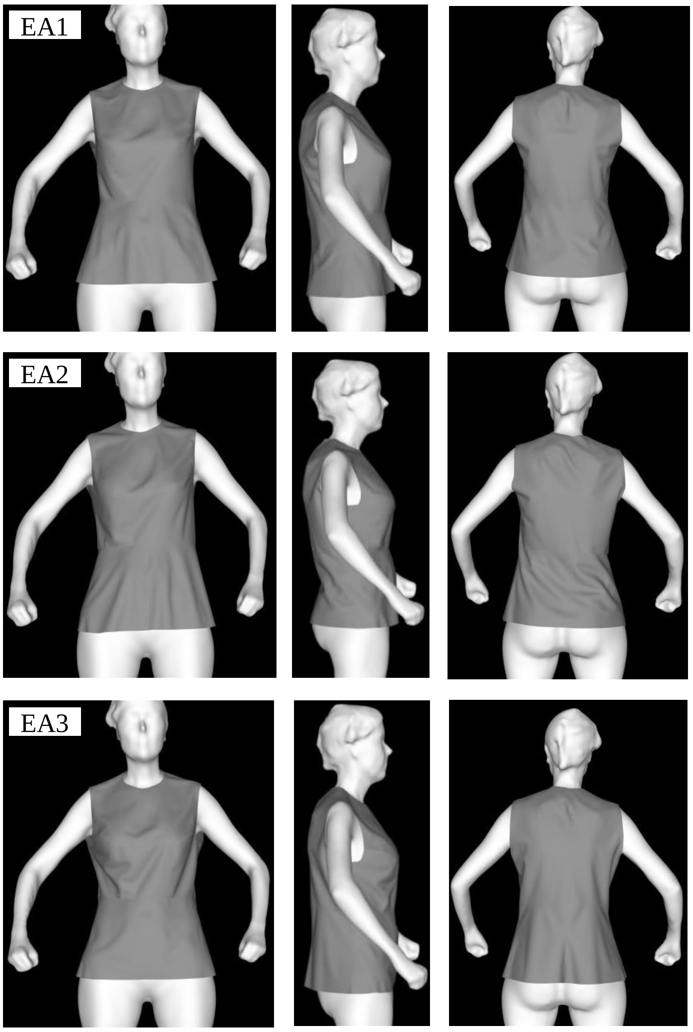


Figure 105: Virtual garment fitting effects on the wearer W1 with three different EA.

V.2.2. Acquisition of technical parameters of fabrics

For garment design, the main concerns for fabric selection include hand feeling and visual image. These two aspects constitute the fabric quality of a garment product. The fitting effects and comfort will be different if fabric properties change.

As discussed in Chapter 2, the fabric hand can be evaluated by using human sensory evaluation and instrumental measurements. However, for a specific scenario in industrial applications, the choice of evaluation method depends on the real conditions of the company. If experts specialized in fabric quality are available and less expensive and human interpretation of fabric quality are strongly requested, we need to organize a sensory evaluation session. If experts are not available or the company needs to obtain more normalized and stable results characterizing the fabric quality, and a testing laboratory is available, we can realize a series of physical testing with the instruments, already presented in Chapter 2, for measuring data of fabric technical parameters.

In our research, we use the Kawabata Evaluation System (KES) for measuring bending resistance, tensile resistance, shearing resistance and friction. For material thickness and density, we use standard test. The samples should be cut and arranged according to the guidelines for each instrument. They must not have any creases or any damage.

The measured KES fabric mechanical properties are introduced to the Modaris 3D software for generating 3D virtual garment prototypes. These 3D prototypes are linked with the Modaris 2D pattern design environment. The compilation of these tools leads to a realistic simulation of a garment with specific fabric properties on a 3D mannequin.

The list of the mechanical properties measured on the selected fabrics {F1, F2, F3, F4} for garment simulation in Modaris is given below (**Table 8**).

In the case where the user does not have the KES, it is always possible to find a fabric very close to the one that is used. For that, it is enough to test it on the drape meter and to compare the draped shape obtained with those of the different tissues obtained from the multi-criteria search engine used in the material database of Modaris (ex: search by its composition and other known specificities). Then we can use the Kawabata parameters of this equivalent fabric.

To enroll the unique fabric properties into Modaris 3D software, we need to input them into the fabric mechanical properties box for storage. After this operation, all the fabric properties are stored in the database, which can be used for 3D garment simulation.

Table 8: Mechanical properties measured for generating 3D garment prototypes.

Mechanical Fabric Properties	Linen 100%		Cotton 100%		PES35% / Cotton 65%		PES 100%	
	WARP	WEFT	WARP	WEFT	WARP	WEFT	WARP	WEFT
Density								
(g/m2)	234		125		210		280	
Material Thickness								
(cm)	0,09		0,06		0,07		0,08	
Bending resistance								
B(1e-6N.m)	13,02	6,43	3,44	1,43	7,43	5,23	5,26	1,47
Tensile resistance								
EMT (%)	3,980	11,790	2,830	8,000	4,980	4,680	17,930	22,470
LT	0,543	0,616	0,629	0,668	0,558	0,632	0,580	0,525
WT (N/m)	5,296	17,799	4,364	13,092	6,816	7,257	25,497	28,930
Shearing resistance								
G(N.m-1/°)	1,010	1,442	1,471	1,599	2,952	3,579	0,922	1,147
T(N.m-1)	30,246		68,972		131,786		19,628	
Friction								
MIU	0,1627	0,1563	0,1467	0,1517	0,1670	0,1623	0,2633	0,2178

V.2.3. Acquisition of human data

As we discussed in Chapter 4, human perception on garment fit and comfort, representing product quality features, are strongly related to the ease allowance at different body positions, selected fabric material as well as the wearer's morphology. In this context, we wish to control the relationship between these factors in order to optimize, for a specific consumer, the choice of design parameters according to the desired garment fit and comfort levels.

Garment fit and comfort evaluation deal with complex interactions between the garment and human body and they cannot be directly measured using instrumental methods. In this situation, a sensory evaluation combining perceptions of both design experts and concerned consumer can lead to more relevant quantitative results with numerical or linguistic values for controlling design parameters.

In our study, sensory evaluation has been used for characterizing human perception on garment fit given by a group of 5 design experts in real and virtual try-on environments of the produced 60 garments (combinations of 5 body shapes, 4 fabrics and 3 styles controlled by ease allowance values) on the 5 wearers/subjects. The relevant bibliography does not set the optimal number of panelists. It is conditioned by the domain, financial resources and research goal. In the same time, for each wearer, the real garment comfort perception on the corresponding 12 garments is directly evaluated by herself.

The sensory procedure in garment fit and comfort evaluation is different from frequently used quantitative descriptive analysis methods [151]. The evaluation dimension is unique and there is no need for generating normalized sensory descriptors. The normalized evaluation scores are employed to describe fit level (design experts) and comfort level (consumer) at different key body positions by using a five-level linguistic scale, shown in **Table 9**.

Table 9: Five level scale describing garment fit level and comfort level .

Loose	A little loose	Adequate	A little tight	Tight

In our study, we transform these five linguistic values into their corresponding numerical values: 2, 1, 0, -1, -2, respectively. One example of garment fit evaluation results given by a design expert for a specific real/virtual garment on a body shape is given in **Table 10**.

Table 10: One example of virtual garment fit evaluation given by a design expert.

		Evaluation scores				
	Positions	Loose	A little loose	Adequate	A little tight	Tight
Posture1	Shoulder			x		
	Collar			x		
	Armhole		x			
	Chest			x		
	Waist		x			
	Hip		x			

In this example, we can find that the evaluation numerical values for posture 1 and this specific design expert are 1 (a little loose) and 0 (adequate) respectively.

The involved sensory panel is composed of five female design professionals, aged from 34 and 58. They all have having experience in garment design and pattern construction. Before the evaluation session, they have been informed of the general principle and basic methodology on sensory evaluation but never received strict training about that. In fact, an evaluation with less constraint can effectively cover all aspects of garment fit, perceived by different design experts.

During the evaluation of design experts on real/virtual garment fit and that of the wearer on comfort, six key positions on the human body are considered (**Figure 106**). Each evaluator receives pictures of each wearer/subject in different poses, with different materials and different ease allowance values. Then, on a separate questionnaire, he/she selects the scores for all the key body positions from the five-level linguistic scale according to his/her personal perception on garment fitting effects to the wearer.

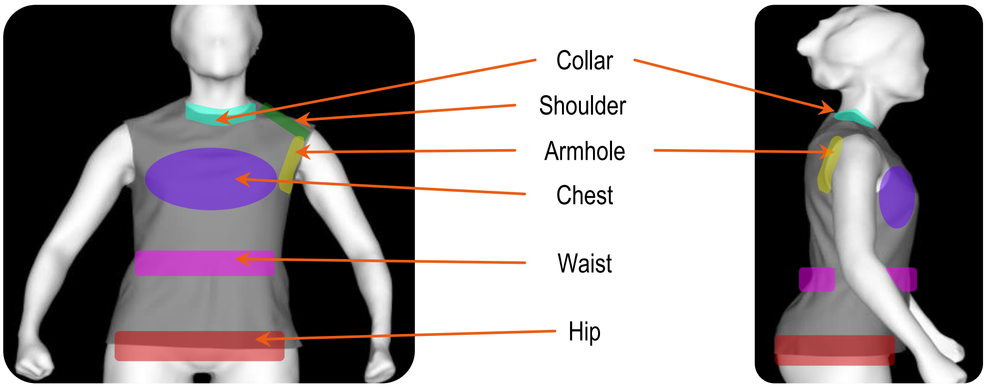


Figure 106: Key positions on the human body to be considered during the evaluation

In the example of **Table 10**, for the posture 1 (straight standing), the design expert considers that the positions of should, collar and chest are "adequate" and those of armhole, waist and hip are "a little loose".

V.3. Modeling procedure

V.3.1. Modeling procedure for Model 1

As discussed in Section V.1, Model 1 can be considered as a function:

< Real ease allowance > = Model 1(real garment fit, comfort, body measures, fabric properties). According to this principle, we define the input and output variables of Model 1 as follows.

According to the previous analysis, there exist 8 variables for body measurements (**Table 6**), 9 variables for fabric properties (**Table 8**), 120 (5×4×6) variables for garment fit perception corresponding to the results given by 5 design experts for all the 4 postures and 6 evaluated key body positions, and 6 variables for comfort perception given by the concerned wearer for the 6 key body positions. The number of output variables is 4, corresponding to 4 key positions on the garment (**Table 7**). The number of learning data is 60, each corresponding to one produced customized garment.

In this situation, the number of input variables is too big so that the extracted fuzzy rules are complex and difficult to be interpreted. For simplicity, according to the results of our previous study [152], we propose to apply Principal Component Analysis (PCA) to extract two variables {BM1, BM2: the two first principal components} from all the body measures. In practice, we consider that all body measures are strongly correlated. By computing with the learning data of body measures, we obtain BM1=(-0.04 -0.66 0.31 -1.11 1.50) and BM2=(-0.13 0.83 1.19 -1.15 -0.74) for all the wearers WP1, …, WP5. The rate of explanation of these two principal components is 83%, meaning that the accuracy is high enough for the further treatment.

According to the same idea, we apply PCA to extract one variable {FP: the 1st principal component} from all the 9 fabric properties. By computing with the learning data of fabric properties, we obtain FP=(-0.19 -0.68 -0.60 1.46) for the 4 fabrics F1 (linen 100%), F2 (cotton 100%), F3 (PES 35%, cotton 65%), F4 (PES 100%). The corresponding rate of explanation is 78%, meaning that the accuracy can be accepted (the total rate of explanation of the two first principal components is 95%).

For the garment fit perception levels given by the 5 design experts for all the 4 postures at the key body position concerned by the specific ease allowance EA_i, we aggregate them by computing their averages in order to form one input variable {R_FIT}. For the comfort perception given by the concerned wearer for the 6 key body positions, we perform the same data aggregation to form one input variable {C}. Theoretically, the data of R_FIT and C are distributed in the range of [-2, 2]. However, in a practical evaluation on a garment fit or comfort, extreme values close to "very tight" (-2) and "very loose" (2) rarely appear for all key positions and all postures. Therefore, we just take the minimal and maximal values of the 60 learning data to form the ranges of these two variables. The corresponding results are: the range of R_FIT is [-1.2, 1.3], the range of C is [-0.9, 1.5]. Also, we have to emphasize that R_FIT and C are correlated between them but they are quite different in some scenarios. For example, for 100% linen, EA1 and W3, the averaged garment fit R_FIT is 0.63 but the averaged of C is -0.13.

The general structure of Model 1 can be expressed in **Figure 107**. It is composed of 4 sub-models each corresponding to the ease allowance at one key position of the garment.

For each of the 5 input variables shown in **Figure 107**, we fuzzify it into a number of fuzzy values (from 4 to 5) with triangular membership functions according to the distribution of the 60 learning data (60 produced garments). For BM1 and BM2, we define 5 triangular fuzzy values corresponding to the body shapes of the 5 wearers (output of the concerned PCA). They are denoted as {very small, small, medium, big, very big}. The membership functions of BM1 and BM2 are given in **Figure 108**.

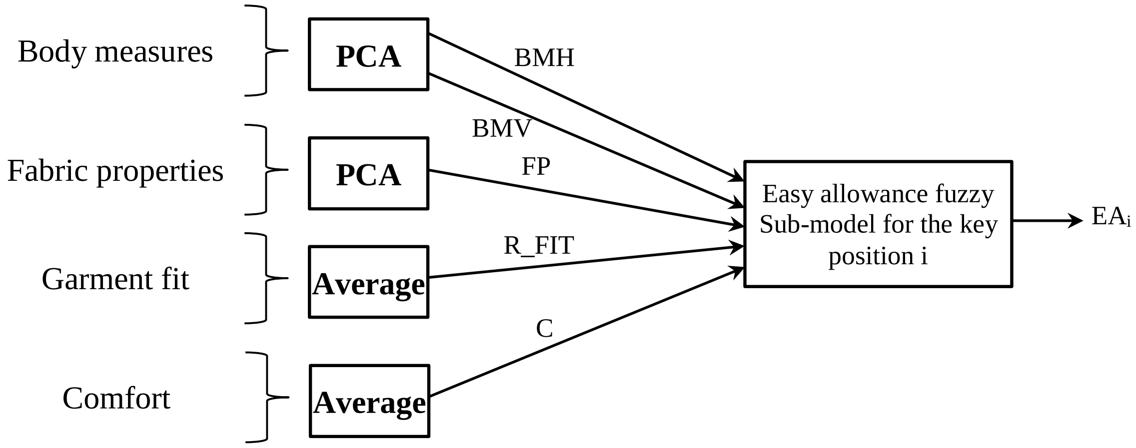


Figure 107: Structure of the fuzzy model for predicting the real ease allowance at the key position i.

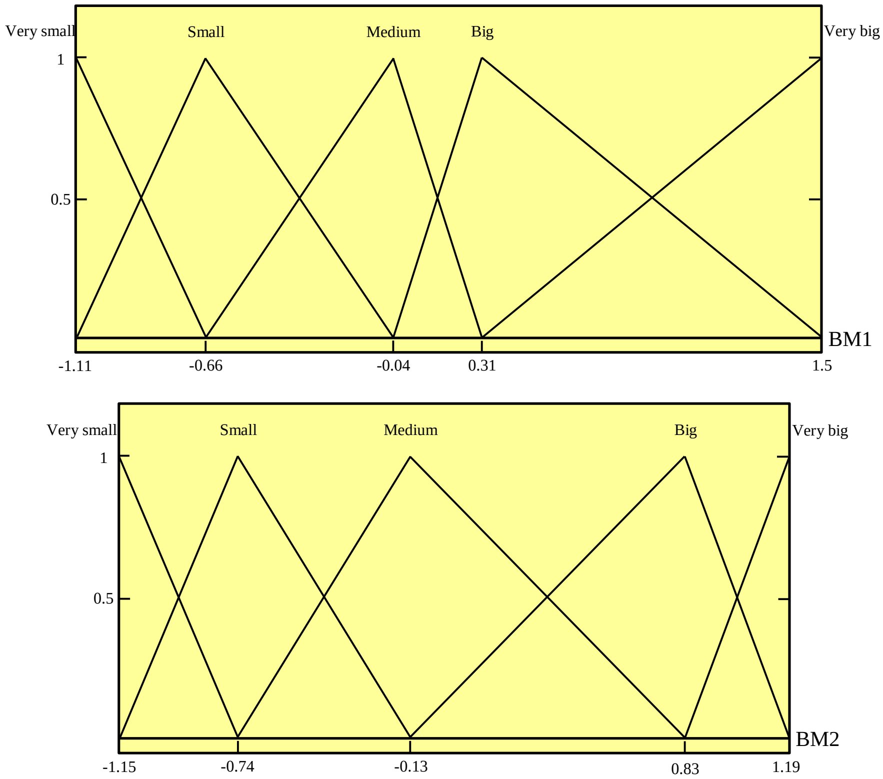


Figure 108: Membership functions of BM1 and BM2.

For FP, we define 4 triangular fuzzy values corresponding to the 4 selected fabrics (output of the concerned PCA). They are denoted as {low, a little low, a little high, high}. The membership function of FP is given in **Figure 109**.

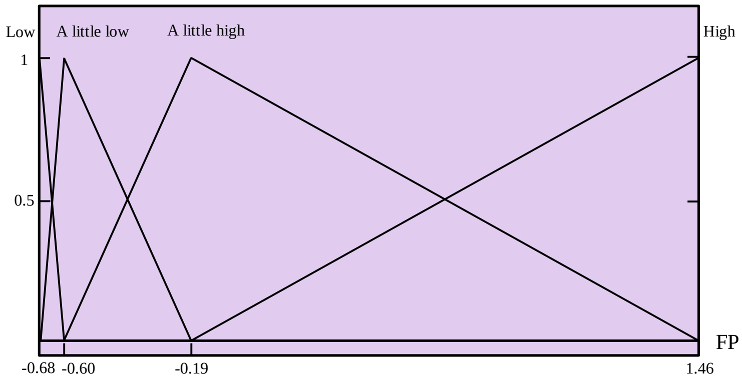


Figure 109: Membership function of FP.

For R_FIT and C, we define 5 triangular fuzzy values uniformly distributed on their real ranges of [-1.2, 1.3] and [-0.9, 1.5], discussed previously. They are denoted as {tight, a little tight, adequate, a little loose, loose}. The membership functions of R_FIT and C are given in **Figure 110**.

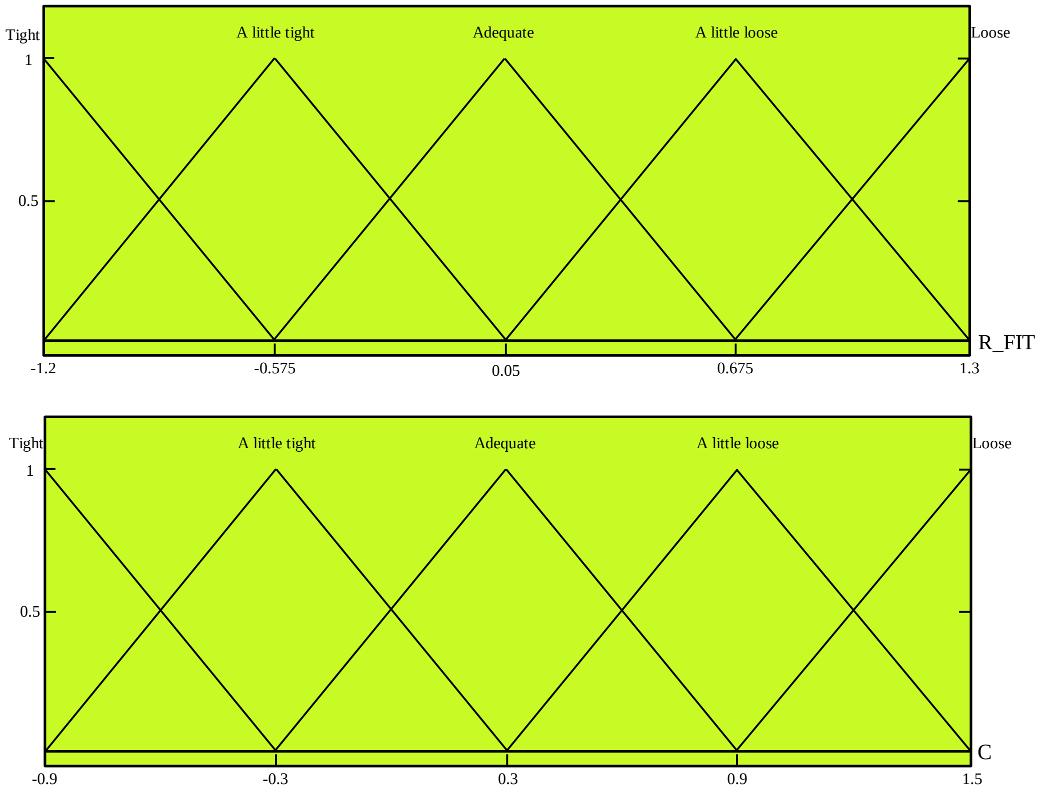


Figure 110: Membership functions of R_FIT and C.

For each sub-model of Model 1 predicting the real ease allowance at the key position i, the output EA_i ($i \in$ {1 (chest), 2 (waist), 3 (hip), 4 (collar)}) is also a linguistic variable which takes triangular fuzzy values from {small, medium, big}. These fuzzy values are centered on the ease allowance values EA1, EA2 and EA3 of the produced garments (**Table 7**) respectively (**Figure 111**).

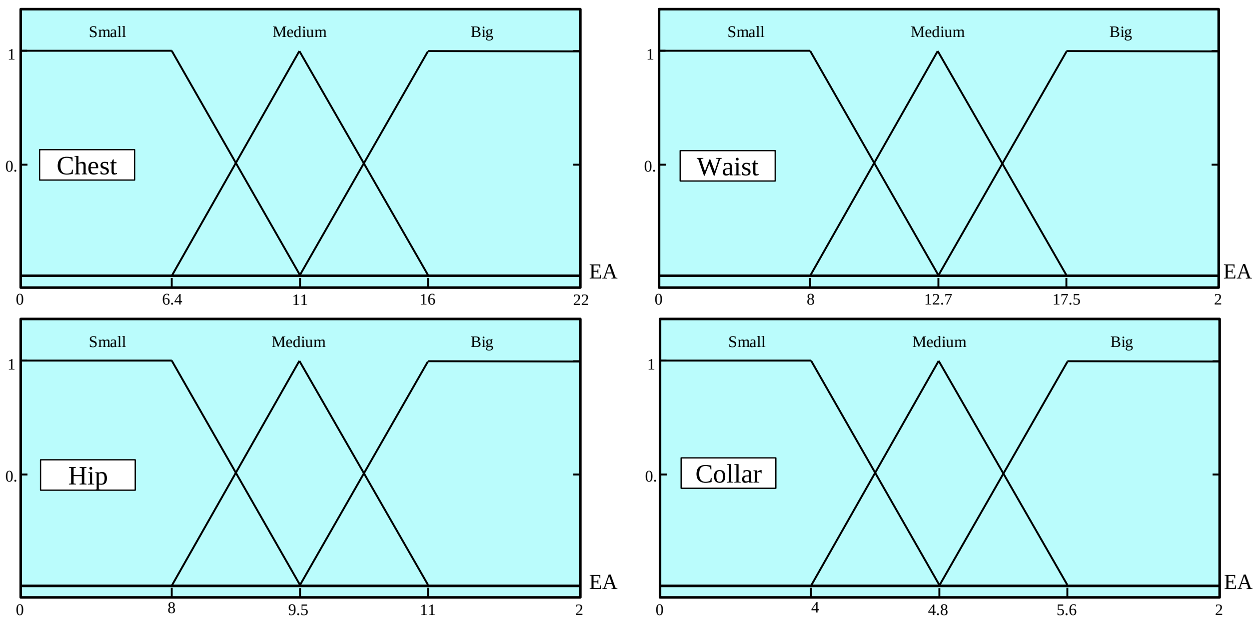


Figure 111 : Membership functions of EA for the chest, the waist, the hip and the collar.

By exploiting the relations between the combinations of fuzzy values of the five input variables and the ease allowance at each key position EA_i in the learning database measured from the 60 produced garment prototypes, we obtain 60 fuzzy rules, each corresponding to one garment prototype. Several examples on fuzzy rules generation are given below.

From the learning database, we find one prototype with the following parameters: for the wearer W_1, the fabric F_1 (100% linen), EA1 (tight style for chest), the corresponding averaged comfort perception is -0.375 and averaged garment fit 0.25. By converting these data into fuzzy values, we have the following rule:

Rule 1: *IF BM1=medium, BM2=medium, FP=a little high, R_FIT=adequate and C=a little tight, THEN EA_1=small (chest)*

In the second example, the prototype has the following parameters: for the wearer W_1, the fabric F_1 (100% linen), EA2 (normal style for chest), the corresponding averaged comfort perception is -0.13 and averaged garment fit 0.7. According to the same principle, we have:

Rule 2**:** *IF BM1=medium, BM2=medium, FP=a little high, R_FIT=loose and C=a little tight, THEN EA_1=medium (chest)*

Compared with Rule 1, we can find that, for the same wearer and same fabric, we need to pass tight style (EA1) to normal style (EA2) if we wish to obtain a perception of loose garment.

For the third example, we change to the wearer W_5 with the same fabric (F_1) and EA1 (tight style), the corresponding averaged comfort perception is 1.5 and averaged garment fit 0.55. We have:

Rule 3: *IF BM1=very big, BM2=small, FP=a little high, R_FIT=loose and C=very loose, THEN EA_1=small (chest)*

This rule is quite different from Rule 1 and Rule 2 due to the morphology of W_5. She has similar height but larger chest measures than W_1. In all the 60 fuzzy rules, the combinations of different fabrics, different body shapes and garment fit and comfort perceptions are taken into account.

However, theoretically, these 60 fuzzy rules cannot cover the whole input space and some combinations of input values cannot be controlled by any fuzzy rule. In fact, the total number of combinations of fuzzy values for all the five input variables is 5×5×4×5×5=2500, largely more than 60. This situation is related to the situation in which some regions are not physically significant due to the restrictions on the corresponding combinations of fuzzy values, especially for extreme values. In general, integration of more fabric and human samples can effectively increase the accuracy of the rules and related models.

For any new wearer and new fabric, given a desired garment fit level and comfort level, we can use the Mamdani method to aggregate the relevancy degrees related to all the fuzzy rules and obtain the final result. One example is given below.

For a new wearer W6 with a body shape between W1 and W5, whose body measures (in cm) are: height: 161, chest girth: 93.5, waist girth: 73, hip: 103, chest width: 41, under-burst circumference: 76, shoulder width (left): 13.5, shoulder width (right): 13.8. We still take fabric F1 and hope that both the desired garment fit and comfort perception are « adequate » (R_FIT=0 and C=0). We compute the corresponding ease allowance values as follows.

We first compute BM1 and BM2 by using the linear combination obtained from the PCA approach with the 5 learning data (5 wearers). We have: BM1=0.39, BM2=0.53. The fuzzy value of BM1 is: big: 0.92, very big: 0.08, and that of BM2 is: medium: 0.21, big: 0.79. For the fabric F1, we still have FP=-0.19, corresponding to a little high. The fuzzy values of R_FIT and C are {M} and {a little tight: 0.5, medium: 0.5} respectively. By applying all the 60 fuzzy rules to the data of W6, we obtain their relevancy degrees (most of them are 0) and then aggregate the corresponding results by using the Mamdani method. The final result for ease allowance is {chest: 9.5, waist: 9.2, hip: 10.7, collar: 4.9}.

V.3.2. Modeling procedure for Model 2

Model 1 aims at predicting real 2D ease allowance from real design parameters, wearer's body measurements and desired garment fit and comfort level. It can be validated using real try-on of garments produced from the predicted ease allowance values.

However, in a remote design related to a virtual environment, real try-on of designed garments is not available. We must validate each design solution with virtual try-on of garments and adjust it by controlling and optimizing 3D ease allowance in the virtual environment. As we discussed previously, 3D ease allowance is related to the distances in the 3D space between the human body model and designed virtual garment. According to the general principle presented at the beginning of Chapter 5, we will set up Model 2 permitting to predict and validate 3D ease allowance, i.e.

< 3D ease allowance > = Model 2(real garment fit, comfort, virtual garment fit, ease allowance, body measures, fabric properties).

The principle of Model 2 is given as follows.

We consider that 3D ease allowance is created by making a series interactions between design in the real environment and virtual garment fit evaluation. The design in the real environment permits to control real ease allowance values from design parameters. For simplicity, we take 3D ease allowance (3D EA) as a function of real ease allowance (EA) and virtual fit evaluation, i.e.

<3D ease allowance > = Model 2(ease allowance, virtual garment fit).

Model 2 is a repeated procedure which can be described by **Figure 112**. For any new data (fabric or wearer), Model 1 is first used for computing the ease allowance for different key positions of the garment. With the predicted ease allowance values and other predefined design parameters, we generate the corresponding 3D virtual garment using the Modaris 3D software. Next, the virtual prototype will be evaluated in terms of fit at the four key positions presented previously. According to the differences between the desired fit level and virtual fit evaluation, Model 2 is used to adjust real ease allowance values so that new virtual garment fit is generated. This procedure is repeated until the satisfaction of virtual garment fit related to the desired level. The values of 3D ease allowance are obtained from the fitting effects of the final virtual prototype on the human model of the wearer.

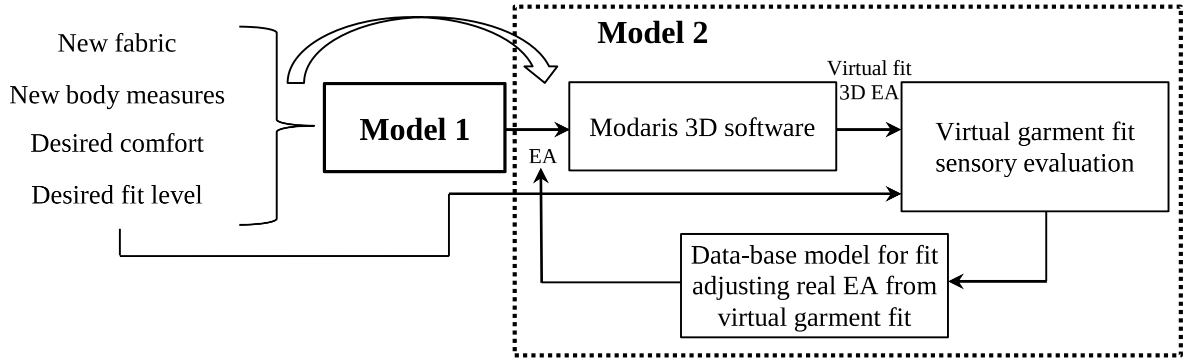


Figure 112: General principle for generating 3D ease allowance in terms of virtual garment fit and real ease allowance.

Concretely, virtual garment fit evaluation is performed by design experts on the same key positions as real garment fit evaluation by using the five-level scale {-2: tight, -1: a little tight, 0: adequate, 1: a little loose, 2: loose} defined in **Table 9**. The real ease allowance EA at one of the four key positions (chest, waist, hip, colar) is adjusted according to the difference of virtual garment fit related to the desired fit level at the same key position by using the following three rules:

1) *IF (V_FIT-R_FIT) at position i is between -0.5 and 0.5, EAi is not changed;*
2) *IF (V_FIT-R_FIT) at position i is smaller than -0.5, THEN EAi:=EAi+δ;*
3) *IF (V_FIT-R_FIT) at position i is bigger than 0.5, THEN EAi:=EAi-δ.*

δ is a small positive value representing the step length of each loop in the procedure of Model 2. In each loop, the change if EA is limited so that the changes of 3D ease allowance and virtual fit are progressive and can be easily controlled. One example of ease allowance adjustment is given in **Table 11**. In this example, we consider that the desired garment fit is 0 (adequate), the selected body shape is W3, and the selected fabric is 100% linen. By computing with Model 1, we obtain initial ease allowance values for these key positions. The value of δ is set to be 0.3.

By applying the previous rules of Model 2, we obtain the results of virtual garment fit evaluations and ease allowance adjustments for these key positions as follows.

Table 11: One example of ease allowance adjustment by virtual garment fit evaluation.

	Ease allowance and virtual garment fit scores					
	Initial values		**After the 1st loop**		**After the 2nd loop**	
Positions	EA	Virtual fit	EA	Virtual fit	EA	Virtual fit
Collar	6.4	-0.3				
Chest	3.7	-0.3				
Waist	7.8	-1	8.1	-0.7	8.4	0.4
Hip	7.8	-0.6	8.1	-0.2		

In this example (see **Figure 111**), for the initial ease allowance values, the virtual fit evaluations at the collar and chest positions are close to 0. Therefore, we do not need to adjust the corresponding EA. However, for the positions of waist and hip, the virtual fit evaluations are smaller than -0.5, and then we adjust the corresponding ease allowance values from 7.8 to 8.1. After the first adjustment of EA, the virtual fit evaluations are -0.7 and -0.2 for waist and hip respectively. Therefore, 8.1 is the final value of ease allowance for hip and we continue another adjustment for waist. After the second adjustment, the virtual fit evaluation for waist is 0.4 (<0.5). Therefore, 8.4 can be considered as the final ease allowance value for waist.

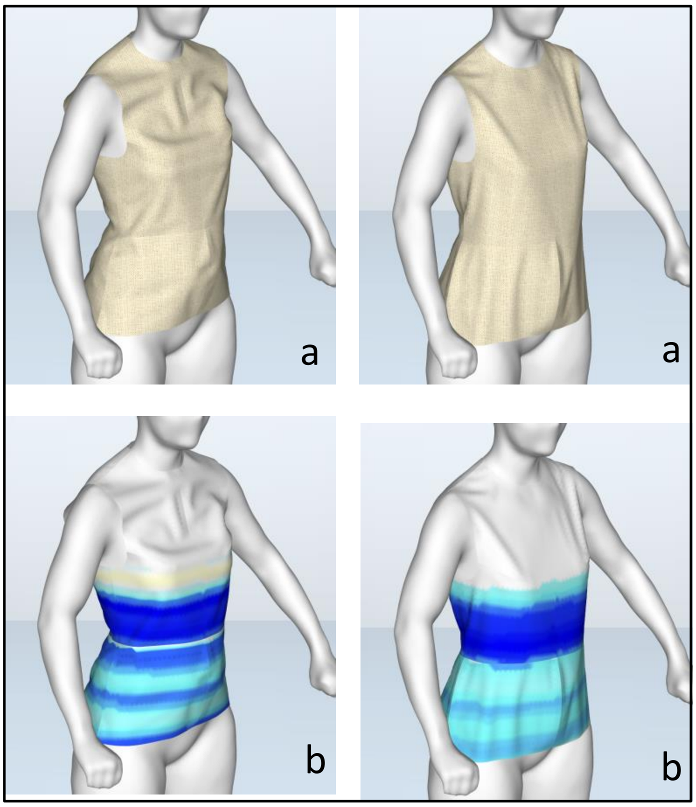


Figure 111. Comparison of 3D garment between the classical method a) and the fuzzy method b)

V.4. CONCLUSION

In this chapter, we proposed a series of models, based on fuzzy modeling techniques, to control and predict 3D ease allowance values at different key positions in remote design environment. The experiment is conducted on several real wearers/subjects and their virtual counterparts to verify the credibility of 3D garment modeling in different style scenario (loose, tight adequate). Moreover, the real ease allowance, taking into account standard, dynamic and fabric aspects, are calculated and implemented directly on the garments, in contrast to 2D garment modeling.

The mathematical models presented in this chapter enable to characterize the relationship between ease allowance, garment design parameters, wearers' morphology and postures as well as her personalized requirements on comfort and garment fit. In this way, a customized garment can be designed by adjusting real ease allowance values.

In a remote design environment, as an effect of 3D design strategy directly on the wearer's virtual counterpart, we make the hypothesis that after adjusting procedure of 3D ease allowance the garment fit can be fully personalized. Compared with traditional methods, which design garments based on a standard morphotype without considering the impact of different fabric types on garment patterns, our method enable to adjust the 3D ease allowance values based on individual body measurements and fabric properties.

The method presented in Chapter 5 can be used to control interactions of garment design elements in the real and virtual environments. We can effectively predict 3D ease allowance values for any specific wearer, fabric material and other design parameters. However, the efficiency of our model is strongly linked to the multiplicity of experiments carried out on various human body types and the choice of input variables, like different fabric mechanical properties.

This method gives information to the pattern maker before cutting material. In contrast to traditional method, where the retouch can be made after cutting and sewing, here we may decries amount of sources and at the same time produce more precise pattern and well fitted garment.

GENERAL CONCLUSION AND PROSPECT

Consumers hope that garment products are capable of not only covering their body surfaces with desired functionnalities but also producing fashionable and unique appearance expressing their images of personality. As a result of customers' demands, market has responded with creation of initiatives, which later became the ongoing business models. The most recognised is the concept of mass customization, which starts to appear with a new range of services, using different advanced technological tools.

We may observe how the experience of "brick-and-mortar" has evolved to e-shopping with virtual reality tools. In the process of development towards more advanced industrialisation, e-shopping is being developed in the direction of costumers' services for faithfully accompanying them to buy goods, like what happens in the real world. Customers have already learned, accepted and appreciated the advantages of e-commerce. However, they are not fully satisfied by the current e-shopping virtual environment due to the lack of relevant services. This situation has had an impact and a significant influence on development strategies of producers and brand companies.

More and more efforts have been made for combining both the 3D virtual reality tools and classical garment retailing knowledge into online garment e-shops. On one hand, the real shopping experience is capable of proving relevant fashion knowledge and business advices to customers. On the other hand, virtual reality tools enable to visually simulate the performances of products and interactions with customers. These two strategies are complementary in the purpose of staying competitive in the fashion market.

The virtual reality tools for designing garments have been massively applied by many researchers in different countries. Their goal is to generate high quality 3D perceptions and assure 'natural' communications between customers and products by using proposed virtual experiences.

All of these considerations are intrinsically linked to the establishment of a new apparel creation process that will allow the design and validation of products in a virtual 3D environment.

In my PhD, we have tried to integrate comfort and fashion into a customized garment co-design platform. In this context, three broad approaches have been proposed.

First: The morphology recognition presented in Chapter 3. The proposed method aims to recognize a consumer's morphology by using a supervised classification methodology and image processing procedures. The classification of body measurements of different people into similar morphological groups or sizes plays a significant role in the fashion industry. In the context of online garment retailing, we propose a method for matching the characteristic morphology of a specific wearer with the already created morphology cluster of a target population. This issue is a fundamental step in the garment creation process.

Second: 3D garment modelling presented in Chapter 4. The step following the wearers' morphology recognition is to develop a precise and repetitive method for garment creation. Working with five different typical virtual human bodies, we developed a methodology of 3D-to-2D design in a virtual environment. This new garment prototyping design process permits to integrate a 3D zoning technique in order to improve 3D modelling and drapeability. Moreover, to assure the automatic adjustment of the garment proportion regarding the body dimensions, we implemented a new concept of 3D ease allowance management.

In my thesis, 60 samples of upper garments, i.e. basic bodices have been designed, sewn and evaluated through the real and virtual try-on.

Third: Ease allowance modelling presented in Chapter 5. From the experiments carried out on the five different virtual human bodies, we determined the overall effect of the fabric drapeability in function of three different styles (loose, normal, and tight). In the next step, we acquire designer expert perception and consumer perception on garment fit and comfort. The linguistic data supported by measures or evaluations of concern design elements (e.g. body measurements, fabric properties, body position) were used to work out the data-based modelling approach, where two complementary models have been developed.

Two models (Model 1 and Model 2), based on the fuzzy theory, allowed us to improve the comfort of clothing. The first model is related to the notion of real ease allowance. The second enable to link the first model with the virtual environment based on the principles of sensory evaluation and fuzzy set theory. As a result, the relationship between 3D ease allowance, virtual garment fit and other concerned elements has been quantitatively identified.

These models can be used as a recommendation system supporting the co-design platform in the online retailing scenario.

Although many research projects have focused on an automatic process of 3D garment creation, the relevancy of designed garments to the existing body morphotypes are rarely considered. From our perspective, the objective is to create the virtual counterpart of the wearer and follow the 3D garment creation directly on it. Therefore, one important issue for online garment retailing should be the recognition of the customer morphology and ensure proper and adjustable methodology for its 3D garment creation. The methodology presented in this thesis has been developed for meeting these objectives.

In the future perspective, it would be profitable to verify the proposed 3D design creation process for other types of garments. Further, the creation of parametric avatars and 3D design can be described with the focus on the study of the industrial application of this method.

Research contributions

As part of this doctoral dissertation, a particular emphasis was placed on creating a technologically coherent overall customized platform that guarantees an appropriate level of garment fit to the customer. Online garment retailing brings a wide range of scenarios. Thus our efforts have focused on technological issues that would provide such a service to customers for their e-shopping at home. The proposed approach required the creation of a logical process consisting of three essential elements: 1) recognition of customer morphology, 2) design of the 3D garment adapted to the morphology of the customer and 3) verification of the garment fit.

Our contribution is essentially related to online clothing retailing, in which we consider that all online services are gathered together in a cooperative to form an integrated design platform. Especially, the garment design process and body morphotypes classification are cooperated in order to propose customized garment products to consumers.

The human body surface is a very complicated three-dimensional structure. Therefore, to better understand its interactions with the garment, we implement the new zoning approach to the 3D design creation process. This integrated approach takes into account the morphological deformations which are not always comprehensive by simple measurements.

Such 3D design techniques supported by data-driven design techniques provide the garment tailored meeting the individual needs. The consumer can participate throughout the design and validate the garment through virtual try-on by adjusting the 3D ease allowance. This attitude fits into mass customization scenario, and by creating bonds with the wearer, it leads to the increase of the active life of clothing.

In 3D design creation process, the strategy of controlling the 3D ease allowance has been developed. It has been worked out based on the processing of experimental data derived from sensory evaluation of the wearers and experts. Two interlinked Models have been developed by using a fuzzy interference process. As a result, the new recommendation service has been elaborated. It permits to produce satisfying personalized solutions in clothing design by indicating the best possible fit. The proposed new technological solution is useful for online garment retailing.

By comparing the 3D garment creation process with traditional pattern making, we can directly explain how a garment is created without converting its spatial silhouette into a two-dimensional object. It can overcome the interpretation error.

In our approach, personalization of garment fit happens in a virtual environment thus provides necessary feedback information to the designers, pattern makers and consumers in real time. The fact that there is no sample making in the design process, can considerably reduce the production and material costs. It creates less stress on the supply chain management, thus making it more sustainable.

In our approach, the recognition of a customer's body shape is linked with the design process and CAD design methods. The new patterns resulting from the 3D ease allowance recommendation system have the advantage of being put into production instantly by importing to other compatible CAD modules.

These studies constitute a rich source of knowledge and a foundation for building an online garment customize platform.

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APPENDIX

Published and submitted papers:

Chapter in the book

[**2015**] : M.KULINSKA, **P.BRUNIAUX** & X.ZENG
New approach to the detection of the morphology of the individual consumer measured by kinect
Chapter in the book "Innovations in clothing design, Materials, Technology and measurement methods", Eds. I.Frydrich, G.Bartkowiak & M.Pawlowa, Publisher Lodz University of Technology (Institute of Architecture of Textiles), Central Institute for Labour (Protection-National Research Institute), Kazimierz Pulaski University of Technology and Humanities in Random / Poland, Monograph, Vol. 122, pp 183-189.

[**2017**] : M.KULINSKA**, P.BRUNIAUX**, X.ZENG, A.AINAMO & Y.CHEN
Virtual mannequins and garment parametrization
Chapter in the book "World Scientific Proceedings Series on Computer Engineering and Information Science: Uncertainty Modelling in Knowledge Engineering and Decision Making", Eds. X. Zeng, J. Lu, E. E Kerre, L. Martinez, L. Koehl, World Scientific, Vol. 10, pp 984-989.

Communications with Proceedings in an International or National Conferences

[**2008**] : F.BOUSSU, A.RAGOT, **M.KULINSKA**, X.LEGRAND & P.BRUNIAUX

Customization of a lightweight ballistic vest
2nd International Scientific Conference Textiles of the Future, Kortrijk, Belgium, 13-15 Novembre.

[**2015**] : **M.KULINSKA**, P.BRUNIAUX & X.ZENG
New approach to the detection of the morphology of the individual consumer measured by kinect
CLOTECH'2015, 11th Joint International Conference on Innovative Materials & Technologies in made-up textile articles, protective clothing and footwear, Lodz, Pologne, 17-19 Juin.

[**2015**] : **M.KULINSKA**, P.BRUNIAUX & X.ZENG
Detecting the morphology of a remote individual consumer in a web-based environment
CIE45, International Conference on Computers & Industrial Engineering, Metz, France, 28-30 October.

[**2016**] : **M.KULINSKA,** P.BRUNIAUX, X.ZENG, A.AINAMO & Y.CHEN
Virtual mannequins and garment parametrization
FLINS 2016, 12th International Flins Conference on uncertainty modelling in knowledge engineering and decision making, Roubaix, France, 24-26 August.

[**2016**] : A.AINAMO, M.KULINSKA**,** P.BRUNIAUX, X.ZENG, & Y.CHEN
How Virtual Fitting Leads to Sustainable Fashion
GFC, Global Fashion Conference 2016, Stockholm University, Sweden, 20-21 October.

Communications By Poster In An International Or National Conferences

[**2016**] : **M.KULINSKA**, F.DASSONVILLE, P.BRUNIAUX & X.ZENG
The conceptualization of the virtual garments
JRDA 2016, 3ème journée régionale des doctorants en automatique, Lille, 30 Juin.

Articles in international or national peer-reviewed journals listed in international databases

[**2018**] : : **M.KULINSKA**, G.TARTARE, P.BRUNIAUX & X.ZENG
Online 3d Unsupervised and 2d Supervised Classification in Clients' Pattern Recognition.
Journal of Textile Science & Engineering Vol8(5): 377. DOI: 10.4172/2165-8064.1000377
[**2018**] : **M.KULINSKA,** P.Bruniaux & X.Zeng
Modelling the made-to-measure garment in a 3D environment
Fibres & Textiles in Eastern Europe, in submission process.