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# Development of a decision tool to select appropriate solutions for quality control depending on the defects occurring in the manufacturing process in the automobile branch of the technical-textiles industry

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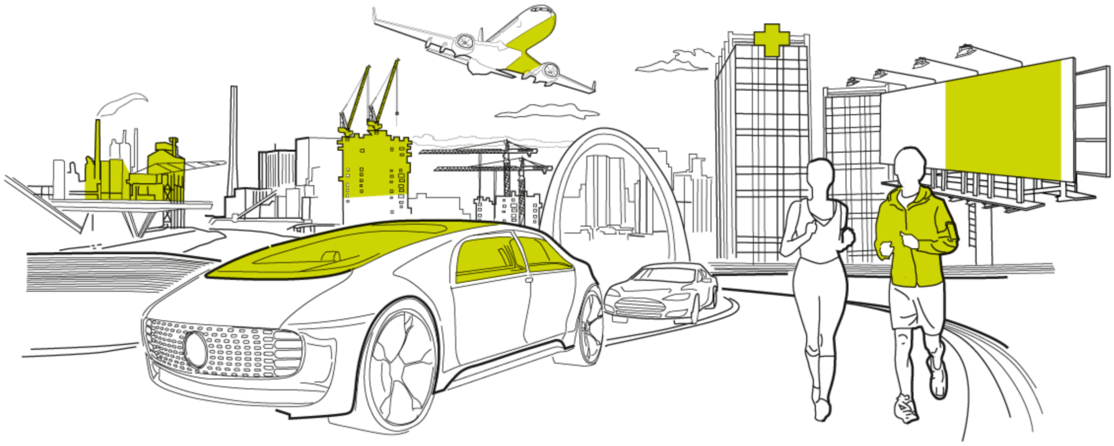

*The world of technical textiles [www20a]*

2020

Master thesis

# Development of a decision tool to select appropriate solutions for quality control depending on the defects occurring in the manufacturing process in the automobile branch of the technical-textiles industry

Aditya Narayan Mishra

## Deutsche Kurzfassung


**Ziel der Arbeit:**

Das Ziel dieser Arbeit ist es, ein Entscheidungstool bezüglich der Qualitätskontrolle bei der Herstellung von technischen Textilien für die Automobilindustrie zu entwickeln. Das Tool soll den Zugang zu Informationen über die bei der Herstellung von technischen Textilien in der Automobilindustrie auftretenden Probleme und die daraus resultierenden Fehler ermöglichen. Anschließend soll es einen Überblick über die entsprechenden Lösungen und Messprinzipien für jedes der identifizierten Probleme geben.

**Lösungsweg:**

Zunächst wird eine Literaturrecherche durchgeführt, um ein tiefes Verständnis für die wichtigen Qualitätsparameter und Fehler in jedem der Herstellungsprozesse technischer Textilien zu erhalten. Basierend auf der Literaturübersicht wird ein Fragebogen erstellt, um eine Marktanalyse in Form von Experteninterviews durchzuführen. Mit Hilfe der Marktanalyse werden Einblicke der Industrie in den aktuellen Stand und die Probleme im Zusammenhang mit der Qualitätskontrolle bei der Herstellung der technischen Textilgewebe in der Automobilindustrie angesprochen. Anschließend werden auf der Grundlage der durch die Experteninterviews gewonnenen Probleme die Lösungen und Messprinzipien identifiziert und ein Konzept für das Entscheidungstool entworfen.

**Zentrale Ergebnisse:**

Die Ergebnisse dieser Untersuchung geben einen Überblick über die Probleme, die bei der Qualitätskontrolle während der Herstellungsprozesse von technischen Textilien in der Automobilindustrie auftreten. Darüber hinaus werden Informationen darüber analysiert, inwieweit digitale Lösungen zur Qualitätskontrolle in der Industrie etabliert sind. Außerdem werden bestehende digitale Lösungen zur Qualitätskontrolle und Messprinzipien zur Lösung der identifizierten Probleme in der Industrie erforscht und identifiziert.


**Schlagwörter:** Digitale Qualitätskontrolle, Technische Textilien, Mobiltech, Industrie 4.0, Technologieauswahl

## English Abstract

**Objective of this thesis:**

The objective of this thesis is to develop a decision tool regarding the quality control in the manufacturing of technical textiles for the automotive industry. The tool shall enable the access to information about the problems being faced and the consequent defects occurring during the manufacturing of technical textiles in the automotive industry. Subsequently, it shall provide an overview of the corresponding solutions and measuring principles for each of the identified problems

**Solution process:**

Firstly, a literature review is carried out to provide a deep profound understanding to the important quality parameters and defects in each of the manufacturing processes of technical textile. Based on the literature review, a questionnaire is created to perform a market analysis in form of expert interviews. With the help of the market analysis, industry insights to the current status and problems associated with the quality control of manufacturing the technical textile fabrics in the automotive industry are addressed. Afterwards, based on the problems acquired through the expert interviews, the solutions and measuring principles are identified and subsequently a concept for the decision tool is designed.

**Key results:**

The results of this research provide an overview of the problems being faced regarding quality control during the manufacturing processes of technical textile in the automotive industry. In addition, information on the extent to which digital solutions for quality control are established in the industry is analyzed. Moreover, existing digital quality control solutions and measuring principles to tackle the identified problems in the industry are researched and identified.

**Key word:** Digital quality control, Technical textiles, Mobiltech, Industry 4.0, Technology selection

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## Abbreviations

| | |
|---|---|
| PET | Polyethylene terephthalate |
| PP | Polypropylene |
| PA | Polyamide |
| $CO_2$ | Carbon dioxide |
| PCM | Phase change material |
| BCF | Bulked continuous filament |
| PDA | Production data acquisition |
| QA | Quality assurance |
| ML | Machine learning |
| GSM | Grams per square meter |
| IoT | Internet of things |

# 1 Introduction and Objectives

## 1.1 Motivation

Germany's textile and fashion industry is represented roughly by 1400 predominantly small and medium-sized enterprises that employ about 135,000 workers in total and generate a total revenue of EUR 32 billion [www20n]. The traditional textile industry includes apparel and clothing as well as home furnishings, however the use of textiles is considerably more varied especially the technical applications [MP99]. Technical textiles have a huge economic scope in comparison to the traditional textiles industry and have a big influence on every sphere of human economic and social life [AH16].

Recently, German companies have started to focus on manufacturing high-quality technical textiles. This has successfully resulted in enhancing their global leadership position. At the same time, however, the companies face severe challenges due to increased cost and innovation pressure as well as shorter product and innovation cycles. The production of technical textiles is estimated at 50 % of total textile production in Germany making it the global market leader. [AH16, KPG17]

It is becoming increasingly difficult to identify potential and changing demands due to rapid market changes. To survive the competition, manufacturing companies need to continuously record key parameters such as product quality and manufacturing costs. The need for companies to introduce product and process technologies for lower manufacturing costs and higher product quality is increasing with the increase in customized products. [BGW18, BSM+14, FG08]

There is a consistent need for improving the manufacturing processes due to the current dynamic manufacturing environment. Companies constantly need to evolve and change, according to the rapidly changing customers' expectations, to remain successful. As a result, process quality control, that deals with the examining, controlling and managing the factors that affect the process quality, has become more challenging. [Jai13, YW08]

In a survey conducted by the Institute for textile technology at RWTH Aachen University, it is discovered that the German textile engineering companies and textile producers are not sufficiently familiar with the terms such as Industry 4.0, cyber-physical systems or smart factory. The diversity of textile products currently hinders the textile industry in implementing Industry 4.0 solutions. [CMG+17]

## 1.2 Objectives

The objective of this thesis is to develop a decision tool regarding the quality control in the manufacturing of technical textiles for the automotive industry. The tool shall enable the access to information about the problems being faced and the consequent defects occurring during the manufacturing of technical textiles in the automotive industry. Subsequently, it shall provide an overview of the corresponding solutions and measuring principles for each of the identified problems. For this purpose, the following research questions need to be clarified:

1) What are the problems being faced regarding quality control during the manufacturing processes of technical textile in the automotive industry?
2) To what extent have digital solutions in quality control become established in the manufacturing processes of technical textile in the automotive industry?
3) Which existing solutions and measuring principles can be used to tackle the identified problems?

## 1.3 Structure of this work

Due to the nature of the research question, the Design Research Methodology according to [BC09] is suitable for the approach of this thesis. Based on the approach, also shown in Fig. 1.1, the research is divided in four steps. In the first step the research objectives are clarified with a literature analysis. In a second step the data collection is done in a first descriptive study with the help of expert interviews. The third step is a prescriptive study, in which a concept design for the decision tool is developed based on the collected data. In the fourth step, this concept is to be validated in a further descriptive study. [BKK+13] Since the execution of the fourth step exceeds the scope of this thesis, it should be performed in subsequent research projects.

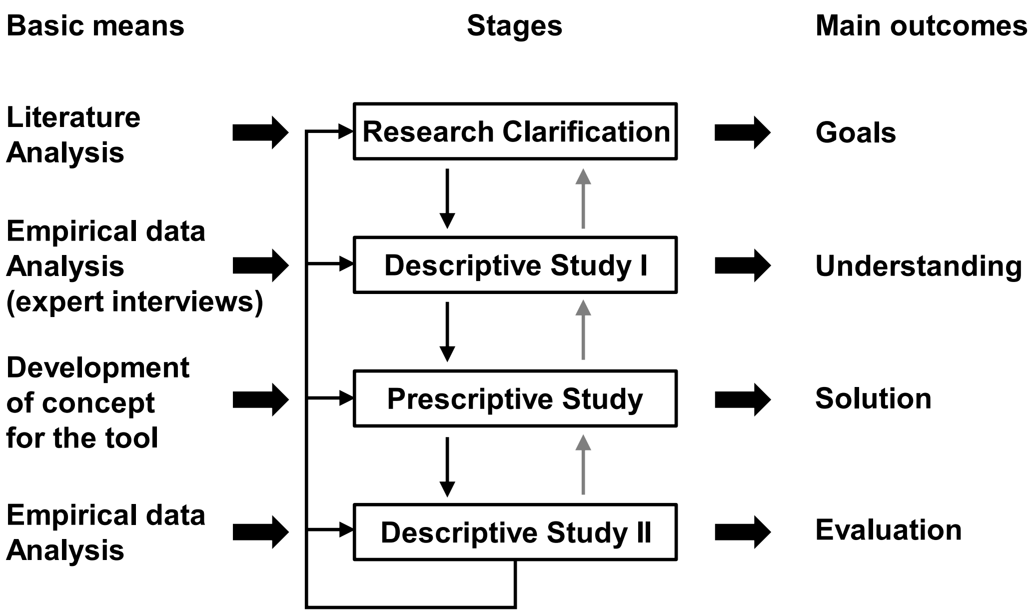



Fig. 1.1: Research approach based on Design Research Methodology according to [BKK+13]

The literature review, chapter 2, provides an overview of the state of the art of manufacturing technical textiles in the automotive industry. This comprises the introduction to technical textiles, the need of technical textiles in automotive industry as well as the steps of production of automotive technical textiles. Furthermore, the literature research is extended in chapter 3 by describing the important parameters for quality control in the manufacturing of technical textiles.

Based on the literature research, a questionnaire is designed in chapter 4 for performing a market analysis through expert interviews. Moreover, the current status and challenges associated with the quality control of manufacturing the technical textiles acquired through expert interviews in the automotive textile industry are discussed.

In chapter 5, based on the problems gained through market analysis in the form of expert interviews, the solutions and measuring principles for quality control in the manufacturing of technical textiles are identified. Subsequently, based on the identified solutions and measuring principles, the concept for a decision tool is designed.

Chapter 6 includes the critical appraisal, in which the approach and methodology as well as the quality of the results gained through the literature review, market analysis in form of expert interviews, identification of solutions and measuring principles and the concept design of the decision tool are assessed. The presented master thesis is closed with a summary and outlook, chapter 7.

# 2 Literature Review

The literature review covers the fundamentals of technical textiles (2.1), the need of technical textiles in the automotive industry (2.2) and the steps of production of automotive textiles (2.3). In more detail, the literature review provides an overview of the state of art of technical textiles in the automotive industry.

Firstly, the introduction to the definition of technical textiles followed by a brief description of the various areas of applications of technical textiles is executed. This is done to provide a basic understanding of the topic technical textiles.

Afterwards, the relevant branch of application for this thesis is discussed. This includes the introduction to the automotive branch of technical textiles. Here, the reasons for the massive use and advancements of technical textiles in the field of automotive industry are explained.

Moreover, the methods for the production of automotive textiles starting from the raw materials, such as fibers, till the end-product are described. This includes the characteristics of the fibers, production methods of yarns, production methods of different types of fabric structures and the finishing methods for fabrics.

## 2.1 Introduction to Technical Textiles

The following chapter provides an overview of the technical textiles industry. It includes the definition as well as the raw materials and process involved in the manufacturing. It is then followed by a brief description of the different areas of the applications of technical-textiles industry.

### 2.1.1 Introduction to the definition of Technical Textiles

The traditional textile industry includes apparel and clothing, or home furnishings, however, the use of textiles is considerably more varied especially the technical applications [MP99]. Technical textiles have a huge economic scope in comparison to the traditional textiles industry and have a big influence on every sphere of human economic and social life. The global technical textiles sector is flourishing at approximately 4 % annually, despite the economic deterioration by the financial crisis of 2008. [AH16]

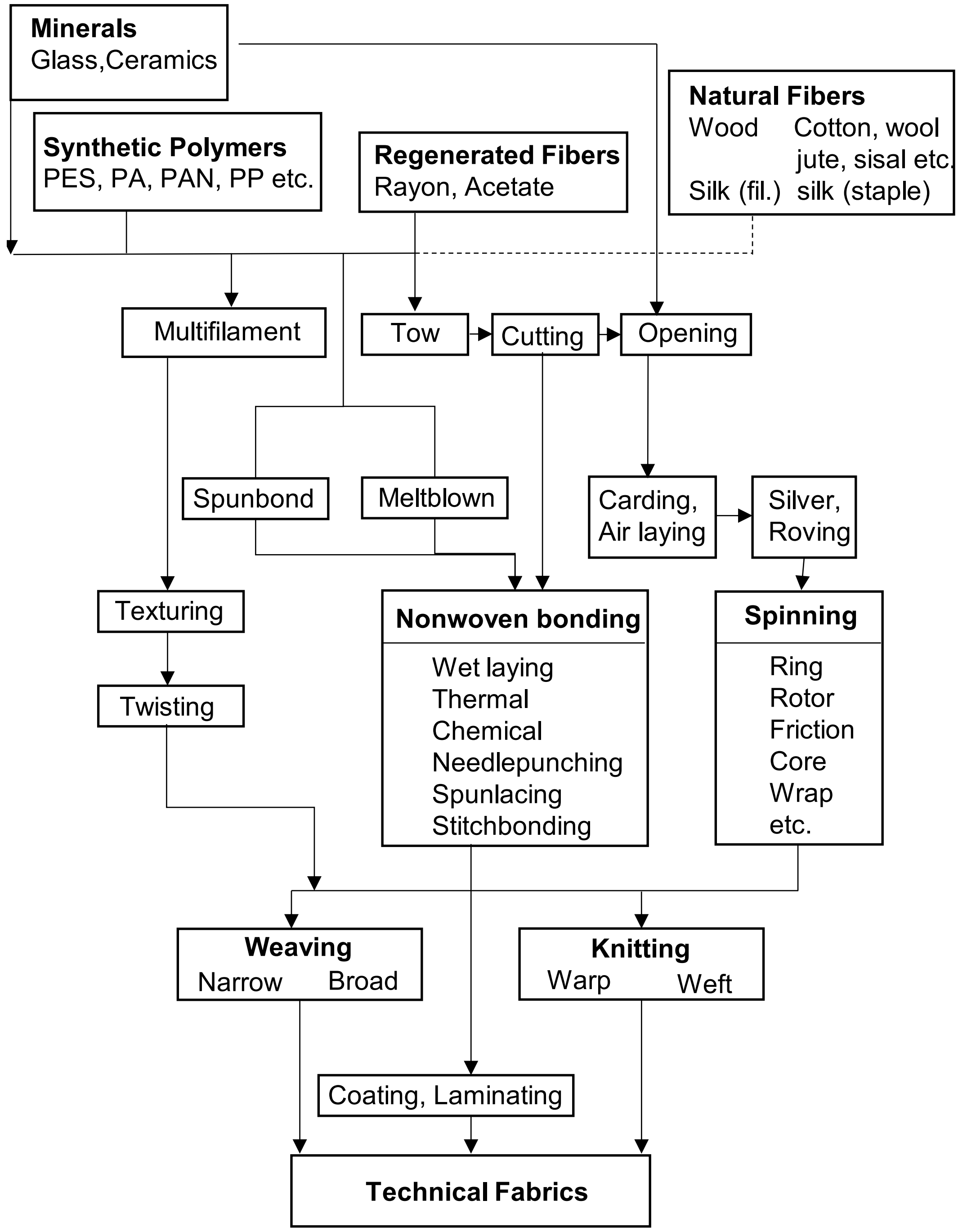
According to [AH16], technical textiles is the fastest developing sector among the others in the textile and clothing industries. The distinction between traditional definitions of textiles and technical textiles are constantly changing, since it is growing in divergent directions with fluctuating speed [HA00]. Originally, textile was characterized as a woven fabric. Gradually with time the term gained a new definition with its emerging applications with fibers, filaments and yarns, natural and manufactured [AH16].

According to [Mcc13], textiles can be woven or knitted, braided, or produced as layers of nonwoven materials. Textiles are normally made from polymers with natural sources such as wool and cotton or with synthetic sources such as polyester and polyamide. Natural fibers have been utilized since a long time now covering various applications for instance tents, ropes, sailcloth and sacking. According to Bremen Cotton Exchange, the world's total fiber consumption will grow promptly in the coming 5-10 years. This is on one hand due to the extensive advancement of technical textiles and nonwovens and on the other hand a result of the rising human population and hence their rising demands for textiles. [AH16, HA00, www20y]

The definition of technical textiles adopted by the internationally authoritative Textile Terms and Definitions suggests that the manufacturing of the textile material and products should primarily be based on the technical and performance properties instead of the aesthetic or decorative properties. [www20b]

The definition with regard to the European Union (EU) states technical textiles are defined as technical fibers, materials, and support materials meeting technical rather than aesthetic criteria, although in some markets both types or criteria are specified [AH16].

The approach for describing and classification specific products and applications as technical textiles is very divergently accepted by various industry bodies or statistical organizations. Technical textiles have neither been a single comprehensible sector of the industry nor a single segment of the market. Therefore any endeavor to define the scope of technical textiles and their markets too closely and too immutably is condemned to failure. Fig. 2.1 describes some of the materials, processes and products which are generally regarded as falling within the scope of technical textiles manufacturing. [HA00]




PES = polyester, PA = polyamide, PAN = polyacrylonitrile

Fig. 2.1: Overview of the scope of technical textiles manufacturing [HA00]

The definition of the boundaries for the scope of technical textiles manufacturing is very complex as well. Many of the techniques applied and finished products obtained are excluded from the scope of technical textiles, regardless of the fact that they are closely related to the conventional fiber equivalents. Woven, knitted, braided, nonwoven and yarn reinforcements made from glass, carbon fiber and organic polymer materials such as aramids are broadly acknowledged as technical textile products, whereas more loosely structured reinforcing materials such as chopped strand mat, milled glass and pulped organic fibers are frequently excluded. [HA00]

The supply chain of technical textiles can be complicated as well as lengthy. The initial step deals with manufacturing of synthetic polymers for technical fibers. It is then followed by specific coating or specialty membranes through to the converter and mill fabricators who incorporate technical textiles into finished products or use them as a component or subunit of a larger component. As a result of which, only 10 % of technical textiles embedded in a modern automobile are visible. [AH16]

### 2.1.2 Areas of Application for Technical Textiles

The textile materials and products that are generally manufactured for their technical performance and functional properties are described as technical textiles. The aim hereby is to boost the efficiency of the products in which the technical textiles can be used as a component or part of another product. With a diversified usage of these textiles for applications in end-use industries, the global demand for these textiles is continuously increasing as well. Some of the various end-use industries for technical textiles are automotive, construction, healthcare, protective clothing, agriculture, sports equipment/sportswear and environmental protection. [Ita16]

The leading international trade exhibition for technical textiles defines 12 main application areas [www20e]. Tab. 2.1 describes the functions of the areas of application for a better understanding and to distinguish the scope of each of the areas. [AH16]

Tab. 2.1: Overview of the various areas of applications of technical textiles according to [AH16]

| Areas | Applications |
|---|---|
| **Agrotech** | Textile products for agriculture, forestry, horticulture, and landscape gardening |
| **Buildtech** | Textile products for membrane construction, lightweight and solid structures, earthworks, hydraulic engineering, and road construction |
| **Clothtech** | Innovations in shoe and clothing manufacture |
| **Geotech** | Products in road construction, civil engineering, and dam and waste site construction |

| | |
|---|---|
| **Hometech** | Innovations in manufacturing furniture, upholstery, floor covering, and carpets |
| **Indutech** | Products for mechanical engineering and for chemical and electrical industries |
| **Medtech** | Innovations in medical and hygiene products |
| **Mobiltech** | Textiles for ship and aerospace construction as well as automotive, railway, and space travel |
| **Oekotex** | Products for environmental protection, waste disposal, and recycling |
| **Packtech** | Innovations in packaging, covering, and transportation |
| **Protech** | Innovations in personal and property protection |
| **Sportech** | Innovations in the sport and leisure world |

The application area Mobiltech includes technical textiles for different branches such as automotive, railway, aerospace. Since this thesis focuses on the automotive branch, the following chapter will discuss the prospects of automotive textiles. [AH16]

## 2.2 Introduction to the Automotive Branch of Technical Textiles

Along with the manufacturing of fabrics for clothing and furnishings, the use of textiles in the automotive branch represents the most important application of textiles in the world. Not only does it serve as the most valuable world market for technical textiles but also it possesses a wide range of products consisting of novel textile structures with performance properties and appealing design [Shi08]. Millions of square meters of textiles are manufactured specifically to fulfill the needs of the transportation sector every year. The automotive industry uses about 25 kg of fibers for a standard passenger car. This amount is continually increasing with raising concerns for the safety and comfort of passengers and for weight reduction of vehicles. [Mat08a]

Similar to most of the technical textile materials, ‘performance/ cost’ is the selection criterion for automotive use, however it is more rigorously enforced to automotive use. For instance, since steel has the best value for ‘(tensile modulus)/cost’ of currently existing materials, steel cord is commonly used as a reinforcing material in tire belt plies for passenger cars. Whereas the criterion for selection could be altered according to the future requirements. Since reduction of the car weight is becoming very important with time, the selection criterion could become '(specific tensile modulus)/ cost'. With increasing pressure on the automotive industry from the environmental requirements to reduce the $CO_2$ mission through reduction in the vehicle's fuel consumption, it is necessary to reduce the weight of the vehicle [Shi08]. Hereby high performance fibers could replace steel to solve the purpose. [Are16, Mat08a]

Recyclability has high requirements on the European automotive sector due to the European Directive on end-of-life vehicles. This makes the development of new textiles products which are 100 % recyclable very essential. For example, some polyurethane foam of car interior components could be replaced with polyester or some other recyclable fiber to boost the effort of recycling. [FH00, Shi08]

The relevant fibers used in automotive textiles and their properties is further discussed in chapter 2.3.

According to [MP99] automotive textiles can be classed into the following categories:

- Upholstery
- Carpeting
- Pre-Assembled interior components
- Tires
- Safety devices
- Filters and engine compartment items

Automotive textile is extensively used in the automotive branch right from light weight vehicles to a heavy truck or duty vehicles. The interior of an average car (Seating areas headliners, side panels, carpets and trunk, lining, tires, filters, belts hoses, airbags etc.) uses about 50 square yards of textile material. These textiles are mainly made of woven, weft knitted, warp knitted, tufted and laminated fabrics and nonwovens. The aim is to meet many end-use requirements such as high resistance to various mechanical actions under severe external environmental conditions. For instance, seat covers must furnish strong soil masking behavior to endure a long life span without washing. Similarly carpets and textile headliners are employed to reduce noise and vibration [FH00]. Interior noise causes discomfort and results in fatigue reducing the driving safety [Are16]. Analog to the functionality of automotive textiles in interior of a vehicle, the other categories accomplish advantages from textiles too. Performance, endurance of the tire and road handling are some contributions of the use of textiles in tires. [CPR18, FH00, Shi08]

The supply chain for textiles in the production process in automotive sector consists of Original equipment manufacturers (OEMs), Tier One, Tier Two, Tier Three and Tier Four companies. OEMs are the vehicle producers in the supply chain. However the products are not directly sold to OEMs by the textile component manufacturers. Their entrance in the supply chain is dependent on the nature of their products and the general specifications passed down and accepted by the OEMs. The OEM is supplied with a complete system component directly by a Tier One supplier. A Tier Two company deals with the supply of subassemblies of the complete system after laminating, cutting and sewing, whereas a Tier Three supplier supplies the individual parts of these subassemblies such as fabric. A Tier Four company serves the provision of material for the parts such as fibers. The focus of this thesis is the textile company which is generally considered a supplier at the third or fourth tier. [Shi08]

## 2.3 Production methods for Automotive textiles

According to [FH00], the three main fabric-forming structures in automotive manufacturing are woven, knitted and non-woven fabrics. The non-woven products are made directly from staple fibers or short natural fibers, whereas the woven and knitted products are made from yarns, which itself are made of fibers [AD10]. A technical textile product can exist and be used in various forms of fibrous structures. It can be used in the form of a simple filament, yarns, fabrics, converted textiles as well as in the form of a complex end product. Fig. 2.2 depicts a flow chart showing the various forms of fibrous structures of technical textiles. [Shi97]

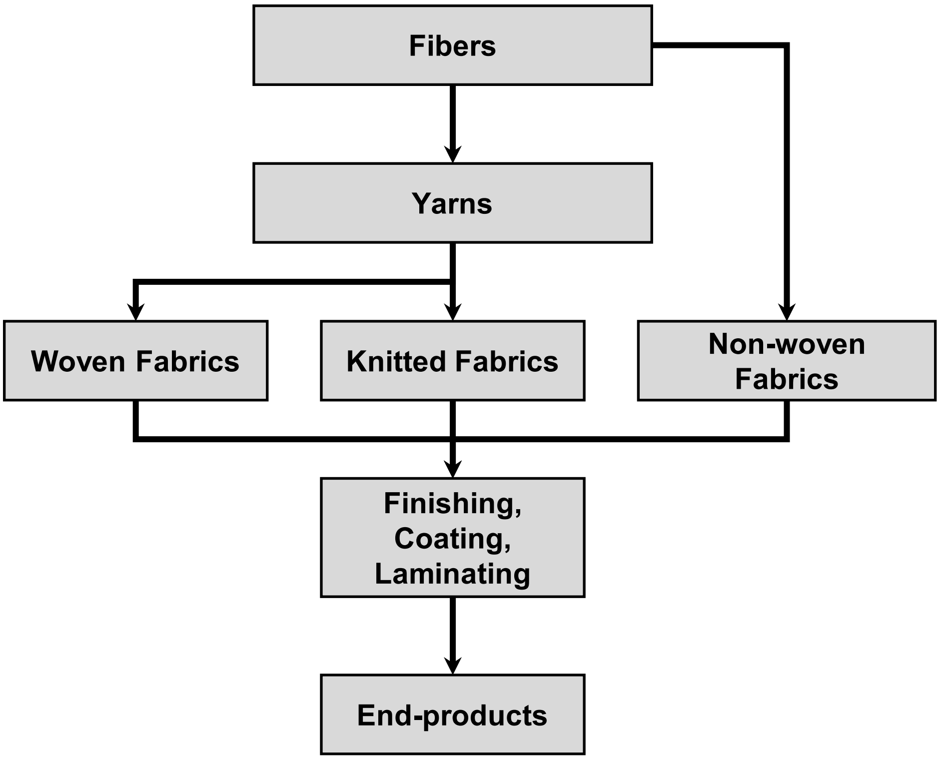



Fig. 2.2: The steps of production of automotive textiles [AD10, Shi97]

### 2.3.1 Fibers in Automotive textiles

Fibers are used in the manufacturing of textile products in the automotive industry. Fibers can be used in various types of textile materials such as circular knitted, warp knitted, woven and nonwoven structures. Each application area in the automotive industry have different performance requirements. The textile products made by the fibers need to fulfill these requirements. This is generally achieved with the help of man-made fibers such as polyester (polyethylene terephthalate or PET), polyamide 6.6, and polypropylene fibers. Some of the requirements are summarized in the following Tab. 2.2. [MP99, SO18]

Tab. 2.2: Different performance requirements of automotive applications according to [SO18]

| Textile products | Requirement | Fibers used |
|---|---|---|
| **Seat covers** | Abrasion and UV resistance, attractive design | Polyester, wool, polyamide, acrylic |
| **Carpets** | Light fastness, moldability | Polyamide, polyester, polypropylene |
| **Seat belts** | Tensile strength, abrasion and UV resistance | Polyester |
| **Airbags** | Ability to withstand high temperature inflation gases, durability for compact storage over many years | Polyamide 6.6, Polyamide 4.6 |
| **Tires** | Heat resistance, adhesion to rubber | Polyester |
| **Headliner, Boot liner** | Stiffness, light weight, strength | Polyester, Glass, Carbon |

Polyester is the most popular fiber for automotive textiles. Along with good mechanical performance including good abrasion resistance, polyester fiber provides high dimensional stability, exceptional resistance to photo-oxidative degradation, and high resistance to fading when exposed to light. It also furnishes high resistance to temperature, high strength and good chemical resistance, outstanding sliding properties and good electrical insulation properties as well as modulus range in tension is between 1700 and 17,000 MPa depending on modifications. [MP99, SGB05]

Out of all the fibers, polyester alone is used for most of fabrics employed in automobile interiors. Recyclability of polyester used in car upholstery, especially in the automobile floor coverings and seat covers in nature makes it even more relevant. Floor covering use almost 45 % of the polyester, whereas seat cover uses 25 % of polyester. Recycling polyester nonwovens can help produce new materials [Dav98]. Furthermore, utilization of polyester resin as a matrix material for especially the natural fiber composites, makes it possible to reuse the waste materials used in the pre-assembled parts of the automobiles such as headliner, boot liners and parcel shelves [HH06, KB01]. Thus, PET is a suitable fiber to support recycling and sustainability. [SO18, www20f]

Moreover, PET has many other advantages like inexpensiveness, higher modulus, higher heat stability, higher resistance to color change, higher durability to sunlight exposure less abrasive nature, and easier and smaller package formation, which makes it more suitable for use in comparison to polyamide. [CPR18, SO18]

Polyamide on the other hand has higher toughness, better tensile strain recovery and adhesiveness compared to polyester [SO18]. It also has an affinity for virtually every class of dyestuff including a wide range of applications, that are disperse, acid premetallized, chrome, selected direct, and certain naphthol dye combination [MP99]. Polyamide 6,6 furnishes higher foldability when it needs to be contained as well as higher resistance to small burning particles [Mat08a]. Therefore it is the most commercially accepted textile fiber for air bags and type construction [CPR18].

Polypropylene is a common by-product of the refinery industry, it can be produced at a lower cost. At the same time it has low density leading to higher covering power and is lightweight. However, polyester and polyamide fibers have better dyeability characteristics, temperature resistance and dimensional stability in comparison to polypropylene. [MP99, SO18]

Acrylic, wool, and high technology fibers such as para-aramid and glass find utilization in small amounts for some specific items in selected cars. Because of acrylic's properties of soft handle and aesthetic appeal, it is considered for luxurious applications. It also possesses properties such as wide color range obtainable, excellent UV resistance, and wool-like handle. However, its application in automotive textile is significantly restricted because of its moderate mechanical performance and poor abrasion resistance. [Mas95, MP99]

Wool fiber has the advantage of high moisture absorption, which helps it in providing a high level of thermal comfort. Since, wool fiber also furnishes a high level of resiliency, the features make it appealing and highly applicable for seat cover fabrics. However, the high cost involved in acquiring wool, makes polyester a better fiber for use in seat cover fabrics, restricting the usage of wool fiber generally only in high-end cars. [SO18] summarizes the advantages and disadvantages of textile fibers used in automotive applications in Tab. 2.3. Polyester and polyamide are the dominating fibers in automotive applications. Polypropylene is included in the table since its low cost makes it desirable for certain applications. [SO18]

Tab. 2.3: Brief properties of the fibers used for automotive textiles [FH00, SO18]

| Fiber type | Advantages | Disadvantages |
|---|---|---|
| **Polyester (PET)** | • High abrasion resistance<br>• High UV resistance<br>• High stiffness<br>• Low cost | • Low moisture absorbency<br>• Low compression resilience<br>• A little less in wearing resistance |
| **Polyamide 6 (PA 6) and 6.6 • (PA 6.6)** | • High strain recovery<br>• High elongation<br>• Good thermal absorptivity<br>• High toughness and wearing resistance | • Moderate UV resistance<br>• High energy consumption for fiber production |
| **Polypropylene** | • Low density<br>• Low energy consumption for fiber production<br>• Excellent resistance to chemicals | • Low melting point<br>• Moderate abrasion resistance<br>• Low moisture absorbency<br>• Low heat resistance |
| **Acrylic** | • High UV resistance<br>• Soft handle | • Moderate abrasion |
| **Wool** | • Good thermal comfort<br>• High resilience | • High cost<br>• Low UV resistance |

### 2.3.2 Production of Yarns

As mentioned in the previous subchapter, the application of wool in automotive textile is significantly restricted because of its moderate mechanical performance and poor abrasion resistance. Hence the use of natural fibers in the production of textile materials for automotive interiors which is mainly wool is very limited. This led to the introduction of synthetic fibers resulting in the growth in products. These products provided advantages with performance, cost and versatility and thereby found their way into automotive end uses. [FH00, SO18]

Synthetic fibers are always produced in a continuous filament form which when further retained as continuous filament helps in producing textured yarns. The synthetic fibers and yarns used in automotive fabrics are mostly thermoplastic in nature. It helps the fiber, yarn and eventually the fabric, to be set without causing a chemical alteration, in different circumstances by the application of heat on a time/temperature basis. In automotive applications there is a need to meet strict performance requirements, such as abrasion and strength. Two important methods of texturizing to meet these requirements are ‘false-twist- textured’ and ‘air-jet-textured’. Textured yarns constitute for more than 70 % of automotive textiles. Out of this of which air-jet textured is approximately 60 %, and false-twist textured is approximately 40 %. [FH00, Shi08]

- False-twist texturizing uses the principle of twisting the filaments in a continuous multifilament thermoplastic yarn, thermal fixing of this twisted yarn and then untwisting at a lower temperature. The supply package or take up package is not rotated during the texturing process but the individual filaments due to their heat memory try to assume the twisted dimension. This results in bulking of the yarn as the filaments try to spiral round each other without any success. The high bulking of the yarn helps the yarn to attain stretch ability or extensibility which can be very useful for automotive applications. False-twist yarns also contribute in automotive fabrics as the pile yarn in cut pile fabrics such as woven plush, double- needle bar, circular knit. Nylon and polyester are mainly used for producing false-twist yarns. However, any strong synthetic fiber which is thermoplastic and can display heat memory can be used for the production as well. [FH00]
- Air-jet texturizing involves the use of several flat individual continuous filament yarns known as feed stock yarns. These are arranged in a creel and run together into the path of an air jet in the filament yarn feed zone. The function of the air jet is to distort and interlace the filaments so that they are adequately fixed in position to create a composite yarn which has strength, a high degree of levelness and uniformity, and at the same time also possesses greater resistance to surface abrasion than almost any other yarn technology. This technique helps in increasing the durability and quality of the fabrics particularly flat-woven fabrics. Fig. 2.3 describes the process of air-jet texturizing according to [ABV+06]. [FH00]

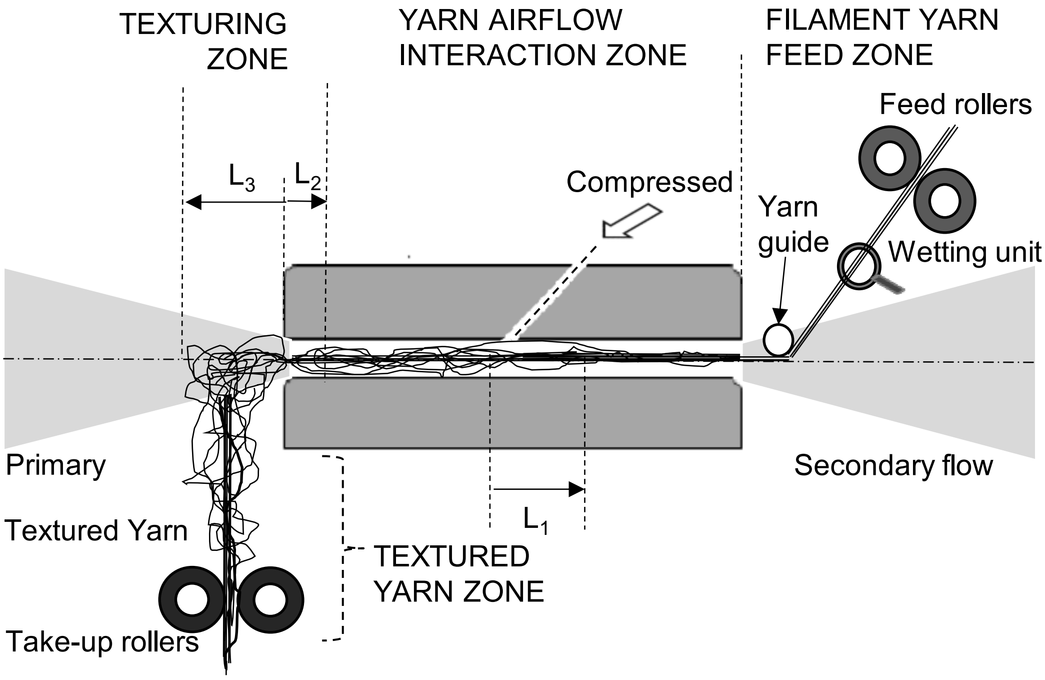



Fig. 2.3: Air-jet texturing process according to [ABV+06]

The woven, knitted and non-woven fabric structures can be classified individually each with its own particular technology or technique. For instance, woven structures generally have a base of two sets of interlacing threads at right angles to each other. On the other hand knitted structures differentiate themselves by having a base of many individual interlacing threads at a variety of angles to each other. Woven and knitted fabric structures are produced from yarns whereas non-woven fabric structures are produced directly from fibers rather than yarn and utilize some bonding or needling process. [FH00]

### 2.3.3 Woven structured fabrics

According to [FH00] the following are the three main factors which influence the properties of woven structures:

- Yarn properties such as thickness, fiber content, extensibility and strength
- Density of the woven yarn
- Method of interlacing of the yarns also referred as the weave of the fabric

Woven structures have a base of two sets of interlacing threads at right angles to each other. The vertical threads are called ‘warp’ as a collective and ‘ends’ as an individual. Similarly, the horizontal threads are called ‘weft’ as a collective and ‘picks’ as an individual. The individual warp ends can be controlled with two methods, by shafts in dobby weaves and by harness cords in jacquard weaves. Dobby looms face the limitation of controlling warp threads in groups whereas jacquard looms can control a far greater number of threads individually with the help of a harness arrangement. However, if a very large number of ends needs to be controlled individually rather than in groups, then jacquards are expensive. In such cases it may cost as much as the basic weaving machine above which it is mounted. [FH00, GS16]

A schematic diagram of the weaving process according to [Kon18] is depicted in Fig. 2.4.

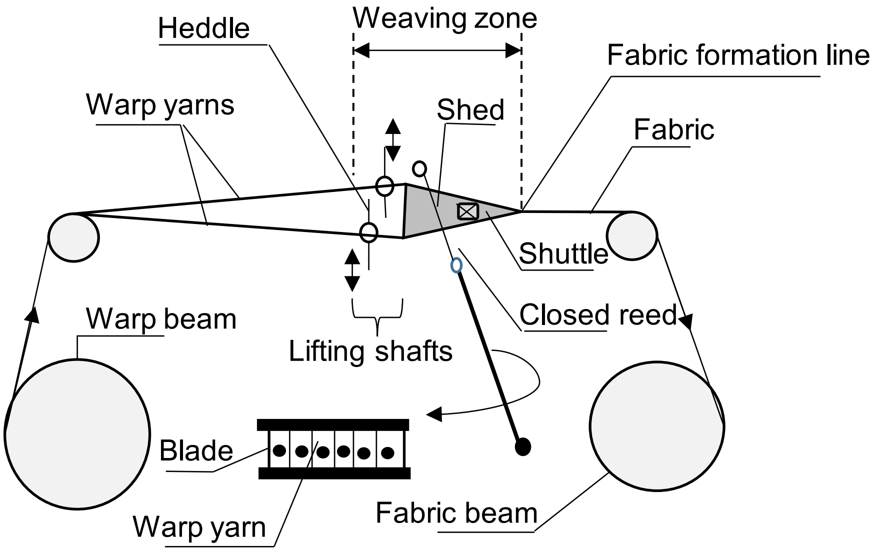



Fig. 2.4: Schematic diagram of the weaving process according to [Kon18]

[SMS+08] mentions that woven fabrics constitute 51 % of the interior automotive fabric production of which dobby weaves make 32 % of the share, followed by jacquard weaves with approximately 18 % and increasing. These fabrics are mainly used for making the seat and door covers.

The production of woven fabrics involves several essential processes such as yarn preparation, warping, production of the warp beam for the loom, entering the warp into the loom, weaving, checking all elements against approved masters, doffing the woven pieces and finally finishing (coating and laminating). [FH00]

### 2.3.4 Knitted structured fabrics

Weft knitting and warp knitting are two main methods to produce knitted structured fabrics.

- Weft knitting is a method in which fabric is produced by making loops from each weft thread that are formed substantially across the width of the fabric. In this method each weft thread is fed more or less at right angles to the direction in which the fabric is produced. Circular weft knits are the second largest fabric group in the automotive textile industry. Circular knitted velour fabrics are used in making the seat and door covers, whereas flat circular knitted fabrics are used mainly for the rear covers of the front seats and headliners. [Ana16, SMS+08]

- Warp knitting on the other hand differentiates itself from weft knitting by making loops from each warp formed substantially along the length of the fabric. In this method each warp thread is fed more or less in line with the direction in which the fabric is produced. This method of production of fabrics from yarn is faster than weaving and weft knitting. Warp knitted fabrics are the third most popular group in the automotive textile industry, which include the Tricot family of knits, brushed or structured, with Tricot pile sinker fabrics and Raschel knits. [Ana16, SMS+08]

### 2.3.5 Non-woven structured fabrics

Non-woven fabrics are generally produced in two steps. Firstly web formation and secondly some method to bond the web fibers together. The web formation processes include dry laid (carding and air laid), wet laid and spun melt (spun bond and melt blown). The different kinds of bonding methods include mechanical, chemical or thermal bonding method. The chemical bonding method uses adhesive binders, thermal hot-melt methods or some form of mechanical treatment such as needling or stitching depending on the properties required in the end-products. The mechanical bonding method includes the method of needle punching. With the help of this method, characteristics of both woven and knitted fabrics can be achieved in the non-woven fabrics. In thermal bonding method, thermoplastic nature of the web fiber itself or at times an external hot-melt adhesive is used. It involves a bicomponent fiber with low melting point functioning as a binder. Bonding is attained with the help of a calendar process, by controlled hot air, infra-red heaters or by high frequency or ultrasonic welding. [FH00, RS16]

According to [RT08], non-woven fabrics possess the following advantages for their usage in the automotive industry:

- They can be integrated into multi-layer, modular components with other materials including foam
- They can be integrated into lightweight and low-density modules
- They can meet tight cost-performance targets in what is a highly price-sensitive industry
- Their ability to be deep-draw molded into complex shapes at relatively low temperature

- They contain recycled raw materials and still meet performance requirements
- Their ability to be compatible with emerging recycling processes.

### 2.3.6 Finishing of the textiles

Finishing of textiles involves treating a base fabric by mechanical or chemical finishing process to improve the appearance, aesthetics, features and efficiency to fulfil the functional needs of the end-product. Textile finishing is in general not just performed on woven and knitted fabrics but also on some non-woven materials in order to manufacture a product with the final overall performance features. For instance, non-woven used in the numerous applications in cars can be categorized as functional or aesthetic and at the same time also as substitutes for other materials. [Con16, FH00]

Some of the methods involved include dyeing and finishing, printing, coating and lamination. Lubricating yarns at different stages of processing can help reduce static electricity and boost the performance of winding, texturizing, warping and weaving. Additionally, the lubricants and processing chemicals present on the yarn are best scoured off to help reduce the phenomenon of fogging. Fogging can be caused by the vaporization of these 'oils' under the action of sunlight resulting in condensation of the windscreen leading to reduced visibility. Similarly back coating of woven fabrics helps increase the abrasion resistance. Attaining a triple laminate, by laminating fabric to polyurethane foam and a scrim on to the back of the foam, helps seam strength and seam fatigue. The processing sequence for the production of woven and knitted car seat fabrics as an example is depicted in Fig. 2.5. [FH00]

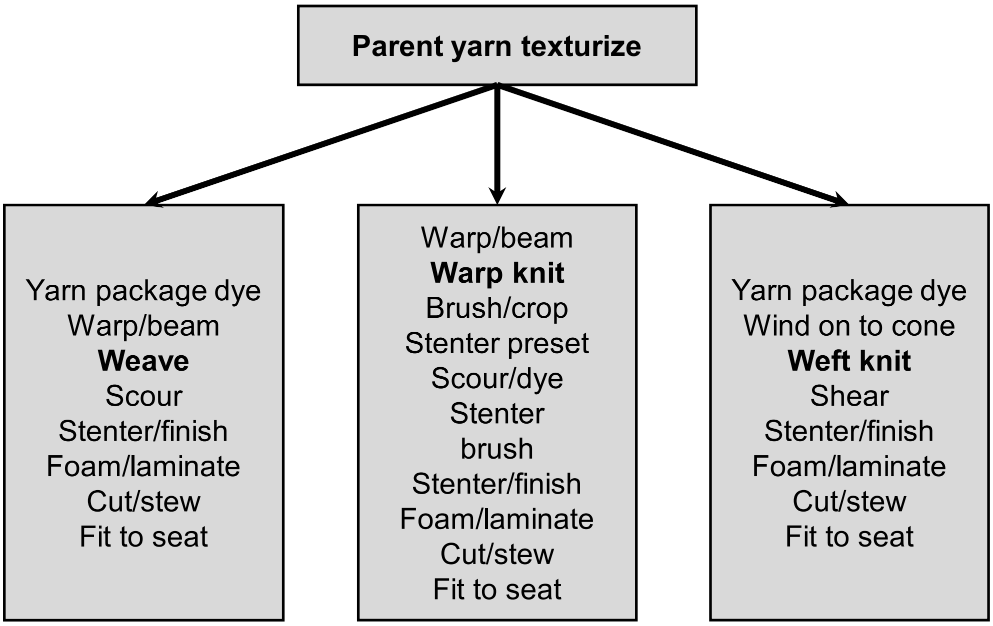



Fig. 2.5: The processing sequence for the production of seat fabrics [FH00]

According to [Shi08], finishing of the textiles requires the following:

- The textile's structure, color and feel needs to be preserved.
- The finishing agent must be permanent taking washing and use into consideration.
- Protecting the downstream processing such as laminating, gluing, bonding or sewing from unfavorable influences.
- Saving the fogging values, emission behavior, fastness, mechanical-physical properties as well as antistatic behavior from impairment.

## 2.4 Conclusion and Resume

The literature review gives a detailed outlook about the manufacturing processes involved in producing various end-products in the automotive textile industry. It describes the fibers used as raw materials and different steps of manufacturing such as methods for yarn preparation, different fabric preparations and the finishing in the end. Based on this information, the furthermore research is conducted in the following chapter to acquire the necessary quality control parameters involved in the manufacturing processes.

# 3 Parameters of Quality Control for Automotive textiles

The goal of the following chapter is to evaluate the relevance of quality control in the manufacturing of technical textiles in the automotive industry. Moreover, the parameters important for the quality control of manufacturing woven, non-woven and knitted fabrics are individually discussed. The results of this chapter is furthermore used for the execution of the market analysis.

## 3.1 Introduction to Quality Control

Enhancing the position in the market is one of the competitive priorities in operations, that is critical to a production firm. It often deals with decisions concerning their production process, planning, capacity and control. [BL02]

Quality is currently among the considerable topics in research on production processes. Production of products with insufficient quality leads to a decline in customer satisfaction and furthermore reduces efficiency thereby increasing the cost of business operations. Because of this the relationship between quality and economics of production has been explored over the past two decades. [TC05]

There is a consistent need for improving the manufacturing processes due to the current dynamic manufacturing environment. Companies constantly need to evolve and change, according to the rapidly changing customers' expectations, to remain successful. As a result, process quality control, that deals with the examining, controlling and managing the factors that affect the process quality, has become more challenging. To maintain quality, a manufacturer conducts offline quality control tests and inline quality control tests. [Jai13, YW08]

The offline quality control tests are executed in the product design phase to maintain the quality by lessening the deviation of the target product. Product development or manufacturing process design are the stages which primarily involve offline quality control [Onw97]. It is aimed to establish the surety that the product can be designed and at the same time to decrease the susceptibility to the effects of random deviations in manufacturing, environment, or even customer usages. [JLI16]

However, offline quality control is usually a time-consuming and strenuous process. It involves the transfer of the parts from the manufacturing area to a separated test area which leads to unfavorable production phenomenon. Moreover, one of the major disadvantage of this process is the inspection of the products after the completion of the process. The judgement about the quality of the product and if its qualified is made at the end. The parts of the product which fail can either be scrapped or reworked, resulting in financial loss. [YW08]

Inline quality control on the other hand takes place during the production process phase in which problems are anticipated and rectified to prevent any out-of-control manufacturing conditions. It prioritizes the supervision of the production process to identify the deviation and to examine and eliminate the causes of variation. [JLI16, MDA+12]

The different parameters for the quality control in manufacturing automotive textiles will be discussed in the following subchapters.

## 3.2 Quality parameters for manufacturing woven fabrics

The quality control for manufacturing woven fabrics depends on the quality of yarn, loom parameters, fabric parameters as well as the environmental conditions. The most common reasons for the stoppage of loom are yarn breakages, machine failures or necessary changes of the warp beam. Some of the important parameters are listed below: [MDA+12]

- loom type, speed and width,
- yarn type, quality and yarn preparation,
- fabric structure, density and style,
- weave room conditions,
- weaver’s skill and workload.

The determination of the quality parameters for all the steps of manufacturing woven fabrics was conducted with the help of literature research and Digital capability center (DCC), Aachen. DCC, Aachen has a setup for a production line for manufacturing textile bands. The production consists of different processes such as warping, weaving, coating, printing, cutting, sewing and testing. The parameters acquired are summarized in Tab. 3.1.

Tab. 3.1: Parameters for quality control of woven fabrics according to DCC and [MDA+12]

| Yarn parameters | Machine parameters | End-fabric parameters |
|---|---|---|
| • Tensile strength<br>• Torsion of the threads<br>• Color<br>• Frequency of thread breakage incidents per bobbin<br>• Drape of the threads<br>• Diameter of the bobbins<br>• Frequency of weft breakage | • Machine temperature<br>• Machine speed<br>• Machine vibrations<br>• Rate of yarn feeding<br>• Yarn tension equal (left, middle, right)<br>• Temperature (external)<br>• Humidity (external) | • Width of output fabric<br>• Weft density<br>• Waviness (fiber crimp)<br>• breaking strength and elongation for dry and wet webbing,<br>• abrasion resistance<br>• shrinkage rate<br>• Color fastness |

Leaving the parameters unmonitored can lead to various problems. The faults that occur when the parameters are left unmonitored are described in the following table. Moreover, the solutions to monitor these parameters are also included in the Tab. 3.2.

Tab. 3.2: Faults due to unmonitored parameters and solution for monitoring these parameters according to DCC

| Parameters | Faults when unmonitored | Solutions |
|---|---|---|
| Yarn tensile strength | Risk of thread breakage | Prior to production with Specialty hardware |
| Torsion of the threads | Risk of thread breakage | Prior to production with Specialty hardware |
| Frequency of thread breakage incidents per bobbin | Yellow application may need to be changed | Sensor-based inline / at machine |
| Drape of the threads | Crossovers jeopardize the quality of the product | Camera-based inline / at machine |

| | | |
|---|---|---|
| Diameter of the bobbins | Deviations may indicate skewed roll-up | Camera-based inline / at machine |
| Yarn tension equal | Deviations jeopardize the quality of the weaving pattern | Sensor-based inline / at machine |
| Width of output fabric | Deviations leads to scrap | Camera-based inline / between stations |
| Weft density of fabric | Deviations leads to scrap | Camera-based inline / between stations |
| Waviness of fabric | Deviations leads to scrap | Sensor-based inline / between stations |
| Machine speed and vibration | Deviations jeopardize the quality of the weaving | Sensor-based inline / at machine |

## 3.3 Quality parameters for manufacturing knitted fabrics

It is very important to investigate and rectify any variation occurring during the knitting process. Defects due to lack of quality belong to the same category, since their occurrence leads to time consuming reparation or fabric rejection. The quality of the knitted fabrics mainly depends on the quality of the yarn used to make it, the machine parameters while knitting as well as the process parameters of knitting. The quality control system of knitted fabrics must start with the inspection of the incoming yarn. Thereafter the machine parameters of the knitting machine need to be monitored and the quality of the knitted fabrics produced needs to be checked in the end. [DCH99, MDA+12]

Some of the important yarn parameters according to [MDA+12] that need to be monitored to ensure the quality control are:

- count,
- unevenness (U %),
- strength,
- twist,
- elongation,
- appearance,
- coefficient of friction,
- bending rigidity.

Variation in the yarn count can cause discrepancies in grams per square meter (GSM) and result in an impact on the quality of the end fabric. Unevenness can cause various defects such as yarn breakages. The softness and absorption properties of the yarn can be influenced by twist in the yarn. Hence the defects occurring in the yarn can strongly affect the appearance of a knitted fabric. [MDA+12]

Some of the important machine parameters for knitting with regards to quality control are:

- yarn input tension,
- stitch cam setting,
- take-down load,
- rate of yarn feeding,
- number of feeders,
- yarn patterning in feeders and
- needle gating.

Yarn input tension has a major influence of the mechanics of knitting especially the loop length. An increase in the yarn input tension leads to a decrease in the loop length. The stitch cam setting and loop length are directly proportional to each other and hence an alteration in the stitch cam setting leads to a change in the loop length as well. Take-down load and rate of yarn feeding influence the yarn tension and thereby also the loop length. The higher the value of the yarn feeding load, the higher the impact not just on loop formation but also on the fabric structure and appearance [FGU11]. Since the order of needle gating is dependent on the design of the knitted fabrics, variations to the order anywhere in the needle bed can alternate the design leading to the manufacturing of defective fabrics. In case of a needle defect during the knitting process, the thread tension undergoes the biggest variation. The speed of the thread variates less in comparison whereas the linear density of the thread has fractional variation. [ČS08, MDA+12]

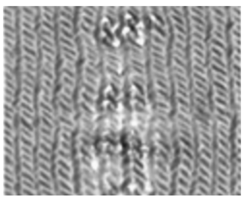
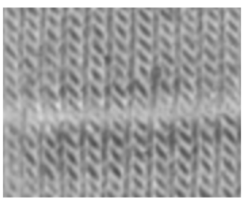
The yarn, machine and end-fabric parameters discussed above are summarized in Tab. 3.3. [MDA+12]

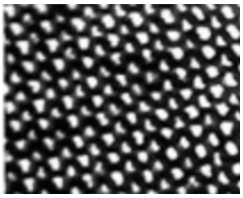
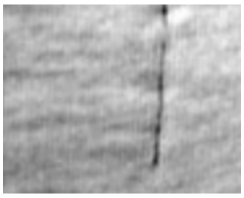
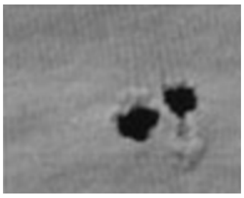
Tab. 3.3: Parameters for quality control of knitted fabrics according to [MDA+12]

| Yarn parameters | Machine parameters | End-fabric parameters |
|---|---|---|
| • count<br>• unevenness (U%)<br>• strength<br>• twist<br>• elongation<br>• appearance<br>• coefficient of friction<br>• bending rigidity | • yarn input tension<br>• stitch cam setting<br>• take-down load<br>• rate of yarn feeding<br>• number of feeders<br>• yarn patterning in feeders<br>• needle gating | • loop length<br>• GSM<br>• courses per inch<br>• fabric width<br>• wales per inch<br>• fabric defects<br>• stitch density<br>• fabric tightness factor<br>• yarn count<br>• fabric construction<br>• yarn type |

Some of the major fabric defects after the process of knitting are vertical stripes, horizontal stripes, fabric spirality, dropped stitches and holes. These faults, the probable causes for these faults and solutions to monitor these faults are summarized in Tab. 3.4.

Tab. 3.4: Fabric faults, their probable causes and solution for monitoring these faults according to [AAM09, MDA+12]

| Knitted fabric fault | Probable causes | Solutions |
|---|---|---|
| <br>**Vertical stripes** | • Defective needles and tricks<br>• Needles loose or tight in the trick<br>• Mixing of needles/sinkers of different types | • Inline monitoring of needles with needle detector<br>• Inline optical inspection to detect fault |
|  | • Uneven yarn<br>• Uneven yarn input tension<br>• Uneven take-down load<br>• Mixed yarn | • Inline monitoring of yarn tension<br>• Inline monitoring of yarn twist |

| | | |
|---|---|---|
| **Horizontal stripes** | • Loose stitch cam<br>• Uneven twist in yarn<br>• Poor unwinding of yarn | • Inline optical inspection to detect fault |
| <br>**Fabric spirality** | • High twist (torque) in yarn<br>• Uneven yarn input tension<br>• Number of feeders too high<br>• Wrong stitch cam setting<br>• Bad or bent needles | • Inline monitoring of yarn twist<br>• Reduction of number of feeders<br>• Inline optical inspection to detect fabric fault |
| <br>**Dropped stitches** | • Low yarn tension<br>• Low take-down load<br>• Stiff needle<br>• Wrong stitch cam setting<br>• Yarn guide not properly set | • Inline monitoring of yarn guide<br>• Inline monitoring of yarn tension<br>• Inline optical inspection to detect fault |
| <br>**Holes** | • Weak yarn<br>• Yarn with knots<br>• Lint in yarn path<br>• Very high speed of the machine<br>• Rough or defective sinker<br>• Needles too tight in the tricks<br>• Higher yarn/fabric tension<br>• Unsuitable or very small loop length | • Inline monitoring of yarn guide<br>• Inline monitoring of yarn tension<br>• Inline optical inspection to detect fault<br>• Inline temperature and humidity control<br>• Inline monitoring of machine speed |

## 3.4 Quality parameters for manufacturing non-woven fabrics

Non-woven fabrics are generally produced in two steps. Firstly, web formation and secondly web bonding to bond the web fibers together. The web formation processes include dry laid and spun laid. The different kinds of bonding methods include mechanical methods such as needle punching and hydroentanglement, and thermal bonding methods such as calendaring. [FH00, RS16]

### 3.4.1 Spun laid method

Some of the machine/inline variables of spun laid method according to [ABS+07, Bo10, MPA13] are:

- Primary air temperature: Fiber diameter and temperature of the primary air are inversely proportional to each other.
- Quench air rate: The orientation of the polymer molecular is influenced from the air-drag force. The quench air velocity regulates this force.
- Air suction speed: Higher speed of the air suction results in finer fibers since the fibers are finely attenuated. It also helps in holding the web together on the conveyer belt.
- Venturi gap: Similar to air suction speed, a larger venturi gap also yields finer fibers.
- Throughput: Throughput is directly proportional to the fiber diameter and inversely proportional to the fineness of the fiber.
- Collection speed: The speed of the conveyor belt regulates the final lay-down of the multi filaments. Increasing the relative speed of the conveyer belt with the deposition results in a machine direction orientation bias of the fiber.
- Bonding temperature and pressure: They have a huge influence on the tensile properties of the final fabric. The pressure also has an influence on the stiffness of the fabric.

Some of the offline variables that play a significant role in the final quality of the produced non-woven include the selection of the die hole size, die setback, web collection type and die hole design parameters. They have a major influence on the fiber diameter. Poor dye design leads to the formation of a non-uniform web. [Lim10, MPA13]

The parameters discussed above for the spun laid method are summarized in Tab. 3.5.

Tab. 3.5: Parameters for quality control of spun laid fabrics [ABS+07, Bo10, MPA13]

| Material parameters | Machine inline parameters | Machine offline parameters |
|---|---|---|
| • Fiber fineness<br>• Fiber orientation<br>• Fiber size<br>• Density of the fiber<br>• Web uniformity<br>• Web weight | • Primary air temperature<br>• Quench air rate<br>• Air suction speed and venturi gap<br>• Collection speed<br>• Through- put<br>• Bonding temperature and pressure | • Die hole size<br>• Die setback<br>• Web collection type<br>• Die hole design |

### 3.4.2 Dry laid needle punching method

The dry laid needle punching parameters include material parameters such as fiber and web types, needle parameters such as needle type, shape, arrangement and number of barbs, and the machine parameters such as depth of needle penetration, stroke frequency and punch density. [MPA13]

Material parameters:

The feed rate plays a crucial role in influencing the web parameters. Employing higher feed rates results in an increase in the web density of the nonwoven formed, whereas lower feed rates results in an increase in the permeability characteristics of the nonwoven. However, when the feed rate and stroke frequency are simultaneously increased, the permeability characteristics of the nonwoven decreases. Swing speed and conveyer speed of the cross-lapper influence the web thickness and web weight [KSC+07]. The needle punching process involves two stages, pre-needling line and a finish needling line with a break in between. In case of a lower mass density of the material, correction is possible in finish needling. [ASK+20, MPA13, RA06]

Machine parameters:

The stroke frequency and the consolidation of the web are directly proportional to each other. The desired degree of consolidation is acquired by balancing the stroke frequency and linear speed of the web. The resistance to abrasion is improved due to fabric consolidation with an increase in the needle punch density and depth of penetration. However, excessive increase in punching density, needling level and depth of penetration weakens the nonwoven fabric. [ASK+20, MPA13, PA09]

Needle Parameters:

The type of needle used has a huge influence on several properties of the nonwoven formed. Correct selection of needles according to the required fabric properties is very essential. The final performance and quality is hugely influenced by the wear of the needles as the barbs wearing causes a much decreased reorientation of the fibers. The resulting in-homogeneity of the fiber web results in massive needle breaks leading to the termination of production. Some of the reasons for needle damage are non-alignment of needles, fiber quality, needle punching condition, needles penetrating a thick web too aggressively and encountering high friction between needles and fibers, deep barbs that increase the load on the needle during penetration, machine vibrations during operation, and improperly designed hole sizes in the bed and stripper plates. [CGK+07, MPA13]

The parameters discussed above for the dry laid needle punching method are summarized in Tab. 3.6.

Tab. 3.6: Parameters for quality control of dry laid needle punched fabrics [ASK+20, MPA13, PA09]

| Material parameters | Machine parameters | Needle parameters |
| --- | --- | --- |
| • Web uniformity<br>• Web thickness<br>• Web weight<br>• Air permeability | • Feed rate<br>• Stroke frequency<br>• Web speed<br>• Machine vibrations | • Needle punch density<br>• Depth of penetration<br>• Needling level<br>• Type of needle<br>• Shape of needle |

## 3.5 Conclusion and Resume

The various quality parameters discussed in the previous subchapters for woven, knitted and non-woven fabrics are summarized together in the appendix (Tab. 9.1) and used as a foundation for the execution of the market analysis through expert interviews. The questionnaire for the expert interviews is based on the processes discussed in chapter 2 as well as the quality parameters discussed in chapter 3.

# 4 Expert interviews in Automotive textile industry

The aim of this chapter is to assess the current status and challenges associated with the quality control of manufacturing the textile fabrics by conducting expert interviews in the automotive textile industry. Moreover, the results include information about the solutions being used for quality control in the industry. The potential for the introduction of digital quality control to manufacture technical fabrics in the automotive textile industry is derived through this market analysis. In the following subchapter, the design of the expert interview is presented at first. Subsequently, the methodology for the evaluation is discussed. The chapter is closed with the presentation of the results.

## 4.1 Questionnaire for expert interviews

The SPSS principle i.e., Sammeln, Prüfen, Sortieren und Subsumieren (Collect, Check, Sort and Subsume), according to [Hel11] is used to prepare the questionnaire for the expert interviews. The questionnaire is created in four steps. First, the questions are collected according to the brainstorming methodology. The brainstorming method is chosen because a large number of questions can be generated in a relatively short time [SB18]. The collected questions are then checked by assessing the added value of their answers based on the processes discussed in chapter 2 as well as the quality parameters discussed in chapter 3 and then subsequently sorted. With the aim of the questionnaire to determine the current status and challenges associated with the quality control in each manufacturing process, the questions are subsumed into categories specified for each manufacturing process such as warping, weaving, dyeing and coating. Subsequently, three different questionnaires are prepared each for woven, knitted and non-woven fabric producers. The structure of the subsumed categories of the questionnaire according to the manufacturing processes in woven, knitted and non-woven fabric industry is presented in Fig. 4.1. The first part includes the introduction followed by general questions applicable for all industries. The last part includes specific questions for each process according to each industry type. The complete questionnaire of the expert interviews are attached in the appendix (chapter 9.2).

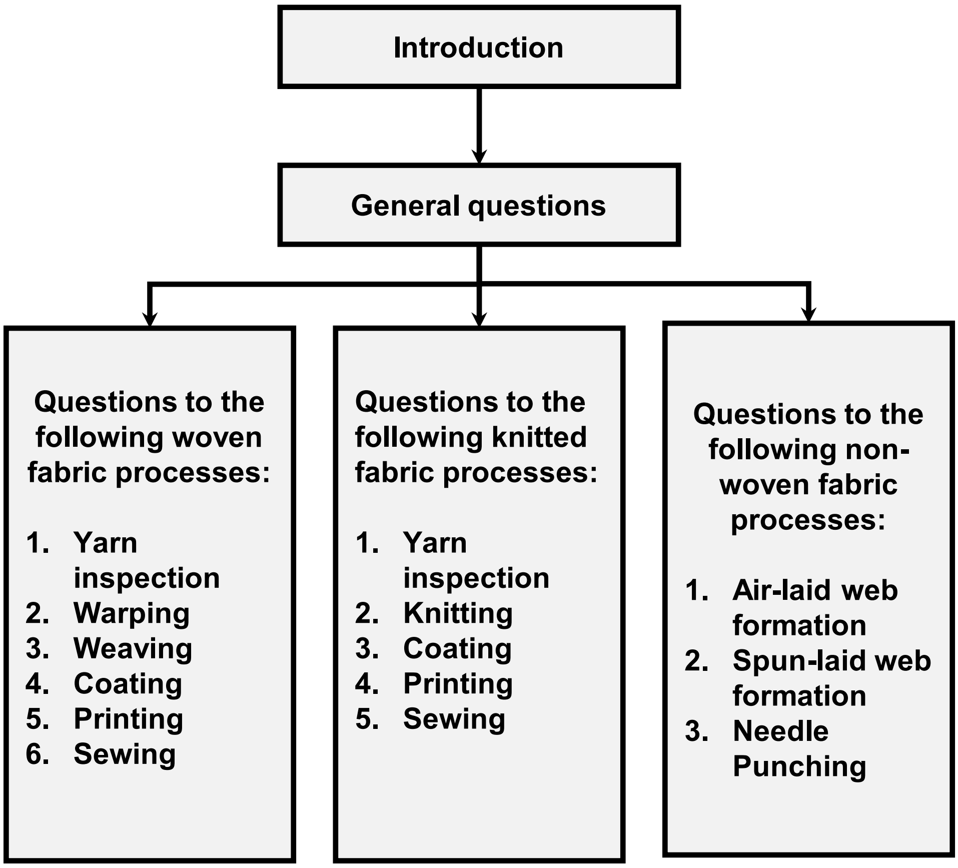



Fig. 4.1: The structure of the subsumed categories of the questionnaire [Hel11]

## 4.2 Evaluation of the Expert interviews

In order to execute a thorough market analysis, eight expert interviews are conducted. These eight interviews involve two expert interviews each with woven fabric and knitted fabric industry respectively and three expert interviews with non-woven fabric industry. Moreover, one expert interview is conducted with a yarn manufacturing company to understand the problems associated with the yarn being purchased by the woven and knitted fabric industry. Non-woven manufacturing process does not require yarn as raw material [AD10]. Since a detailed transcription with dialects and expletive words is not of interest for this master thesis, the key information for each interview is categorized and summarized. The summarized information is attached in the appendix (chapter 9.3). In the following the key findings for each the industry interview will be investigated in more detail. [BLM14]

### 4.2.1 Evaluation of the interview with a yarn manufacturer

The fabric manufacturing industry is the main focus of this thesis. However, the yarn required for manufacturing fabrics in woven and knitted fabric industry is generally purchased from yarn manufacturers, as shown in Fig. 4.2. Since the quality of the yarn is very essential in the quality control of the fabric manufacturing, it is necessary to analyze the manufacturing process of yarn. Therefore, one expert interview is conducted to understand the current status and challenges associated with the quality control of manufacturing yarn. The company interviewed is involved in the manufacturing of weaving yarn, that is later manufactured into woven fabrics used in the automotive industry. It is determined in the interview, that the manufacturing processes for weaving yarn is similar to that of knitting yarn. Therefore, the results of this interview are also relevant for the knitted yarn manufacturing.

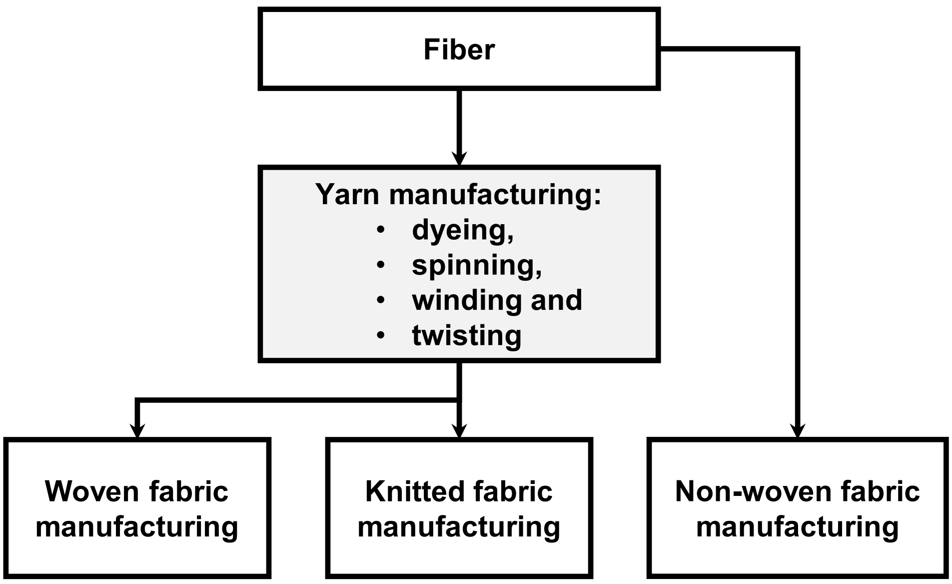



Fig. 4.2: Relation between yarn and fabric manufacturing determined through expert interview

Synthetic as well as natural fibers are purchased by the company to manufacture yarn. The quality of natural fiber is more diversified than the quality of synthetically produced fibers and therefore require a higher scope of testing through a control for the incoming goods inspection. The control sheet precisely specifies the role of each employee at each stage as well defines the parameters to be tested. Since the tests are destructive, only random tests on small volumes of purchased fibers are performed in quality assurance (QA) before the product is released for manufacturing.

The production processes in the company include the dyeing, spinning, winding and twisting, and for each of the process, the important parameters are observed. Practically every article has its own production regulation so that the responsible employees in the production area know exactly how to set up the machine accordingly. Automatic collection of data through production data acquisition (PDA) system is being developed internally. Like the incoming goods inspection plan, there is also an intermediate inspection plan, where it is precisely defined what quality aspects of the yarn are to be inspected individually. This is performed offline between the processes at the moment where the control sheets for the individual areas are filled out by the employees.

Some of the general errors are:

- From raw materials: the straw parts in the wool, packing remainders or other foreign fibers.
- From fiber dyeing: the color accuracy of the pattern, the color fastness.
- From the other spinning technical areas: deep confusions leading to contamination of different orders with each other.

The general errors involved in the manufacturing processes of yarn are depicted in Fig. 4.3.

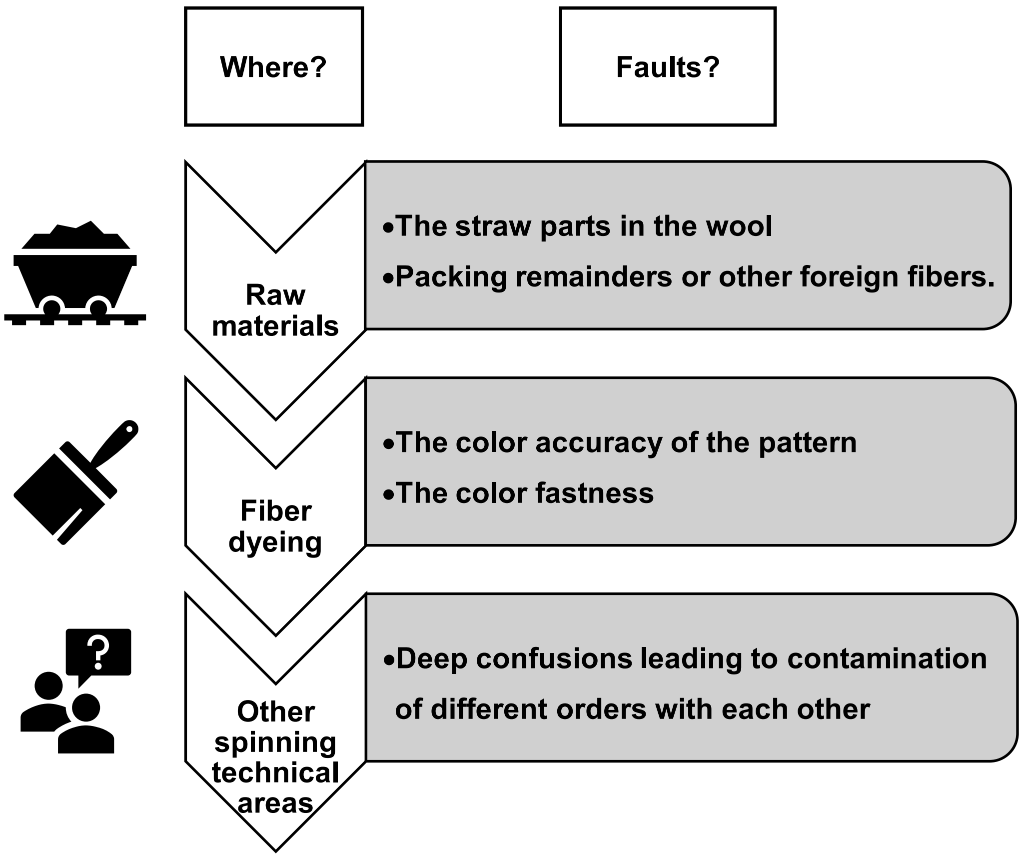



Fig. 4.3: General errors in yarn manufacturing

Random inspections are performed manually to control these errors. The only permanent monitoring that takes place is a visual inspection in the winding department. An optical sensor is used that permanently detects the yarn defects. However, it does not automatically detect the errors and requires to be monitored by the employees.

Since the various articles that the company processes, such as wool, silk, linen, and cotton are so diverse, it is very difficult to develop and establish an automatic inline quality control system, which automatically monitors the parameters and detects the errors in the process. Hence offline quality control is performed manually throughout the manufacturing process.

The current status of technology and the reason behind the limitation in the technology determined through the interview with a yarn manufacturing company are summarized in the following Tab. 4.1.

Tab. 4.1: Current status of technology and reason behind the limitation in a yarn manufacturing company

| **Technology** | **Reason** |
|---|---|
| Random tests only on small volumes of purchased fibers | Destructive tests |
| Intermediate inspection plan to monitor the yarn parameters between the processes offline | Inline monitoring with production data acquisition (PDA) system still being developed internally in the company |
| Absence of an automatic inline quality control system for example ML-based automatic camera inspection | Diversity of the various articles makes it difficult to establish inline control system. |

### 4.2.2 Evaluation of the interview with woven fabric industry

For analyzing the woven fabric industry, two expert interviews are conducted. The end-products with the woven fabrics that are manufactured by the Tier 1 industries in the end are the following:

- Convertible top fabrics
- Car cover fabric
- Head or seat cover
- Reinforcement tapes, binding, loop straps
- Elastics and sealings and panorama roofs

Based on the interviews, the different steps of manufacturing processes involved are evaluated. The different steps include purchase of yarn, warping and weaving, dyeing, finishing and end inspection. The steps are depicted in Fig. 4.4.

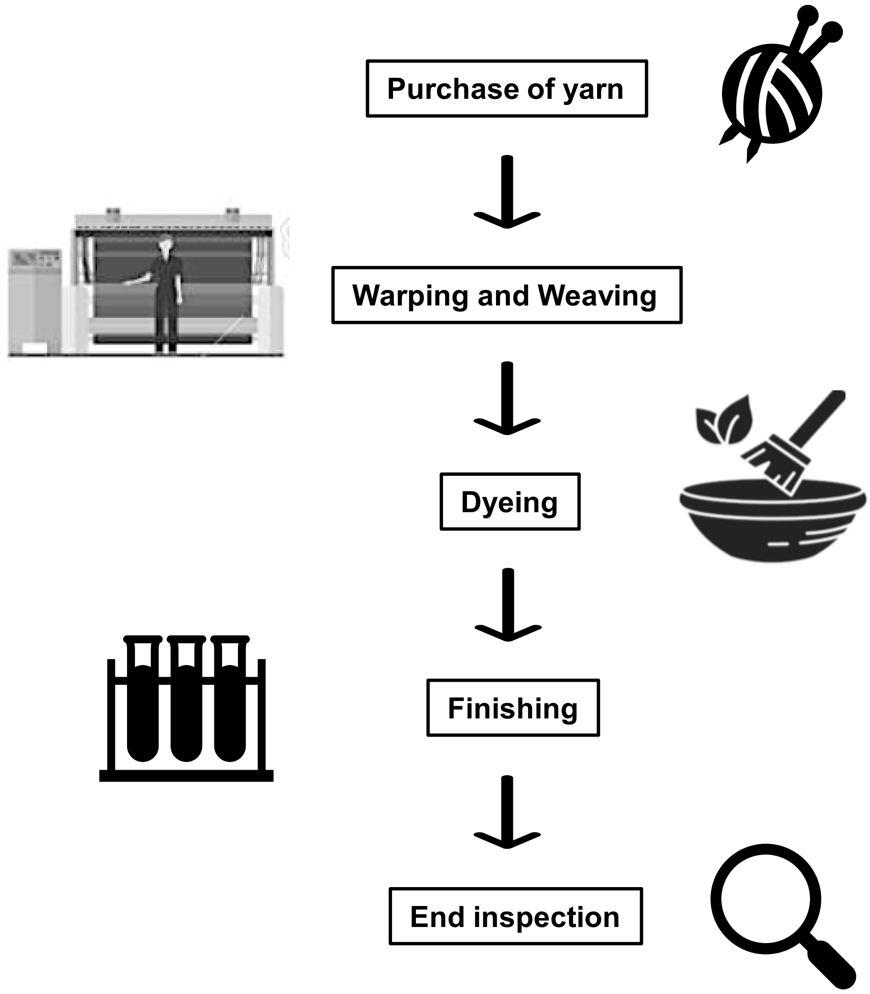



Fig. 4.4: Different steps of manufacturing woven fabrics

To keep the internal data of each company anonymous, the companies are named as company A and company B. The current situation with the quality control in both the companies are compared and the potential for the introduction of digital quality control is identified in the following:

**Purchase of yarn:**

The first step involved in manufacturing woven fabrics is the purchase of yarn from a yarn manufacturer. The yarn manufacturers generally test the yarn and prepare a specification list according to the tests. The woven fabric manufacturers usually rely on the yarn manufacturers and their specification list.

- In the case of company A, it is entirely relied on the specification list and hence no quality control takes place before the production release. This leads to the occurrence of defects on a weekly basis in the latter processes of manufacturing resulting in weaving loom stoppages.

- On the other hand, in the case of company B random quality control on a small amount of material is conducted before releasing the entire lot. Thereby the amount of defects detected afterwards is quite small.

**Warping and Weaving:**

- The second step is the preparation of weaving, also called warping and subsequently weaving. Parameters such as temperature and humidity are set and controlled in the hall according to the specifications. However, none of the parameters are monitored continuously inline in company A during warping and weaving. Neither the yarn parameters during warping nor the machine parameters during weaving are monitored. This means that each gear of the machine has to be checked by the weaver every two hours for changes in intermediate products, according to the test protocol, test plan and documentation. Width, thickness and elongation are the only parameters that are controlled manually offline after the weaving process. The camera inspection for quality control is not yet fully operational and still in validation phase. Lack of inline control leads to detection of problem later in the following processes. Sustainability such as shrinking of fabric through a change in ratio of width and thickness of the fabric as well as elongation of fabrics are major problems.
- In company B on the other hand temperature is continuously measured with sensors and a visual quality inspection to detect the errors during the process is conducted manually and not automatically due to economic reasons. The defects that occur during weaving are start-up marks as well as faults due to dust/contamination.

The manufacturing process of warping and weaving in company A and company B respectively is compared in the following Fig. 4.5. The points of comparison include the general defects, the current status of technology and the reason behind the limitation in the technology.

| | Warping and Weaving | |
|---|---|---|
| | **Company A** | **Company B** |
| **General defects** | • Shrinkage<br>• Elongation | • Start-up marks<br>• Faults due to dust/contamination |
| **Current status of technology** | • Temperature and humidity are set in the hall<br>• The camera inspection is still in validation phase.<br>• Machine parameters are not recorded automatically | • Measures temperature continuously with sensors<br>• Conducts a visual quality inspection manually<br>• Machine parameters are not recorded automatically |
| **Reason** | • Main focus is not automotive textiles, therefore economically not feasible to invest in the betterment of the existing quality control for automotive textiles. | • Lack of knowledge about the digital solutions available on the market and their potential.<br>• Fear about the feasibility of the solutions. |

Fig. 4.5: Comparison of warping and weaving process between company A and B respectively

**Dyeing:**

- During this process self-defined recipe for colors are used by company A. The control of the fabric color after the process take place manually, in which the employees compare the fabric color with color matrix measuring system. Depending on the standard, there are standardized light sources, which are also maintained and serviced. Other offline tests for color fastness and abrasion resistance are carried out in labs. Moreover, a lot of lab tests are outsourced to external companies depending on the requirements and test standards of the customers.
- In company B visual color inspection is conducted both manually and automatically with spectrophotometric testing device. The color is compared

with the given standards and according to the results, the goods are re-shelved or re-colored if required so that the color specifications are met. Temperature sensors are used to measure the surface temperatures of the goods and accordingly the equipment parameters are precisely controlled and maintained.

**Finishing:**

- The last step of manufacturing is generally finishing followed by an end inspection. In company A the facility of performing the finishing with the help of chemical agent is conducted. Using wrong Chemical agent for finishing is a problem. The making/mixing of chemical agent is performed and controlled manually with the four-eyes principle. Additionally, wrong temperature and wrong speed of conveyer belts are also common problems. The problems with the fabrics are shrinkage of the fabric and damaged elongation properties of the band.
- In company B, there are no facilities of finishing fabrics.

**End inspection:**

- The end inspection is a visual inspection of the end-products in company A as well as company B. In company A, built-in camera is used for visual inspection. It is, however, not yet fully operational and still in validation phase.
- In company B the visual inspection is carried out by two visual inspectors manually with the help of cameras and faults are declared accordingly by entering them in a visual inspection program.

**Improvement measures:**

- Company A wishes to execute inline quality control continuously to be able to perform immediate actions. Especially inline measurement of each gear of a weaving machine for parameters such as elongation and shrinkage.
- Company B wishes a 100 % monitoring through automatic detection using camera optics, in order to be able to quickly intervene on errors and take countermeasures to counteract them. It needs to be scientifically possible, cost-effective and efficient.

The current status and challenges associated with the quality control of manufacturing woven fabrics in both the companies are briefly summarized in Tab. 4.2.

Tab. 4.2: Comparison of the interviewed companies in woven fabric industry

| Step | Company A | Company B |
|---|---|---|
| **Purchase of yarn** | • No quality control before the production release<br>• Loom stoppages on a weekly basis | • Random quality control on a small volume of purchased yarn<br>• Lesser loom stoppages than Company A |
| **Warping and Weaving** | • Lack of inline control leads to detection of problem later in the following processes<br>• Machine parameters are not recorded automatically | • Measures temperature continuously with sensors and conducts a visual quality inspection manually<br>• Machine parameters are not recorded automatically |
| **Dyeing** | • Control of the fabric color manually | • Color inspection process both manually and with spectrophotometric testing device |
| **Finishing** | • Making/mixing of chemical agent is performed and controlled manually | • Not performed |
| **End inspection** | • Automatic Camera inspection for quality control, which is not yet fully operational and still in validation phase | • Manual camera inspection |
| **Improvement measures** | • Inline quality control especially for each gear of a weaving machine | • Cost effective, complete monitoring through automatic detection using camera optics |

### 4.2.3 Evaluation of the interview with Knitted fabric industry

In order to gain insights into the knitted fabric industry, two expert interviews are conducted. The end-products with the knitted fabrics of the interviewed company that are manufactured by the Tier 1 industries in the end are the following:

- Panoramic roofs,
- Interior fittings such as headliners and pillars cladding,

- B-pillars, bonnets, roofs, under floor protection materials, battery covers for sports cars and regular cars

Based on the interviews, the different steps of manufacturing processes involved are evaluated. The different steps include purchase of yarn, knitting, dyeing, finishing and end inspection. The steps are depicted in Fig. 4.6.

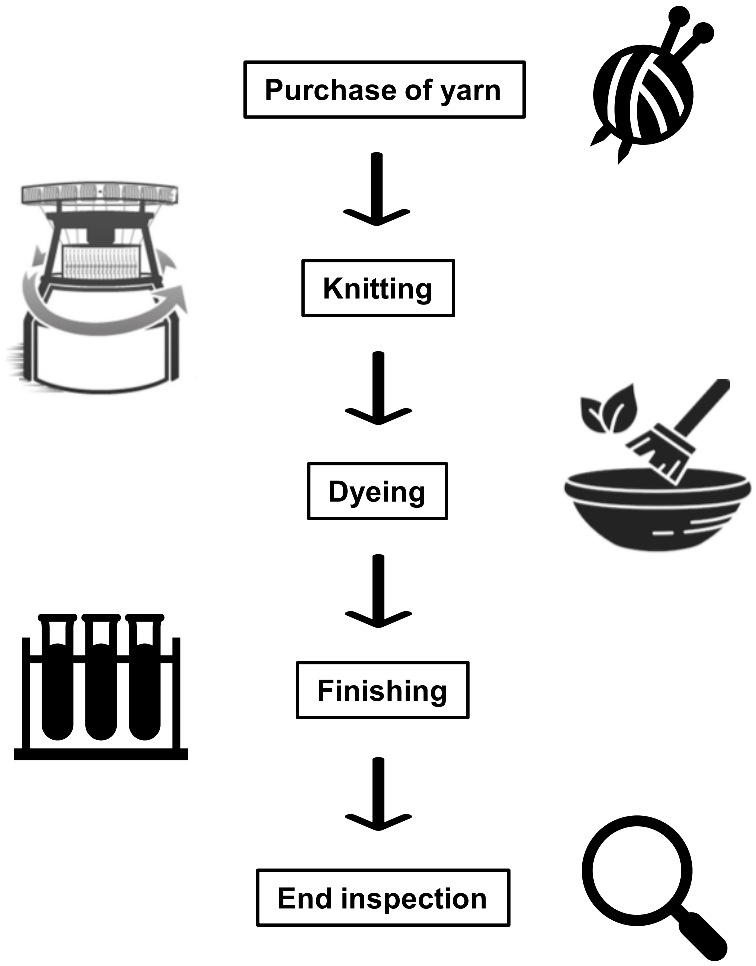



Fig. 4.6: Different steps of manufacturing knitted fabrics

To keep the internal data of each company anonymous, the companies are named as company C and company D. The current situation with the quality control in both the companies are compared and the potential for the introduction of digital quality control is identified in the following:

**Purchase of yarn:**

- Both the companies purchase yarn from a yarn manufacturer and rely entirely on them regarding quality control. In company C a random check of the quality of the yarn is performed, such as the fineness of the yarn, only when it is a customer requirement, since measuring a few meters of the bobbin is not very informative for the entire volume.

- In company D small scaled random tests are performed either to fulfill customer requirements or if problems due to the material of the yarn in the production cannot be assigned.

**Knitting:**

- The yarn is knitted into fabrics after the material is released for production. In company C the process is controlled by a machine operator. The settings of the machine and the properties of the material is measured at the beginning of the process by producing the first meters. Temperature and humidity are set and controlled in the hall. Contamination due to broken needles during the process is identified with a metallic object detector. Every other parameter is measured offline after the process, hence breaking of yarn and other errors are identified after the process. Depending on the amount of errors per unit area, the fabric is either cut and modified or rejected after knitting. Some general errors that occur are missing sewing thread, missing reinforcing thread, gaps in the scrim in the different layers and contamination.
- In company D on the other hand machine parameters for each of its article are predefined, which are then set up by an operator, and later checked and released by the shift supervisor before starting the process. Yarn tension is not measured individually because thousand yarns are lined up next to each other. But all the machine parameters are monitored. The machine independently monitors these parameters and corrects and regulates them. The company has an internally developed production data acquisition (PDA) software to which the machine is coupled, and the standard machine parameters are recorded. Furthermore, they have predefined stop reason mechanisms to track the reasons for stoppage continuously. Key operative figures are monitored on a daily basis. The hall is acclimatized, and the environmental parameters are monitored. Some of the typical errors are stripes formation and missing stitches. However, stripes formation is difficult to detect directly after knitting. It is visible and evaluable at the very end of the process after dyeing and finishing. Therefore, a camera based automatic visual inspection is not performed during knitting to detect the above-mentioned errors because both the errors are invisible to naked human eye during knitting and the camera system of the company can only detect errors visible to human eye.

The manufacturing process of knitting in company C and company D respectively is compared in the following Fig. 4.7. The points of comparison include the general defects, the current status of technology and the reason behind the limitation in the technology.

| | Knitting | |
|---|---|---|
| | **Company C** | **Company D** |
| **General defects** | • Missing sewing thread<br>• Missing reinforcing thread<br>• Gaps in the scrim in the different layers<br>• Contamination | • Vertical stripes<br>• Horizontal stripes<br>• Missing stitches |
| **Current status of technology** | • Machine parameters not recorded automatically<br>• Temperature and humidity set and controlled in the hall<br>• Metal detectors detect needle breakages<br>• Manual visual camera inspection | • Machine parameters recorded with PDA software<br>• Temperature and humidity set and controlled in the hall<br>• Predefined stop reason mechanisms to track the reasons for stoppage<br>• Automatic camera based visual inspection is not performed |
| **Reason** | • Lack of knowledge about the required competencies of the employees for implementing the digital solutions.<br>• Lack of IT support.<br>• Lack of knowledge about Big-data<br>• The products are interdisciplinary, hence difficulty in developing automated camera inspection | • The camera inspection automatically cannot detect errors, which are invisible to naked eye<br>• Since the defects are mostly invisible to naked eye right after knitting, therefore automatic camera inspection is not implemented |

Fig. 4.7: Comparison of knitting process between company C and D respectively

**Dyeing:**

- In company C there are no facilities of dyeing fabrics.
- In company D, defined color recipes are used for dyeing. A photo spectral testing device is used to control the quality of the color automatically.

**Finishing:**

- In company C there are no facilities for finishing.
- In company D, the finishing of the fabrics is performed to provide the technical properties on the fabric that the customer expects. For flame protection, chemicals are added by the employees manually. The employees are provided with step by step instructions from an automated manual for the addition of the chemicals.

**End inspection:**

- In company C, camera based visual inspection is used and monitored by the employees manually for the final inspection of the fabric. Machine learning based camera inspection is being developed since years. Since a lot of articles are manufactured, it is very difficult to develop a machine learning based camera inspection for each article that automatically identifies the error and classifies them.
- In company D, there are two steps of visual inspection. Firstly, an automated fabric inspection is performed where the material is photographed by cameras from different angles and the software background compares the images with the defect catalogue. Secondly, a manual inspection is performed where the material is photographed by cameras and monitored by the employees to target the defects detected in the first step automatically for confirmation. Subsequently, according to the customer requirements the defects are either marked and cut out or delivered to the customer with the markings for them to cut it. The company has a pilot project along with the cooperation of a machine manufacturer regarding machine learning based camera inspection. The machine manufacturer is developing the solution on its own machine with company D as a development partner. The solution is developed, tested and validated at the company premises. The solution is applicable for the most parts, however, it still needs the finishing touches of the experienced employees because of a huge variety of different articles or materials.

**Improvement measures:**

- Company C wishes to reduce the human influence and implement inline measurement as far as possible. However, the problem with inline measurement is the handling of the huge amount of data generated. Additionally, in the textile industry the structure of each technology is very interdisciplinary. Therefore, every company has to work for their own quality solution to get best results. Moreover, the combination of the experience of a textile expert and IT competence makes it difficult to develop the solutions.

- Company D on the other hand is comparatively very automated and wishes to have a better automated camera inspection system which also detects the errors not visible to human naked eye.

The current status and challenges associated with the quality control of manufacturing knitted fabrics in both the companies are briefly summarized in the following Tab. 4.3.

Tab. 4.3: Comparison of the interviewed companies in knitted fabric industry

| Steps | Company C | Company D |
|---|---|---|
| **Purchase of yarn** | • Random quality check when customer requires it | • Random quality check when either customer requires it or in case of a reclamation |
| **Knitting** | • Machine parameters not recorded automatically<br>• Temperature and humidity set and controlled in the hall<br>• Metal detectors detect needle breakages<br>• Manual visual camera inspection | • Machine parameters recorded with PDA software<br>• Temperature and humidity set and controlled in the hall<br>• Predefined stop reason mechanisms to track the reasons for stoppage<br>• Automatic camera based visual inspection is not performed |
| **Dyeing** | • No facilities | • Photo spectral testing device to control the quality of the color |
| **Finishing** | • No facilities | • Automated manual to guide employees' for addition of chemicals |
| **End inspection** | • Manual visual inspection with cameras | • ML based camera inspection as well as manual visual inspection |
| **Improvement measures** | • Inline measurement with data handling and required competences | • ML based camera inspection, where camera can detect errors human eye cannot detect. |

### 4.2.4 Evaluation of the interview with non-woven fabric industry

In order to gain insights into the non-woven fabric industry, three expert interviews are conducted. The end-products with the non-woven fabrics of the interviewed company that are manufactured by the Tier 1 industries in the end are the following:

- Automotive headliners, roof liners and boot liners
- Automotive carpets
- Tuft backing for automotive carpets
- Underbody panels and wheel liners
- Air filters and cabin filters
- Bonnets
- Parel shelves
- Dashboards
- Door/side panels

Based on the interviews, the different steps of manufacturing processes involved are evaluated. The different steps include purchase of yarn, web formation and web bonding. The steps are depicted in Fig. 4.8.


Fig. 4.8: Different steps of manufacturing non-woven fabrics

To keep the internal data of each company anonym, the companies are named as company E, company F and company G respectively. The current situation with the quality control in both the companies are compared and the potential for the introduction of digital quality control is identified in the following:

**Purchase of fiber:**

- In company E random quality control of fiber parameters such as diameter and weight, mechanical properties such as elasticity and tensile strength are performed and compared with the specification list of parameters tested by the supplier.
- In company F on the other hand an optical and humidity test for the viscose fibers along with random quality parameter test with the yarn manufacturer's specification list are performed. After having problems with the equipment due to moisture, which is visible through discoloration, both the tests were introduced. During the optical test, a complete visual check of the insides of each individual bale is not performed, rather it is bypassed from the outside to detect the presence of dirt, if the film is badly damaged and is manually monitored by employees without the use of cameras. This is because the

company does not have a developed solution for automatic camera inspection for testing the quality of purchased fiber. The moisture is measured with actual moisture meters for bales, in which two sample bars are screwed in and then with the help of electrical voltage the resistance is measured. On the basis of the material, it is then possible to draw conclusions about how moist the material is and then compared with specification list of the supplier.

- In company G quality control for the purchased yarn is not performed.

**Web formation and bonding:**

- In company E there are facilities for air-laid with carding and spun-laid web formation processes. Machine parameters for spun-laid machine such as quench air rate, air suction speed and venturi gap, collection speed, throughput, bonding temperature and pressure are not measured. Furthermore, it has facilities for mechanical (needle punching) and thermal (calendaring) web bonding processes. Automatic quality inspection with camera system is used to detect contamination, discoloration and stains at the surface of the nonwoven, and then marked manually. The product is either totally rejected or the defected part, that is marked, is cut separately depending on the number of defects. Radioactive measuring instruments with x-ray principle is used for inspecting surface weight and thickness continuously inline. The employee can check the changes in dimensions on the screen can take countermeasures directly. Offline quality tests for product parameters such as thickness, surface weight by weighing (gm/m$^2$) and tensile strength are performed after the process.
- In company F there are facilities for an air-laid web formation process and mechanical (needle punching, waterjet) bonding processes. One of the inspection systems during the process inline is the metal detection on every machine, because during needle punching process, the needles tend to break off. If a metal part is detected, the employee has a siren and must then find this piece of needle and mark or push it out. After the web bonding and finishing processes the non-woven fabric is controlled with an automatic visual inspection with cameras. The camera system has a self-learning algorithm, which classify errors such as contamination and deformities automatically. In case, the camera system is not able to detect or classify the detected error, manual inspection of the defect is performed. The hot chamber where the material is refined, the temperatures are recorded and stored. Moreover, Temperature is also controlled at every furnace. The temperature distribution is displayed on a monitor and controlled manually. Additionally, there are offline laboratory tests, where the test plan is followed by random tests for length, width, surface weight, thickness and strength.

- In company G there are facilities for thermal (calendaring) web bonding process. ML-based automatic camera inspection is performed to detect and classify foreign particles, machine faults and deformities. Moreover, magnetic metal detectors are used to identify broken needles during the process. Machine parameters are not recorded inline and are manually set and controlled by the employees.

The manufacturing processes of web forming and web bonding in company E, F and G respectively are compared in the following Fig. 4.9. The points of comparison include the general defects, the current status of technology and the reason behind the limitation in the technology.

| | **Web formation and Web bonding** | | |
|---|---|---|---|
| | **Company E** | **Company F** | **Company G** |
| **General defects** | • Contamination<br>• Discoloration<br>• Stains | • Contamination<br>• Deformities<br>• Broken needle | • Foreign particles<br>• Machine faults<br>• Deformities<br>• Broken needle |
| **Current status of techno-logy** | • ML-based automatic visual inspection with cameras<br>• Machine parameters are not recorded automatically | • ML-based automatic visual inspection with cameras<br>• Metal detector<br>• Machine parameters are not recorded automatically | • ML-based automatic visual inspection with cameras<br>• Metal detector<br>• Machine parameters are not recorded automatically |
| **Reason** | • The errors that occur can still be corrected at the Tier 1 level before they reach the car manufacturers. This could be the reason for not being entirely digitalized yet. | | |

Fig. 4.9: Comparison of web forming and web bonding processes between company E, F and G respectively

**Improvement measure:**

- Company E wishes to implement better statistical process control by monitoring quality influences during the process inline to gather the information rather than reworking afterwards.
- Company F wishes to implement automated thickness, fiber orientation, web guidance and width measurements of the fabric. Additionally, automated error control of bad edge cutting of knives is desired, which is done manually so far. That is, if the knives are not set properly or if they don't cut properly.
- Company G wishes to achieve a uniform structure and surface of the nonwoven. It also wishes radioactive or laser-based measuring instruments for inspecting surface weight and thickness continuously inline.

The current status and challenges associated with the quality control of manufacturing non-woven fabrics in the companies E, F and G respectively are briefly summarized in the following Tab. 4.4.

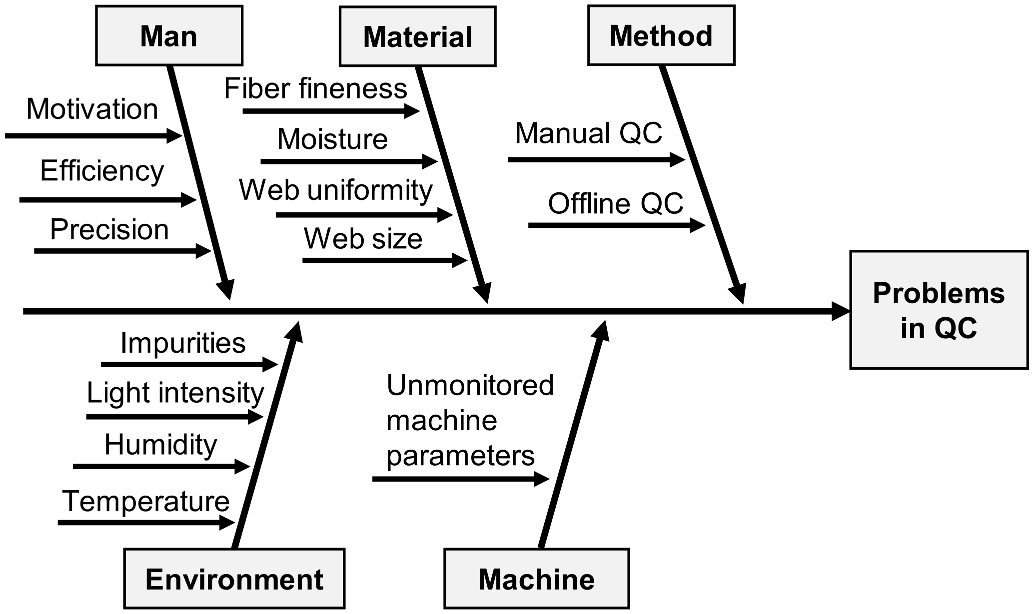
Tab. 4.4: Comparison of the interviewed companies in non-woven fabric industry

| Steps | Company E | Company F | Company G |
|---|---|---|---|
| **Purchase of yarn** | • Random quality control of fiber parameters | • Performs an optical and humidity test for the viscose fibers along with random quality parameter test | • Does not perform any quality control |
| **Web formation and bonding** | • Machine parameters not recorded automatically<br>• ML-based automatic visual inspection with cameras<br>• Radioactive measuring instruments with x-ray principle is | • Machine parameters not recorded automatically<br>• ML-based automatic visual inspection with cameras<br>• Inline metal detection on every machine to detect | • Machine parameters not recorded automatically<br>• ML-based automatic visual inspection with cameras<br>• Magnetic metal detectors are used to identify broken needles |

| | | | |
|---|---|---|---|
| | used for inspecting surface weight and thickness continuously inline<br>• Offline quality tests for product parameters after the process | needle breakage<br>• Temperature is also controlled at every furnace<br>• Offline laboratory tests | |
| **Improve-ment measures** | • Better statistical process control by monitoring quality influences during the process inline | • Automated thickness and width measurements of the fabric<br>• Automated error control of bad edge cutting of knives | • Uniform structure and surface of the nonwoven<br>• Radioactive or laser-based measuring instruments for inspecting surface weight and thickness continuously inline. |

## 4.3 Conclusion and Resume

The evaluation of the interviews with experts in woven, knitted and non-woven fabric industry has resulted in insightful information described in subchapter 4.2.2, 4.2.3 and 4.2.4 respectively. With the help of a cause effect diagram, the possible reasons which are the sources of problems in the process of quality control in woven, knitted and non-woven fabric industry are derived and depicted in Fig. 4.10.




*QC- Quality Control

Fig. 4.10: Cause effect diagram to derive the possible sources of problems in the process of quality control

The factors for environment such as temperature, humidity and light intensity have a huge influence on the quality of the fabric manufactured. At the same time, material parameters such as fineness, elongation, tensile strength and shrinkage need to be tested and controlled throughout the process and after the process to ensure the quality. Motivation, efficiency and precision are factors for the influence of man which are often the sources of problems. The involvement of these factors for manual process of quality control leads to problems. High precision and efficiency can be acquired by replacing the manual aspects in the process with automated processes such as machine learning based camera inspection and spectrophotometric devices. The machine parameters play a very essential role in the quality of the fabric produced. Manual setting and control of these parameters can lead to faulty settings resulting in fabric defects. The problems occurring in the manufacturing processes of woven, knitted, non-woven fabrics, that are gained through the expert interviews are summarized in Tab. 4.5. The company (A-F) facing the problems are assigned accordingly next to the problems. The problems without an assignment of a company are derived in general for the industry.

Tab. 4.5: Problems occurring in the manufacturing processes of woven, knitted and non-woven fabrics

| **Manufacturing of woven fabrics** | |
|---|---|
| **Process** | **Problems** |
| **Warping** | • Yarn breakage due to poor yarn quality (A, B)<br>• Yarn breakage due to temperature and humidity (A, B) |
| **Weaving** | • Warp breaks due to manual setting of loom (A,B)<br>• Warp breaks due to insufficient humidity and temperature around loom sphere (A) |
| **After Weaving** | • Fabric errors due to machine parameters and dust/impurities (A,B) |
| **Dyeing and Finishing** | • Faults due to wrong temperature (A)<br>• Faults due to wrong chemical agent (A)<br>• Faults due to wrong speed of conveyer belt (A) |
| **End inspection** | • Faults due to color fastness (A)<br>• Faulty fabric color (A) |
| **Manufacturing of knitted fabrics** | |
| **Process** | **Problems** |
| **Before Knitting** | • Yarn breakage due to poor yarn quality (C,D)<br>• Yarn breakage due to temperature and humidity |
| **Knitting** | • Faults due to no unmonitored machine parameters (C) |
| **After Knitting** | • Fabric errors due to machine parameters and dust/impurities (C)<br>• Stitching faults (C,D)<br>• Contamination due to broken needles (C) |
| **Dyeing and Finishing** | • Faults due to wrong temperature<br>• Faults due to wrong chemical agent<br>• Faults due to wrong speed of conveyer belt |
| **End inspection** | • Faults due to color fastness<br>• Faulty fabric color |

| Manufacturing of non-woven fabrics | |
|---|---|
| **Process** | **Problems** |
| **Purchase of fiber (before manufacturing)** | • Poor quality of fiber (E,F)<br>• Presence of moisture (E,F) |
| **Web formation and bonding** | • Faults due to the moisture content in the web<br>• Influence of temperature and humidity on web<br>• Faults due to the fiber orientation (E,F,G)<br>• Faults due to change in the surface weight of the web (E,F,G)<br>• Faults due to change in the web size (E,F,G)<br>• Faults due to improper web guidance |
| **End inspection (after manufacturing)** | • Fabric errors due to discoloration and contamination by dust/impurities (E,F,G)<br>• Fabric errors due to broken needles (E,F,G) |

The hypothesis according to [CMG+17] says that no efforts of the machine or fabric producers to implement industry 4.0 solutions in the non-woven production is currently visible. It is partly fulfilled since none of the non-woven fabric producers have introduced the concept of big data analytics. However, the introduction of ML-based camera inspection shows signs of motivation to introduce industry 4.0 solutions.

The graph in Fig. 4.11 compares the extent to which the companies interviewed for this thesis are digitalized. A total number of eight companies are interviewed out of which machine learning based quality control solution to detect errors automatically is possessed by only four companies (Company D,E,F and G). A production data acquisition software is used by one company (Company D) to measure and monitor the important parameters continuously. Two companies (Company A and yarn manufacturing company) are attempting on developing digital solutions internally whereas two companies (Company B and C) have absolutely no digital solutions for quality control.

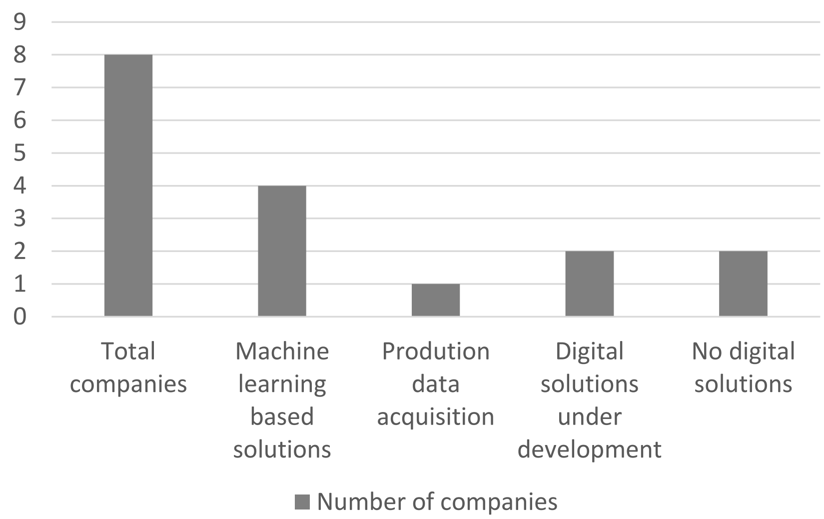



Fig. 4.11: Comparison of all the companies regarding digitalization in quality control

The reasons for the obstacles to the digitalization of the textile industry determined from the interviews conclude the following:

- No desire to change the status quo.
- The errors that occur can still be corrected at the Tier 1 level before they reach the car manufacturers. So, less desire for better quality control.
- Low customer requirements.
- Main focus is not automotive textiles, therefore economically not feasible to invest in the betterment of the existing quality control for automotive textiles.
- Lack of knowledge about the digital solutions available on the market and their potential.
- Lack of knowledge about the implementation of these digital solutions.
- Lack of knowledge about the required competencies of the employees for implementing the digital solutions.
- Lack of IT support.
- Fear due to lack of knowledge about Big-data or the use of data.
- Fear about the feasibility of the solutions.
- The products are interdisciplinary, hence more trust in experienced employees in comparison to digital solutions such as ML-based camera inspection.

# 5 Development of the decision tool

The aim of this chapter is to develop a decision tool to select appropriate solutions and measuring principles for the problems occurring during the manufacturing processes of technical textiles fabric in the automotive industry. Firstly, based on the problems gained in the previous chapter through market analysis in the form of expert interviews, the solutions and measuring principles for quality control in the manufacturing of technical textiles are identified. Subsequently, based on the identified solutions and measuring principles, the concept for a decision tool is designed.

## 5.1 Identification of the quality control solutions and measuring principles

In the following subchapters the suitable sensors and solutions for each of the industries i.e., woven, knitted and non-woven fabric industry respectively are derived. The focus of the solutions and measuring principles lies on inline quality control with the help of sensors, to identify the error promptly during the process of manufacturing in order to take proper countermeasures. The data recorded with the sensors can be collected with the help of an Internet of things (IoT) gateway.

### 5.1.1 Identification of solutions and measuring principles for the woven fabric industry

The problems in the woven fabric industry are identified with the help of the expert interviews. Similarly, the occurrence of these problems i.e., either during the process or in between processes, is also determined. These problems are depicted in Fig. 5.1.

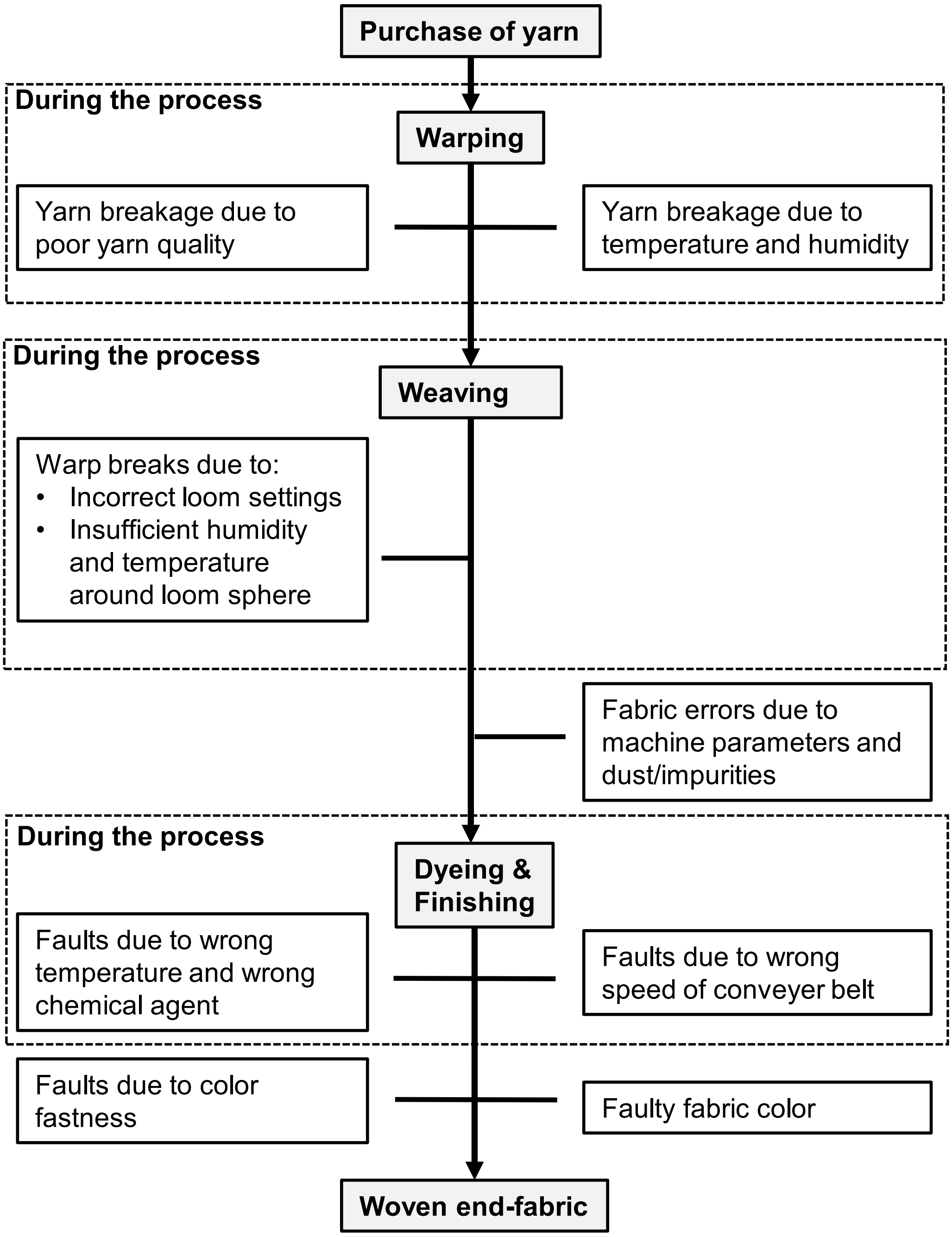



Fig. 5.1: Simplified illustrations of the problems occurring in the manufacturing of woven fabrics

The problems identified in the woven fabric industry and the subsequent solutions and measuring principles to monitor these problems are discussed in the following individually for each manufacturing step:

- **Warping:**


Fig. 5.2: Process location: Warping (woven fabric)

As shown in Fig. 5.2, the process of warping takes place after the purchase of yarn and before weaving. One of the reasons acquired in the expert interviews for the breakage of yarn is the poor quality of the yarn. Continuing the operation of the machine in spite of broken yarn can result in poor quality of fabric. It also leads to high loss of machine efficiency, since the reparation of the defect and subsequent restart of the machine costs time. Therefore, it is necessary for the yarn breakage to be sensed on time in order to stop the machine. Sensors of various principles can be used to sense the breakage of yarn. [MDA+12]
Capacitive sensors are used to detect magnetically and electrically conductive objects. The sensors work contact-free. They monitor the tension variations produced by the electrical charges into the yarn in linear motion. [www20i]
Optical sensors are used to control the presence of the yarn contact-free during motion. These sensors use include automatic camera inspection in which continuous nominal/actual value comparison between the pre-set and actual number of yarn is performed [www20r]. They also use the principle of infrared beam to monitor the presence of yarn. [www20i]
Electromechanical sensors are also used to detect the breakage of the yarn. They monitor the strength of the running yarn and mechanical changes in the strength due to yarn breakage are transformed into electrical signals. [www20i]
Piezo-electric sensors can be used to monitor the final yarn output. It measures the vibration of the yarn and identifies the deviations leading to defects promptly. [www20d, www20i]
Optical sensors can also be used to monitor the visual appearance of the yarn by monitoring yarn properties such as yarn shape and hairiness, and at the same time help analyze the presence of foreign fibers in the yarn [SBL04, www20p].
The characteristics of the various sensors according to [SBL04, www20d, www20i, www20p] used to monitor the yarn properties and defects are described in Tab. 5.1. For problems like yarn breakage, where there are more than one measuring principle available to detect the error, a concept for

selecting the suitable measuring principle is described in the following subchapter 5.2.

Tab. 5.1: Comparison of sensors used to monitor yarn properties and defects according to [SBL04, www20d, www20i, www20p]

| | Capacitive | Optic | Electro-mechanical | Piezo-electric |
|---|---|---|---|---|
| **Position** | Input | Input | Input | Output |
| **Principle** | Contact-free | Contact-free | Contact | Contact |
| **Function** | Presence of yarn | Presence of yarn, Visual check of yarn properties and errors | Presence of yarn | Presence of yarn |

Moreover, the influence of environmental parameters such as temperature and humidity affects the quality of yarn by influencing properties such as dimensions, weight, tensile strength, elastic recovery and rigidity. [PM16, www20i]
Temperature sensors are used for process monitoring. If the measured temperature deviates from a defined target temperature, a warning message is sent by SMS or e-mail to a person responsible for the process. Similarly, the capacitive-type sensor is used to monitor humidity. The working principle involves detection of changes in relative permittivity by adsorption of water, since water has an abnormally large dielectric constant. [Ber13, FJ16]
The problems along with the solutions and measuring principles to monitor these problems are summarized in Tab. 5.2.

Tab. 5.2: Problems along with corresponding solutions and measuring principles during warping (Cited above in the previous paragraphs)

| Warping | |
|---|---|
| **Problems** | **Solutions and Measuring Principles** |
| Yarn breakage (input) | Capacitive sensors |
| | Optical sensors |
| | Electromechanical sensors |
| Yarn breakage (output) | Piezo-electric sensors |
| Foreign fibers in yarn | Optical sensors |
| Environmental influence | Temperature, Humidity sensors |

- **Weaving:**

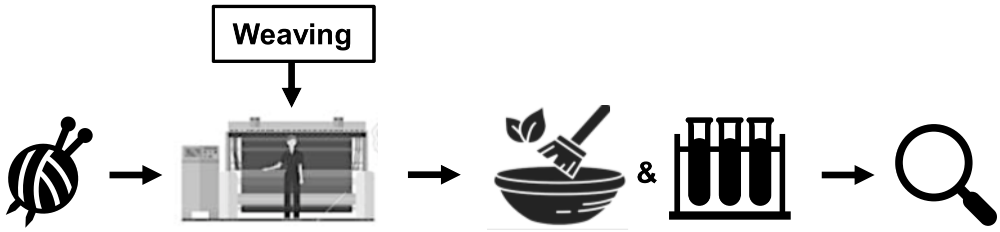



Fig. 5.3: Process location: Weaving (woven fabric)

As shown in Fig. 5.3, the process of weaving takes place after warping. General problems during the process of weaving include incorrect weaving loom settings, influence of weaving loom temperature and vibration as well as weave room conditions. [MDA+12]

To minimize the human influenced error, digital assistance system can be integrated to provide tailored operating procedure and work instructions as well as suggest optimal machine settings to machine operators. This can help minimize the errors due to incorrect weaving loom settings. [KPG17, www20q]

Vibration sensors such as piezo-electric sensors and are often used for monitoring the machine vibration, since increased vibrations are a frequent side effect of machine wear. Similarly, machine temperature can also be measured with temperature sensors. [Mat18]

Temperature and humidity sensors can be used to monitor the environmental influence on the process of weaving. [Ber13, FJ16]

- **After Weaving:**

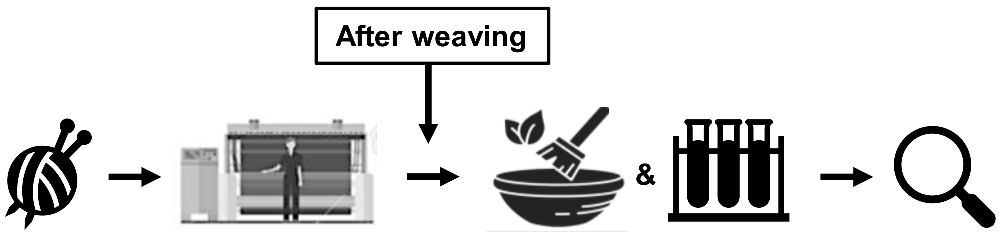



Fig. 5.4: Process location: After Weaving (woven fabric)

The problems with the woven fabric after being manufactured in the process of weaving (see Fig. 5.4), that are acquired in the expert interviews include elongation, shrinkage, start-up marks as well as faults due to dust/contamination.

Machine learning based automatic camera inspection can be used to detect and classify the fabric errors. The machine learning algorithm can be trained specifically for the above mentioned errors, in order to make it able to detect the errors automatically. [www20t]

The problems along with the solutions and measuring principles to monitor the above mentioned problems during and after the process of weaving are summarized in Tab. 5.3.

Tab. 5.3: Problems along with corresponding solutions and measuring principles during and after weaving (Cited above)

| Weaving | |
|---|---|
| **Problems** | **Solutions and Measuring Principles** |
| Incorrect loom setting | Digital assistance system |
| Machine vibration | Piezo-electric sensors |
| Machine temperature | Temperature sensors |
| Environmental influence | Temperature sensors |
| | Humidity sensors |
| **After Weaving** | |
| **Problems** | **Solutions and Measuring Principles** |
| Fabric errors | Machine learning based automatic camera inspection |

- **Dyeing and Finishing:**

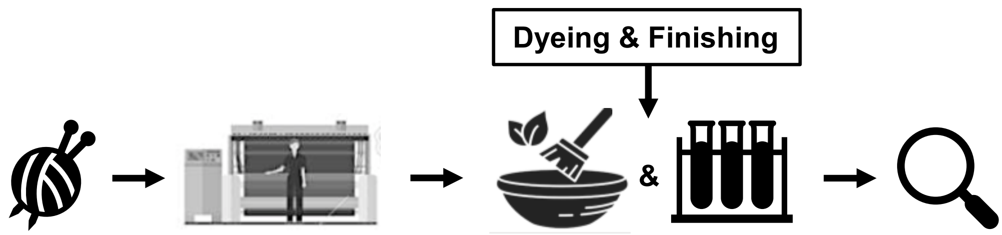



Fig. 5.5: Process location: Dyeing and Finishing (woven fabric)

Problems faced by the interviewed companies during dyeing and finishing (see Fig. 5.5) include faults due to wrong temperature as well faults due to the usage of wrong chemical agent by the employees. Moreover, faulty setting of the speed of conveyer belt also leads to error.

Similar to the process of weaving, the above mentioned human influenced error can be minimized with the help of a digital assistance system that provides tailored operating procedures and work instructions as well as suggests optimal machine settings to machine operators. [KPG17, www20q]

Temperature and humidity sensors can be used to monitor the environmental influence on the process of dyeing and finishing [Ber13, FJ16].

- **End inspection:**


Fig. 5.6: Process location: End inspection (woven fabric)

Common problems faced during the end inspection (see Fig. 5.6) include shrinkage of the fabric, damaged elongation properties of the fabric as well as fault in the color of the fabric.
The color of the fabric can be controlled with a spectrophotometer and a software to measure, analyze, and visualize accurate color results [www20g].
Machine learning based algorithm can be developed and used with high resolution camera to detect and classify these errors automatically inline during the end inspection [www20t].
The problems along with the solutions and measuring principles to monitor the above mentioned problems during and after the process of dyeing and finishing are summarized in Tab. 5.4.

Tab. 5.4: Problems along with corresponding solutions and measuring principles during and after dyeing and finishing (Cited above)

| **Dyeing and Finishing** | |
|---|---|
| **Problems** | **Solutions and Measuring Principles** |
| Wrong temperature setting | Digital assistance system |
| Wrong usage of chemical agent | |
| Wrong speed setting of conveyer belt | |
| Environmental influence | Temperature sensors |
| | Humidity sensors |
| **End inspection** | |
| **Problems** | **Solutions and Measuring Principles** |
| Faulty fabric color | Spectrophotometer |
| Fabric error | Machine learning based automatic camera inspection |

### 5.1.2 Identification of solutions and measuring principles for the knitting industry

The problems in the knitting industry are identified with the help of the expert interviews. Similarly, the occurrence of these problems i.e., either during the process or in between processes, is also determined. These problems are depicted in Fig. 5.7.

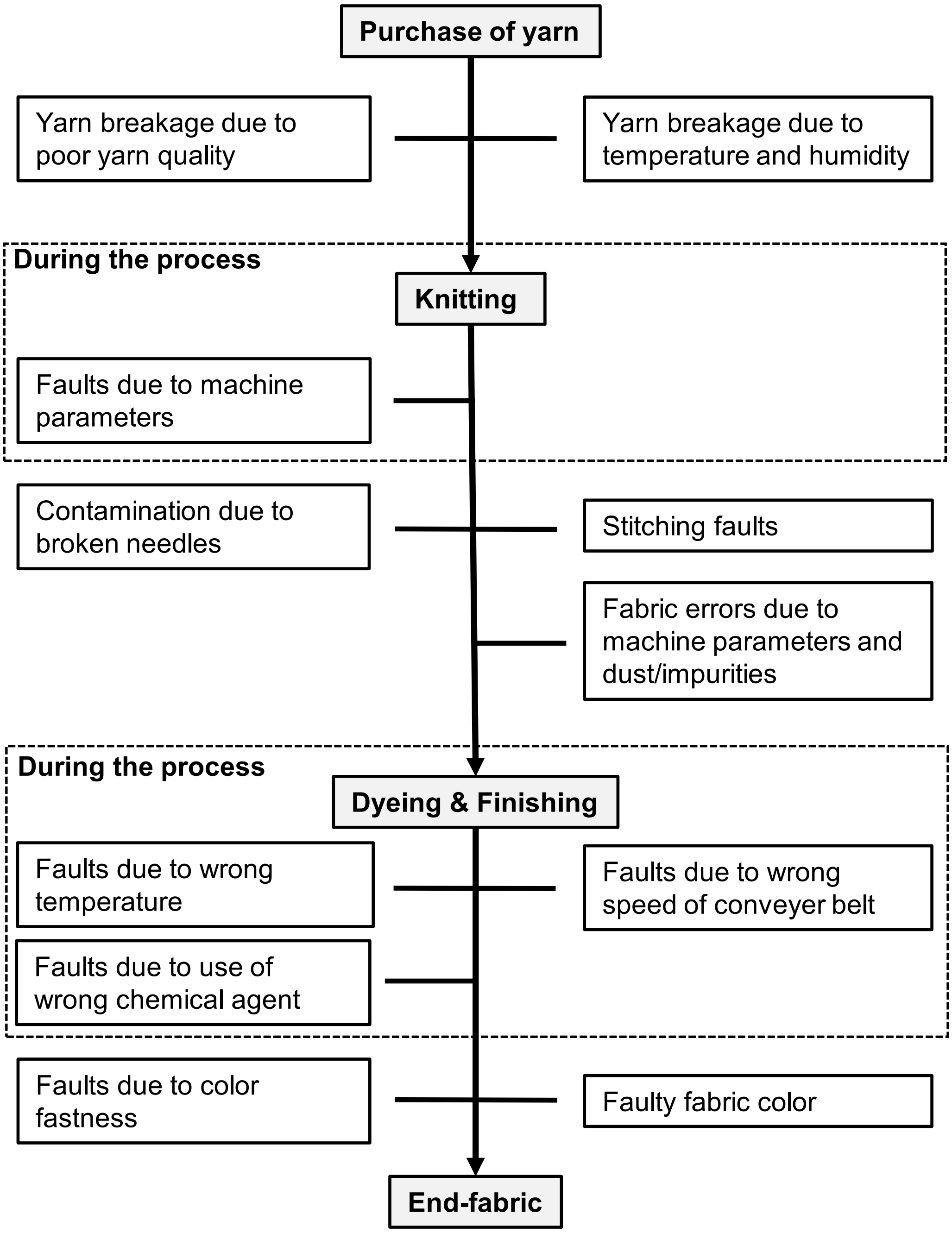



Fig. 5.7: Simplified illustration of the problems occurring in the manufacturing of knitted fabrics

The problems identified in the knitting industry and the subsequent solutions and measuring principles to monitor these problems are discussed in the following individually for each manufacturing step:

- **Prior to knitting:**


Fig. 5.8: Process location: Prior to Knitting (knitted fabric)

Analog to weaving industry, the common problems after the purchase of yarn and prior to knitting (see Fig. 5.8) are the poor quality of yarn and environmental influence on the yarn. The presence of yarn can be monitored with capacitive, optical, electromechanical and piezo-electric sensors whereas the environmental factors can be monitored with temperature and humidity sensors respectively. [Ber13, FJ16, www20d, www20i]

- **Knitting:**


Fig. 5.9: Process location: Knitting (knitted fabric)

To minimize the human influenced error during the process of knitting (see Fig. 5.9), a digital assistance system that provides tailored operating procedures and work instructions as well as suggests optimal machine settings to machine operators. [KPG17, www20q]. Temperature and humidity sensors can be used to monitor the environmental influence [Ber13, FJ16]. Machine vibration and machine temperature can be measured with vibration sensors such as piezo-electric sensors and temperature sensors respectively [Mat18].

- **After knitting:**

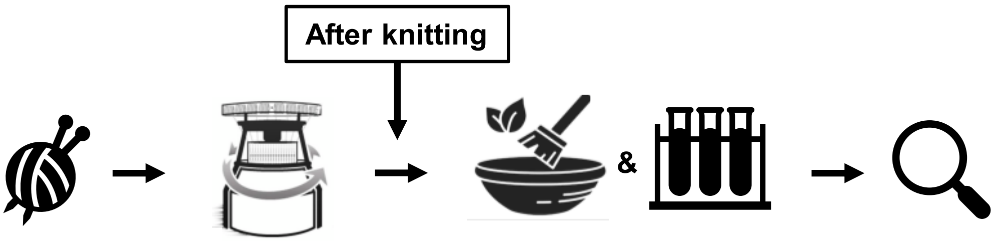



Fig. 5.10: Process location: After Knitting (knitted fabric)

The problems occurring after the process of knitting (see Fig. 5.10) that are acquired through expert interviews are missing sewing thread, missing reinforcing thread, gaps in the scrim in the different layers, contamination, vertical stripes and horizontal stripes. Machine learning based algorithm can be developed and used with high resolution camera to detect and classify the above mentioned fabric errors automatically inline [www20t]. Differing loop length of the stitch due to variation in yarn tension can be controlled with image processing techniques [MDA+12]. Furthermore, metal detector can be used in line to detect the broken needles after the process of needle punching. [www20w]

- **Dyeing and Finishing:**

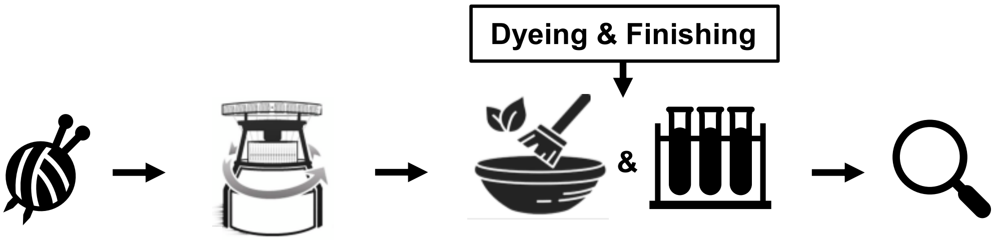



Fig. 5.11: Process location: Dyeing and Finishing (knitted fabric)

Analog to the weaving industry, the common problems during the process of dyeing and finishing (see Fig. 5.11) are faulty selection of chemical agent as well as faulty settings of temperature on one hand and the environmental influence on the other. Digital assistance system as well as temperature and humidity sensors respectively can be integrated in the process to tackle the problems. [Ber13, FJ16, KPG17]

- **End inspection:**

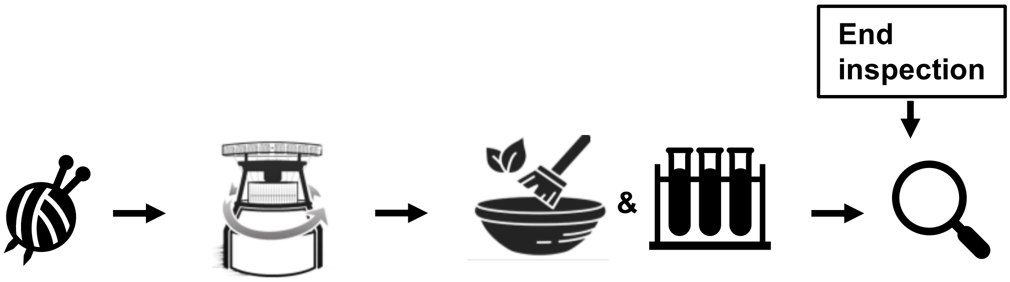



Fig. 5.12: Process location: End inspection (knitted fabric)

According to the expert interview with knitting fabric industry, most of the fabric errors that occur during the process of knitting are discovered after the process of dyeing and finishing at the end inspection (see Fig. 5.12). Machine learning based algorithm can be developed and used with high resolution camera to detect and classify these errors automatically inline [www20t]. Moreover, fault in the fabric color can be controlled with the help of a spectrometer [www20g].

The problems along with the solutions and measuring principles to monitor the above mentioned problems in the knitting industry are summarized in Tab. 5.5.

Tab. 5.5: Problems along with corresponding solutions and measuring principles in the knitting industry (Cited above)

| Problems | Solutions and Measuring Principles |
|---|---|
| **Prior to Knitting** | |
| Yarn breakage (input) | Capacitive sensors |
| | Optical sensors |
| | Electromechanical sensors |
| Yarn breakage (output) | Piezo-electric sensors |
| Foreign fibers in yarn | Optical sensors |
| Environmental influence | Temperature sensors |
| | Humidity sensors |
| **Knitting** | |
| Incorrect machine setting | Digital assistance system |
| Machine vibration | Piezo-electric sensors |
| Machine temperature | Temperature sensors |
| Environmental influence | Temperature sensors |
| | Humidity sensors |
| **After Knitting** | |
| Broken needles | Metal detector |

| | |
|---|---|
| Stitching fault | Image processing techniques |
| Fabric errors | Machine learning based automatic camera inspection |
| **Dyeing and Finishing** | |
| Wrong temperature setting | Digital assistance system |
| Wrong usage of chemical agent | |
| Wrong speed setting of conveyer belt | |
| Environmental influence | Temperature sensors |
| | Humidity sensors |
| **End inspection** | |
| Faulty fabric color | Spectrophotometer |
| Fabric error | Machine learning based automatic camera inspection |

### 5.1.3 Identification of solutions and measuring principles for the non-woven industry

The problems in the non-woven industry are identified with the help of the expert interviews. Similarly, the occurrence of these problems i.e., either during the process or in between processes, is also determined. These problems are depicted in Fig. 5.13.

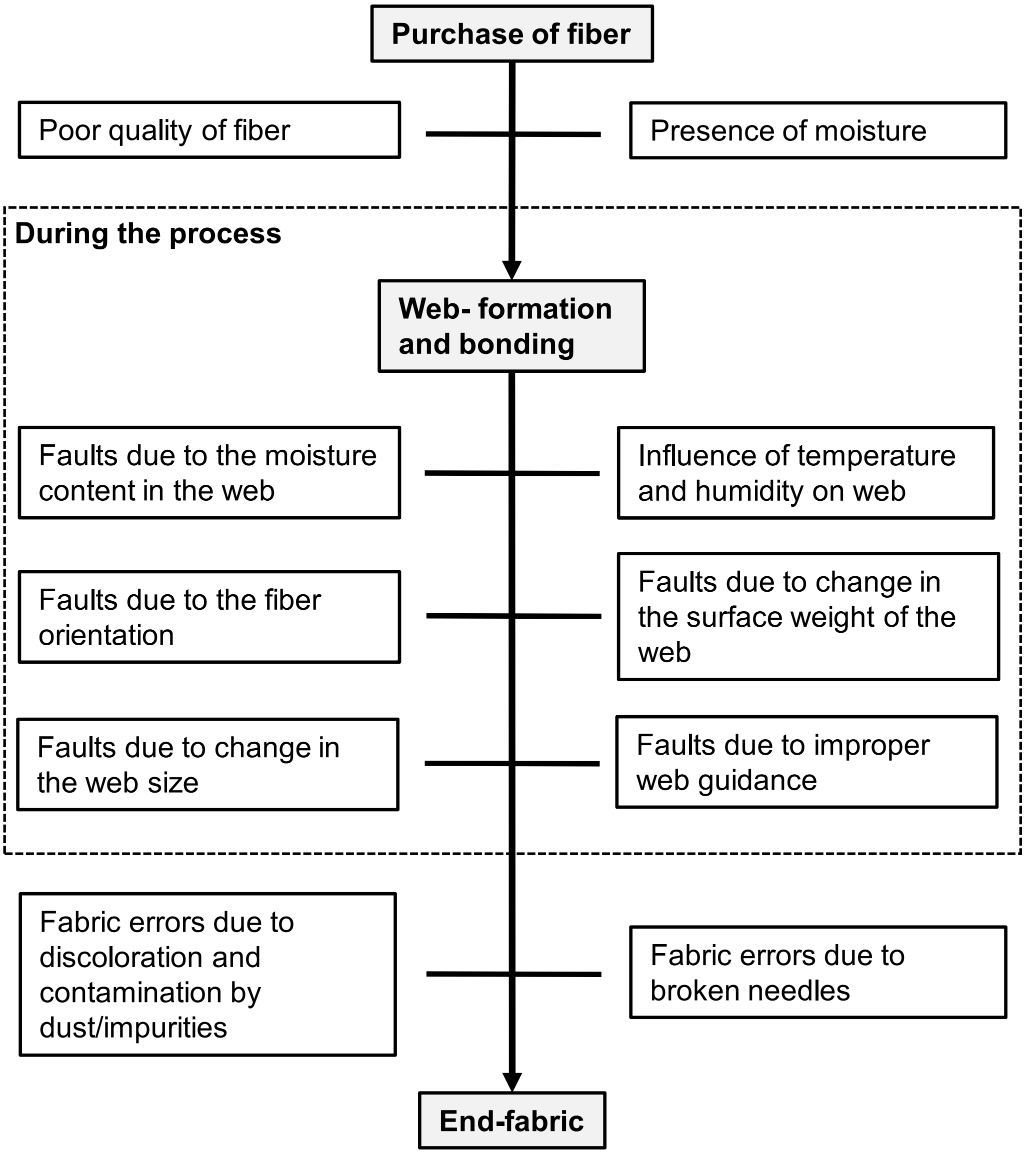



Fig. 5.13: Simplified illustrations of the problems occurring in the manufacturing of non-woven fabrics

The problems identified in the non-woven industry and the subsequent solutions and measuring principles to monitor these problems are discussed in the following individually for each manufacturing step:

- **Purchase of fiber:**
  According to the expert interviews, controlling the poor quality of the purchased fiber is a problem before releasing the fiber for manufacturing. The quality of the fiber can be controlled with infrared optical sensors and infrared sensitive cameras. Along with the development of an algorithm, the errors in the purchased fiber can be automatically detected. [www20o]

Furthermore, the moisture content in the fiber is another reason for problems later in the manufacturing of non-woven fabric. A capacitive measuring gate can be used to scan every bale passing through the gate to measure its moisture content. It generally consists of reference plates on top and bottom and measuring electrodes on both sides. [www20v]
The problems along with the solutions and measuring principles to monitor the above mentioned problems after the purchase of yarn before manufacturing are summarized in Tab. 5.6.

Tab. 5.6: Problems along with corresponding solutions and measuring principles after purchase of fiber (Cited above)

| **Purchase of fiber (before manufacturing)** | |
|---|---|
| **Problems** | **Solutions and Measuring Principles** |
| Poor quality of fiber | Infrared sensor |
| Moisture content in fiber | Capacitive measuring gate |
| Environmental influence | Temperature, Humidity sensors |

- **Web formation and bonding:**

According to the literature research and the expert interviews, problems during the process of web formation and bonding include faulty web parameters, machine parameters as well as environmental parameters. Web parameters such as web surface temperature, weight, thickness and width. Additionally, moisture in the web as well as the fiber orientation play an important role in the quality of the fabric. [ABS+07, Bo10, MPA13]

The moisture in the web can be measured with infrared sensors with the principle of infrared transmission and reflection, since water absorbs light in the infrared range and can be differentiated through different spectral range. Furthermore, the moisture content of the web can be measured with microwave resonance measurement by measuring the changes in the resonance frequency of the wave. [www20c]

The surface temperature of the running web can also be measured with the help of infrared sensors [www20h].
The fiber orientation along and across the machine direction is crucial for web characteristics such as strength and tenacity. With the help of a high resolution camera and specifically developed algorithm, that analyses frequency of the fiber position angle related to the machine- and cross directions, the fiber orientation can be calculated. [www20u]
Web weight can be measured with the help of M-rays, gamma backscatter, x-ray, beta gauge and infrared sensors. The concept of using M-rays to measure

web weight involves transmission of wireless waves through the web to derive the weight according to the delay in transmission. The principle of x-ray can be used to measure the weight of the web depending on the weakening of the intensity of the x-ray passing through the web. Similar, different isotopes can be used to generate beta rays and the weakening in the intensity of the beta rays passing through the web can be used to determine the weight. The weight of the web can also be measured with infrared sensors with the principle of infrared transmission and reflection. [www20c, www20x]

Whereas web thickness can be measured with the help of M-rays, x-ray, Beta gauge, infrared sensor and laser. The working principle of M-rays, x-ray, Beta gauge and infrared sensor is described above. Reflection of laser on the web material from both sides and by taking the distance of laser from the web material into account, the thickness of the web can be measured. [www20c, www20x]

Web width can similarly be measured with the help of infrared sensors [www20w].

The advantages and disadvantages of various measuring principles used to measure the same parameters are summarized in Tab. 5.7.

Tab. 5.7: Comparison of different measuring principles for measuring web parameters [www20c, www20j, www20x]

| Technique | Advantage | Disadvantage |
|---|---|---|
| **M-ray** | • Non-radioactive<br>• Works for high stand-off distances and very heavy materials | • Maximum measurable weight Up to 10000 gsm validated |
| **Beta gauge** | • Most precise technology | • No long lasting precision |
| **x-ray** | • Increased stability of high-voltage supplies | • Licensing related administration and costs |
| **Gamma backscatter** | • Material can be measured from a single side<br>• High-power nature | • Requires physical contact with the material, potentially introducing markings or leaving traces behind |
| **Infrared waves** | • Provides good stability over time | • Affected by hard objects, dust and sunlight |

Machine parameter such as properly guided movement of the web over the conveyer belt is crucial for the quality of the fabric. Electromechanical sensors can be used to detect the edges of the web on the conveyer belt in order to ensure guidance. Infrared sensors based on the principle of retroreflection can be used to determine the edges of the web as well. [www20w]

Environmental parameters such as temperature and humidity also play an important role in the quality of the fabric.Problems faced by the environmental parameters can be monitored with temperature and humidity sensors respectively. [Ber13, FJ16]

The problems along with the solutions and measuring principles to monitor the above mentioned problems during the process of web formation and bonding are summarized in Tab. 5.8.

Tab. 5.8: Problems along with corresponding solutions and measuring principles during web formation and bonding (Cited above)

| **Web formation and bonding** | |
|---|---|
| **Problems** | **Solutions and Measuring Principles** |
| **Web parameters** | |
| Surface temperature of web | Infrared sensor |
| Moisture content in web | Infrared sensor |
| | Microwave resonance measurement |
| Fiber orientation | High resolution camera with an specifically developed algorithm |
| Web weight | M-ray |
| | Gamma backscatter |
| | x-ray |
| | Beta gauge |
| | Infrared sensor |
| Web thickness | M-ray |
| | x-ray |
| | Beta gauge |
| | Infrared sensor |
| | Laser |
| Web width | Infrared sensor |
| **Machine parameter** | |
| Web guidance | Electromechanical sensor |
| | Infrared sensor |
| **Environmental parameters** | |
| Environmental influence | Temperature, Humidity sensors |

- **End inspection:**
  According to the expert interviews with non-woven fabric industry, most of the fabric errors that occur after the process of web formation and bonding are contamination, discoloration, stains, foreign particles, deformities and broken needles. Machine learning based algorithm can be developed and used with high resolution camera to detect and classify these errors automatically inline [www20s]. Moreover, fault in the fabric color can be controlled with the help of a spectrometer. Furthermore, metal detector can be used in line to detect the broken needles after the process of needle punching. [www20w]
  The problems along with the solutions and measuring principles to monitor the above mentioned problems after the manufacturing of the fabric during the end inspection are summarized in Tab. 5.9.

Tab. 5.9: Problems along with corresponding solutions and measuring principles during end inspection (Cited above)

| **End inspection (after manufacturing)** | |
|---|---|
| **Problems** | **Solutions and Measuring Principles** |
| Broken needles | Inline metal detector |
| Faulty fabric color | Spectrophotometer |
| Fabric error | Machine learning based automatic camera inspection |

Based on the problems acquired through the expert interviews, the solutions and measuring principles to monitor these problems have been identified. The problems along with the solutions and measuring principles are categorized in respect to the corresponding manufacturing process. An overview of all the acquired problems and their corresponding identified solutions and measuring principles is summarized in Tab. 9.3. A schematic depiction of the working principles of the sensors discussed above is shown in Fig. 9.1 and Fig. 9.2.

## 5.2 Concept design for the decision tool

This chapter describes the concept of a decision tool to select appropriate solutions and measuring principles according to the problems occurring during the manufacturing of technical textiles in the automotive industry. The problems are acquired with the help of market analysis through expert interviews with various companies. The tool is divided in four different steps of finding the solution. The first step includes identification of the end-product i.e., woven, knitted or non-woven end-product, in which a problem is being faced during its manufacturing. It is followed by the second step in which the manufacturing process facing the problem is identified. The third step includes the identification of the problem associated with the chosen manufacturing process. It is followed by the fourth step in which the criteria to choose a suitable solution is included. Finally after having chosen the criteria, the solution for the chosen problem is provided by the tool. The structure of the steps with the appropriate question is depicted in Fig. 5.14.

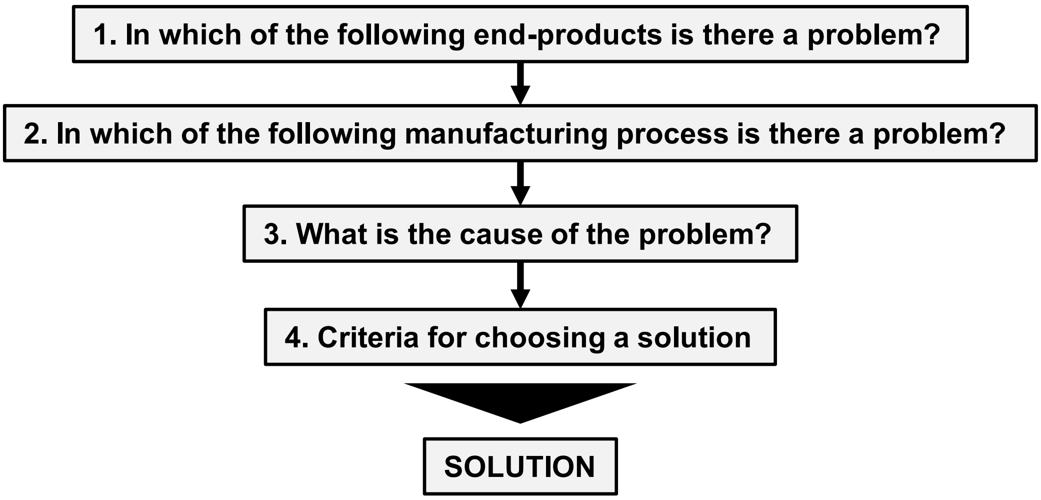



Fig. 5.14: The four steps of the decision tool

The following Fig. 5.15 provides the graphical overview for the first three steps of the tool. The first step allows the user to choose the end-product, that is facing a problem. The context of this thesis consists of three different manufacturing industry namely woven, knitted and non-woven industry. Therefore, for the first question of the step one, the user is provided with the options of end-products that are woven, knitted or non-woven.

Having chosen the option of woven end-product, the step two provides the options of the processes involved in the manufacturing of the woven end-product. The options of manufacturing processes for woven end-products are acquired with the help of the expert interviews and include warping, weaving, dyeing and finishing, and end inspection. In this step, the user is required to select the process in which a problem is being faced.

After executing the first two steps of the problem and solution finding process, the problem facing end-product and the certain manufacturing process consisting of the problem has been narrowed down. In the third step, the user is provided with the option of choosing the cause of the problem occurring during the chosen manufacturing process. In this case, the causes of problems occurring during the process of warping include yarn breakage and environmental influence.

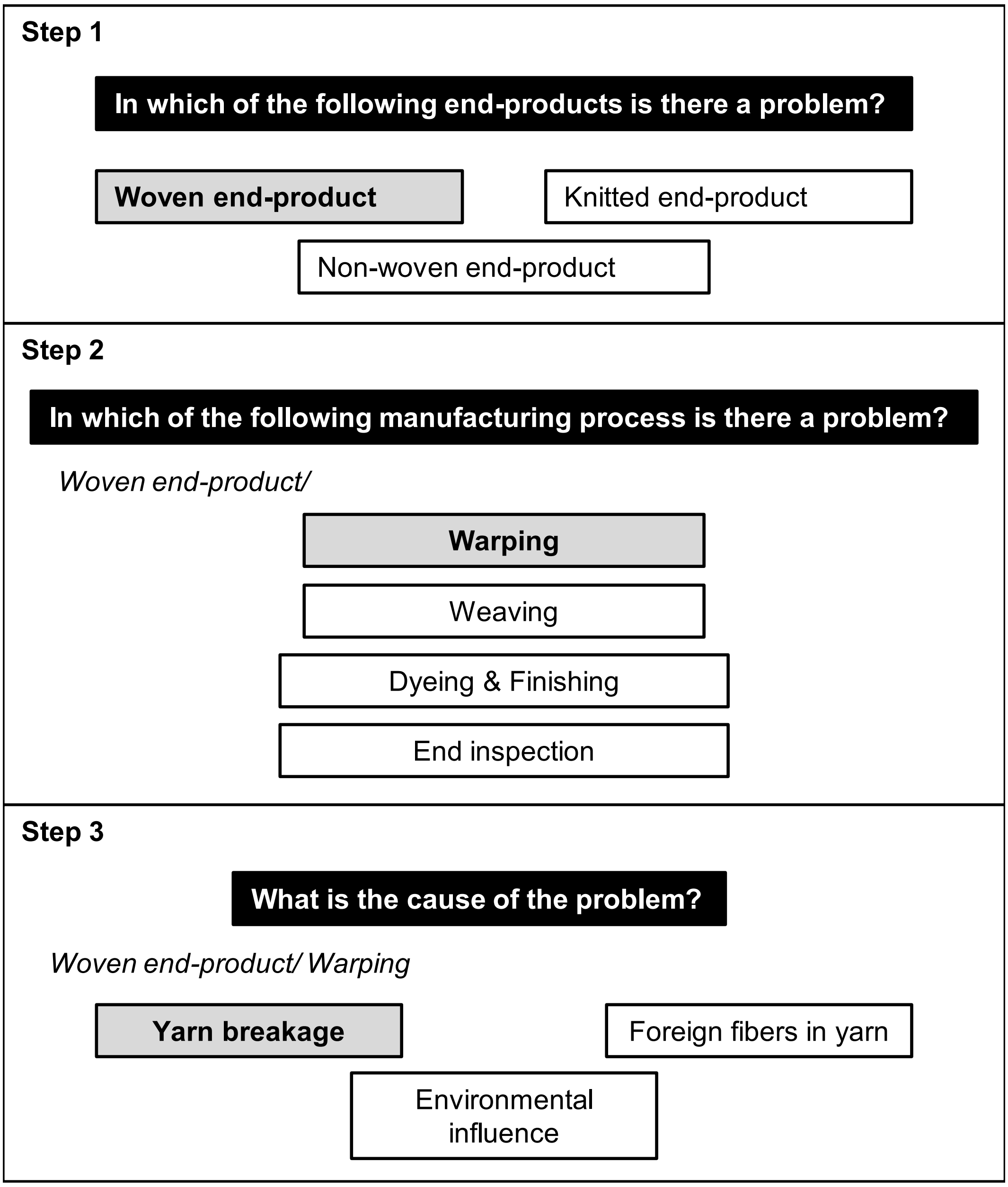



Fig. 5.15: The graphical overview for the first three steps of the tool

After having chosen the cause of the problem occurring during the process, the final step has the function of selecting the criteria for finding the appropriate solution for the problem. In this case, to monitor the problem of yarn breakage, various solutions can be used, as suggested in the previous subchapter. The criteria for this case include the position of usage and the principle of the solution. The monitoring of the breakage of yarn can be performed at two positions, production input and output. The presence of input yarn during the process is monitored with several yarn tension sensors such as capacitive-, optical- and electromechanical sensors. At the end of the process of warping, a vibration sensor on the warp beam allows deviations to be detected at an early stage. The principle of operation is either with contact of yarn or contact-free. The Fig. 5.16 depicts the selection of an appropriate solution based on two criteria, position and principle.

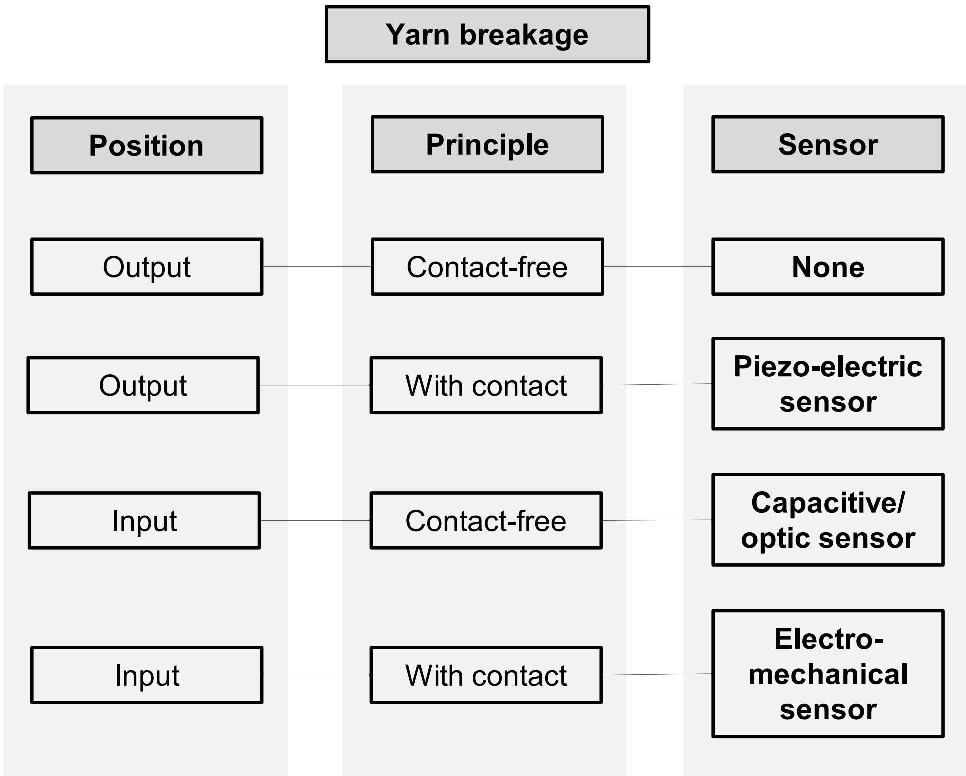



Fig. 5.16: Selection logic for solution based on two criteria

Based on the selection logic shown in the Fig. 5.16, the final step for the selection of the solution is carried out. With the integration of further quality parameters, problems and solutions in the future, a larger pool of hardware and software options will be available to choose from. The suggested concept can be helpful in selecting the appropriate option for the solution by defining more solution specific criteria. As shown in Fig. 5.17 the criteria for choosing the solution is questioned to the user. Based on the choice of the criteria, a suitable solution will be suggested. According to Fig. 5.17, the user chooses to monitor the presence of yarn at the production input and wishes to have a solution with a yarn contact. According to the logic described in the Fig. 5.16, the corresponding solution is electromechanical sensor. The suggestion for the solution in the tool can also be seen in the figure.

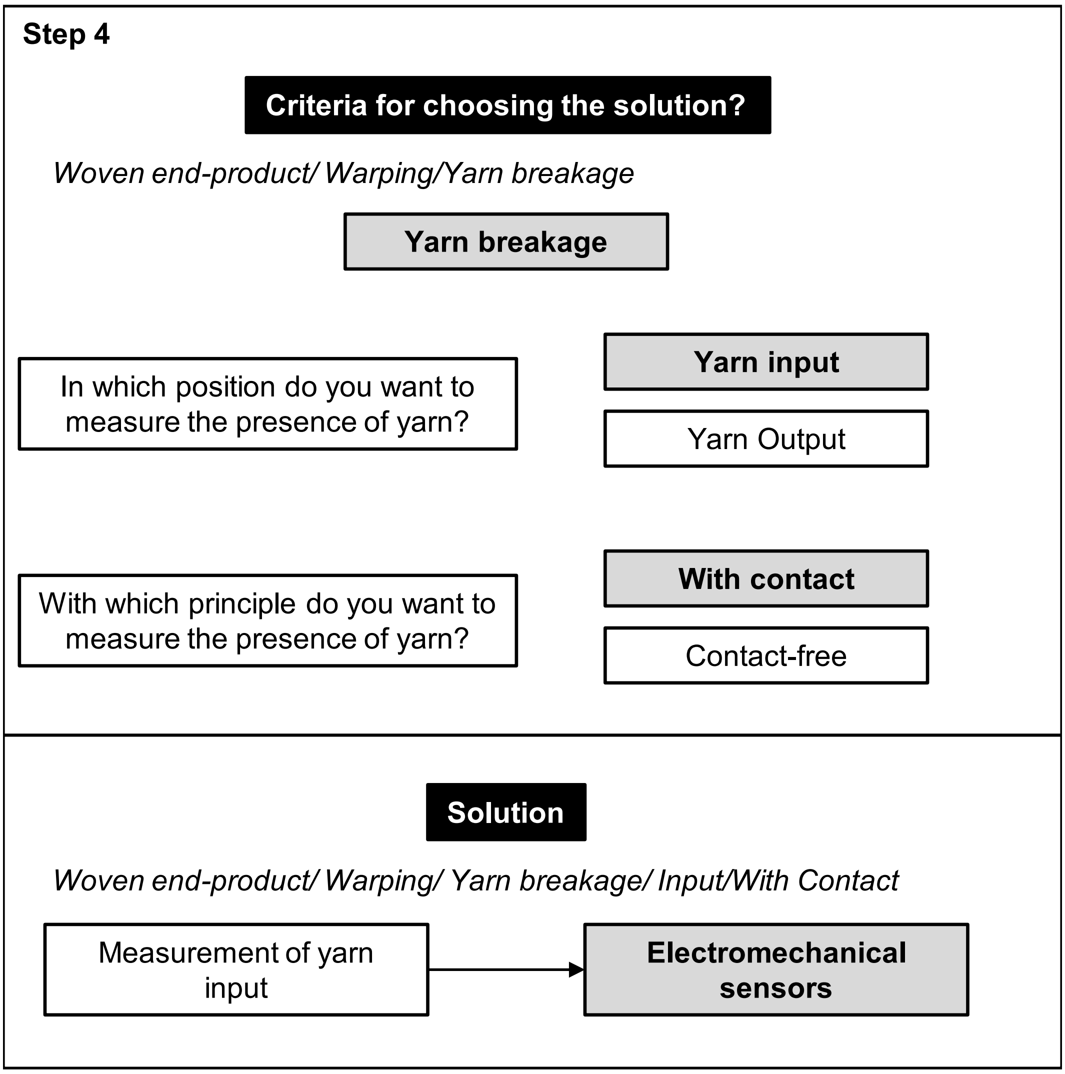



Fig. 5.17: The graphical overview for the final step of the tool

Similarly, the tool is designed for all the problems and their corresponding solutions described in subchapter 5.1. An overview of the entire decision tree for the concept including manufacturing processes, problems occurring in each of the processes and their corresponding solutions and measuring principles for woven, knitted and non-woven end-products can be seen in Fig. 5.18, Fig. 5.19 and Fig. 5.20 respectively.

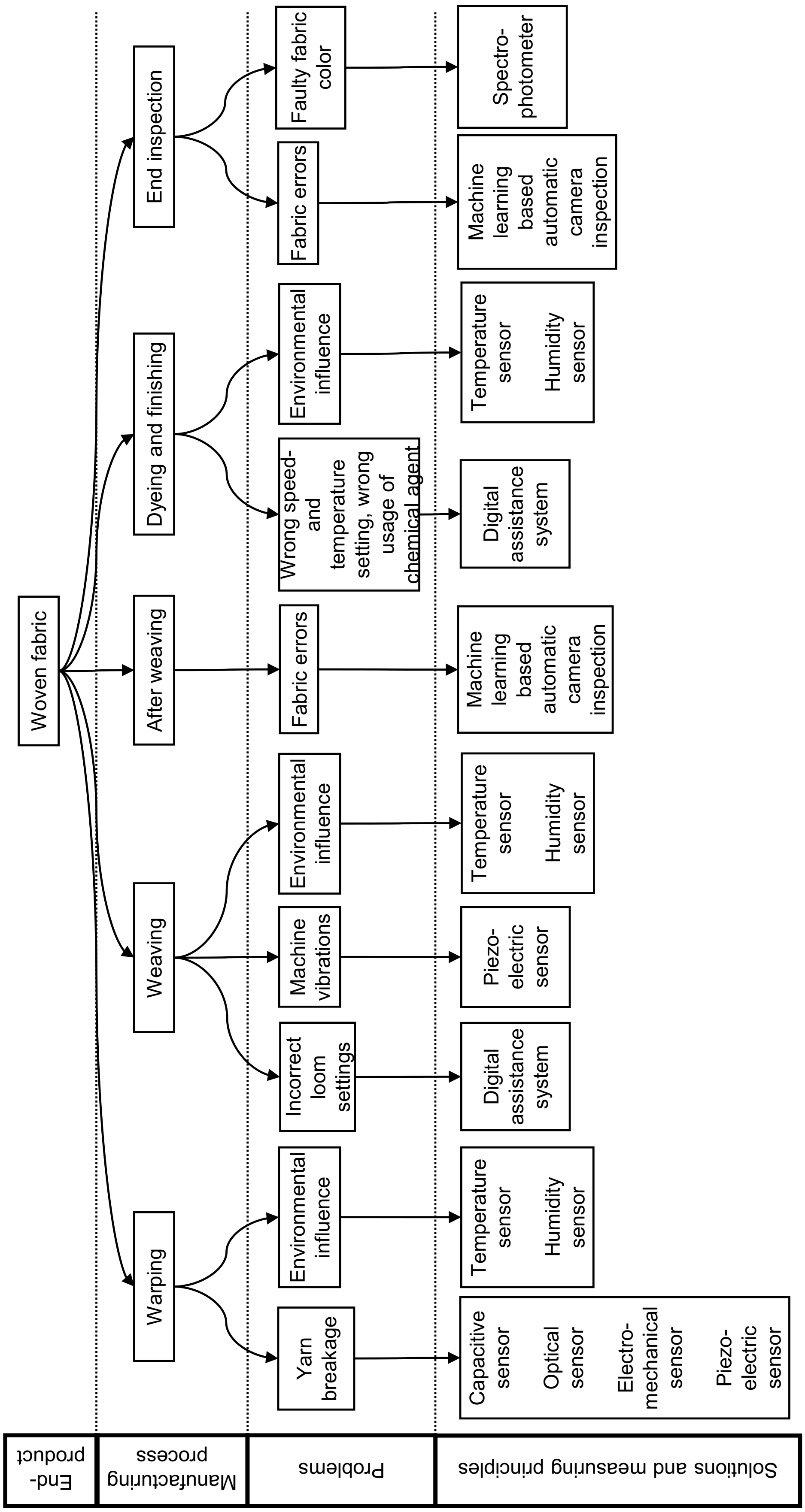



Fig. 5.18: Decision tree for selection logic in manufacturing of woven fabric

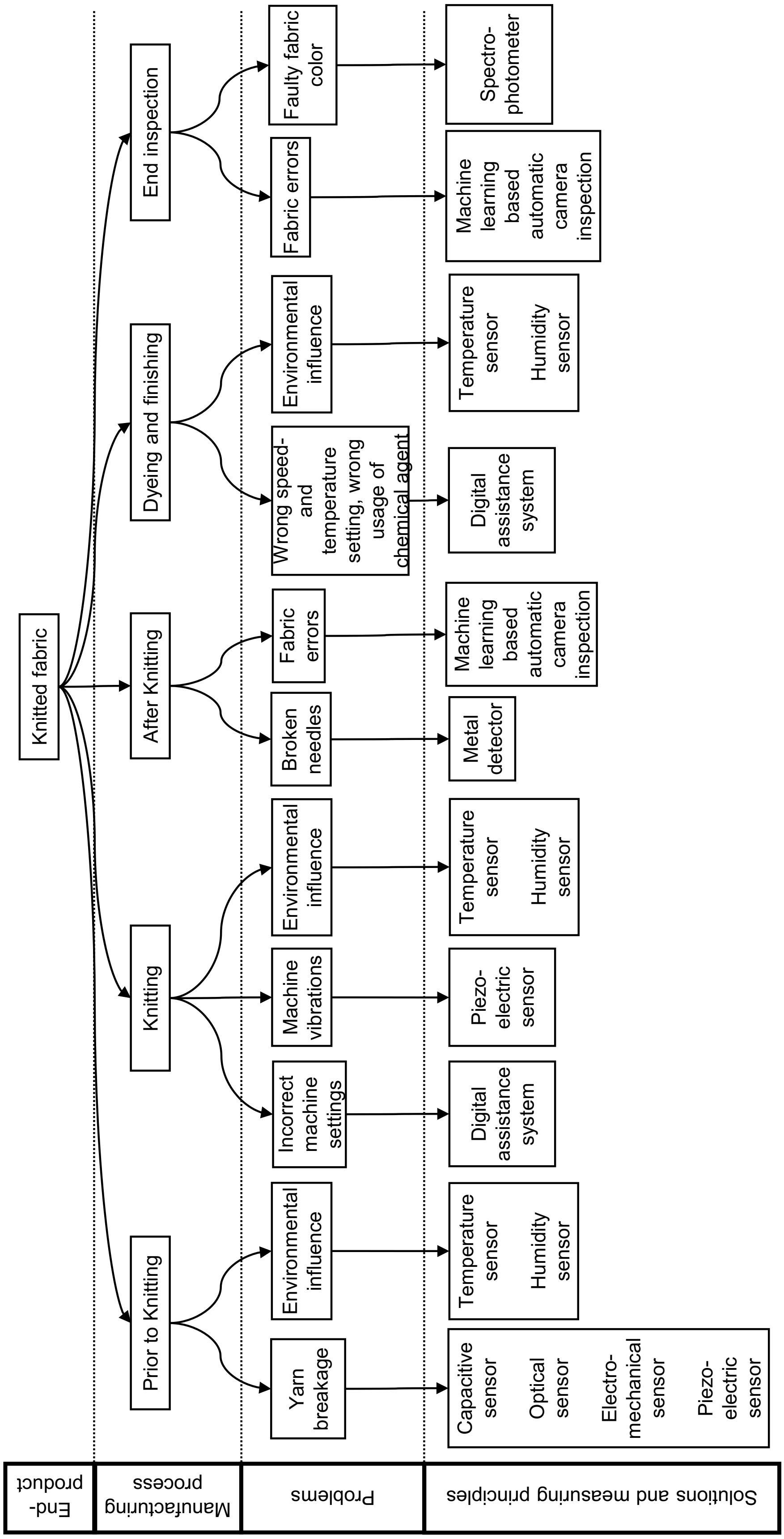



Fig. 5.19: Decision tree for selection logic in manufacturing of knitted fabric

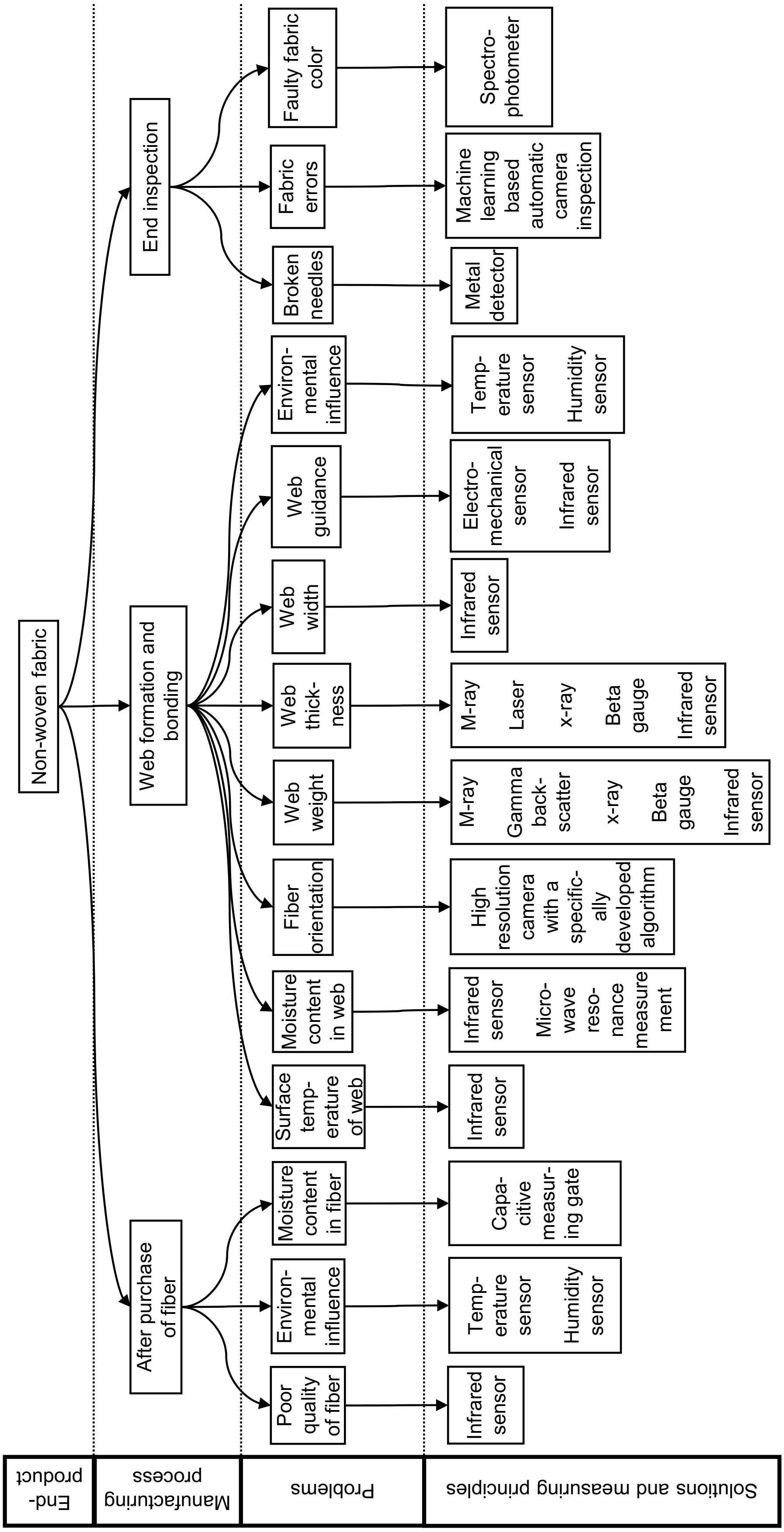



Fig. 5.20: Decision tree for selection logic in manufacturing of non-woven fabric

# 6 Critical appraisal

The critical appraisal of the presented master thesis focuses on the approach, methodology and the quality of the results.

***Approach and methodology:***

The goal of this thesis is to develop a decision tool to select appropriate solutions and measuring principles for the problems being faced in the technical textiles industry with focus on the automotive industry. The approach to develop the decision tool consists of four phases, namely literature review, market analysis, identification of solutions and design of a concept for the decision tool. The level of detail increases with each step, narrowing down the relevant topic. The literature review gives a deep profound understanding to the important quality parameters and defects in each of the manufacturing process of technical textile. Based on the literature review, a questionnaire is created to perform a market analysis in form of expert interviews. With the help of the market analysis, industry insights to the current status and problems associated with the quality control of manufacturing the technical textile fabrics in the automotive industry are addressed. Afterwards, based on the problems acquired through the expert interviews, the solutions and measuring principles are identified and subsequently a concept for the decision tool is designed. In conclusion, the approach and methodology of the presented thesis systematically narrows down industry-relevant information.

***Quality of results:***

Since the questionnaire made for the execution of expert interviews is based on the literature review, the actuality of the questions is ensured. Even though the interview was based on structured standard questions, the interviewees might have had limited time to explain and navigate through the problems being faced in the manufacturing processes regarding quality control.

Additionally, the expert interviews are conducted with a minimum of two companies in each of the relevant industry i.e., woven, knitted and non-woven industry respectively, including several professions, e.g. managing director, quality manager, laboratory team leader, team leader R&D and plant manager. Therefore, each of the person interviewed possessed a different understanding of the modern state of the art quality control through digitalization. This on one hand provided many different insights to the topic from different expertise. On the other hand, however, different professions have different level of detailed information and depth in understanding of the problems. Therefore, the input gained through these interviews i.e., problems, challenges and most importantly the measures to improve the quality control, might be biased.

As remote execution of the interviews through virtual platforms is chosen as the medium, even companies situated far away could be interviewed. However, this results in the lack in visualization of experienced problems. Thus, the analyzation of the problems faced during the manufacturing processes of technical textiles with remote interviews might have resulted in limited exchange of information

The identification of the solutions is depended on the problems gained through the market analysis. Depending on the amount of problem gained, it might have led to a restricted search for solutions. However, an intensive market research ensures the actuality of these solutions.

The concept of the decision tool explains not only the use of the current set of data acquired through this thesis, but is also designed to function for future purposes upon extension of the tool through further research and development.

Tab. 6.1: Keyword based summary of the critical appraisal and the described strengths and weaknesses

| | **Strengths** | **Weaknesses** |
|---|---|---|
| **Relevance** | Highly relevant topic to gain insights for introduction of digital technologies for quality control in the technical textile industry | |
| **Approach** | The actuality of the questionnaire derived through literature research is ensured. | |
| **Results** | Expert interviews are conducted with each of the relevant technical textile fabric manufacturing industry and with several professions for gaining different insights to the topic from different expertise | Time limitation for the interviewees to explain and difference in the understanding of the topic amongst different professions and companies |
| | Remote interviews prevented the geographical barriers | Lack of visualization and limited exchange of information due to remote interviews |

| | | |
|---|---|---|
| | An intensive market research with the help of expert interviews ensures the actuality of the identified solutions | Restriction in the market research due to the dependence on the acquisition of problems through market analysis |
| | Flexible concept for decision tool designed to function for future purposes upon extension of the tool through further research and development | |

# 7 Summary and Outlook

The aim of this master thesis is to develop a decision tool to select appropriate solutions and measuring principles for the problems being faced in the technical textiles industry with focus on the automotive industry. A systematic approach based on Design Research Methodology according to [Hel11] is pursued to obtain reliable results.

In the first step, a thorough literature research is performed that provides a profound overview of the fundamentals to technical textiles in the automotive industry. This includes manufacturing of yarn, manufacturing of fabrics and finishing methods. The three major methods of manufacturing technical textile fabrics, woven fabrics, knitted fabrics and non-woven fabrics are the focus of this thesis and therefore each of the methods are individually discussed. Consequently, the quality control parameters for each of the fabric manufacturing method are described.

Subsequently, the literature research serves as the foundation for the design of a questionnaire for performing market analysis in form of expert interviews. With the help of the questionnaire eight expert interviews are conducted with eight different companies. These eight interviews involve two expert interviews each with woven and knitted fabric industry respectively and three expert interviews with non-woven fabric industry. Moreover, one expert interview is conducted with a yarn manufacturing company to understand the problems associated with the yarn being purchased by the woven and knitted fabric industry. Key findings of the interviews include the current status of technology possessed by the companies, occurrence of various defects during the manufacturing processes, challenges faced by the companies as well as the motivational reason for not being entirely digitalized.

Based on the challenges acquired through market analysis, the potential for the introduction of digital quality control to manufacture technical textiles in the automotive industry is derived. This includes identification of solutions as well as measuring principles and methods to measure and monitor the defects occurring during the manufacturing processes of technical textiles for each of the fabric, namely the woven, knitted and non-woven fabric, manufacturing industry

Finally, a concept for a decision tool to select appropriate solutions and measuring principles according to the defects occurring during the manufacturing of technical textiles in the automotive industry is developed. The tool is divided in four different steps of finding the solution. The first step includes identification of the end-product i.e., woven, knitted or non-woven end-product, in which a problem is being faced during its manufacturing. It is followed by the second step in which the particular manufacturing process facing the problem is identified. The third step includes the identification of the problem associated with the chosen manufacturing process. It is followed by the fourth step in which the criteria to choose a suitable solution is included. Finally, after having chosen the criteria, the solution for the chosen problem is provided by the tool.

**Outlook:**

**Further development of the decision tool**

Not all the parameters described in the literature review could be fully integrated into the selection logic of the decision tool. This is mainly because the information for the solutions to monitor all the parameters was not easily accessible in the context of market research. With a more detailed and extensive market research, additional information could be obtained and integrated into the database of the selection logic for the decision tool.

Furthermore, an intensive market analysis by interviewing more companies in each of the industries could help provide a more detailed overview of the problems. Personalized interviews on-site could help to have a better visualization and understanding of the problems associated with the different manufacturing processes.

In the future, dynamic relations between problems and solutions could be established, in which an algorithm for the selection logic with the help of various criteria can be developed. This could help the user find an appropriate solution with the tool, where various defined criteria could be mutually weighed within the framework of the developed algorithm. Through the extension of data regarding quality control parameters, problems and solutions to the tool in the future, the relevance for an automatic selection logic increases.

One of the important criteria, also strongly emphasized during the interviews, is the economic feasibility of the solutions. A thorough cost analysis of the solutions could be carried out, to check whether the implementation of these solutions in comparison to manual quality check cost-effective is. Moreover, the feasibility for using a solution multiple times along the manufacturing processes could be analyzed to check the necessity for an appropriate amount of usage.

Weighting of the defects according to its severity is another important criterion. Each of the defects occurring during the manufacturing of the technical textiles have different impact on the quality of the product and the financial loss. According to the severity of the defects, it would be possible to determine if drastic measures need to be taken to handle a defect. With increasing severity, the control measures could be made more stringent. Prioritization of the defects through weighting the relevant factors could optimize the decision making function of the tool.

Depending on the severity of the defect, further investigations can be executed to determine the optimal conditions for detection of the defects. The necessity of the discovery of defects right during their occurrence, later in the surface or during the individualization of the manufacturing process could be determined.

**Further research and development of the solutions**

According to most of the expert interviews performed, the companies have been facing difficulties developing an automatic camera inspection system for controlling the yarn as well as fabric errors. This is mainly due to the diversity of the products. The solution could therefore be further developed and the algorithm can be trained for all possible types of products and defects.

# 8 Bibliography

[AAM09] Saber Ben Abdessalem, M. A., And Sofiene Mokhtari:
Knitted fabric faults: Inspection, causes & solutions
(2009).

[ABS+07] Anand, S., Brunnschweiler, D., Swarbrick, G., Russell, S.:
Mechanical bonding
Handbook of nonwovens (2007), S. 201-297.

[ABV+06] Acar, M., Bilgin, S., Versteeg, H. K., Dani, N., Oxenham, W.:
The mechanism of the air-jet texturing: the role of wetting, spin finish and friction in forming and fixing loops
Textile Research Journal 76 (2006), H. 2, S. 116-125.

[AD10] Alagirusamy, R., Das, A.:
Technical textile yarns. : Elsevier, 2010.

[AH16] Anand, S. C., Horrocks, A. R.:
Handbook of technical textiles; Volume 1: Technical textile processes. : Elsevier, 2016.

[Ana16] Anand, S.:
Technical fabric structures–2. Knitted fabrics.
Handbook of Technical Textiles. : Elsevier, 2016, S. 107-162.

[Are16] Arenas, J. P.:
Applications of Acoustic Textiles in Automotive/Transportation.
Acoustic Textiles. : Springer, 2016, S. 143-163.

[ASK+20] Atakan, R., Sezer, S., Karakas, H.:
Development of nonwoven automotive carpets made of recycled PET fibers with improved abrasion resistance
Journal of Industrial Textiles 49 (2020), H. 7, S. 835-857.

[BC09] Blessing, L. T., Chakrabarti, A.:
DRM: A design reseach methodology. : Springer, 2009.

[Ber13] Bernhard, F.:

Technische Temperaturmessung: Physikalische und meßtechnische Grundlagen, Sensoren und Meßverfahren, Meßfehler und Kalibrierung. : Springer-Verlag, 2013.

[BGW18] Bracht, U., Geckler, D., Wenzel, S.:

Digitale Fabrik: Methoden und Praxisbeispiele. :Springer-Verlag, 2018.

[BKK+13] Biedermann, W., Kirner, K., Kissel, M., Langer, S., Münzberg, C.:

Forschungsmethodik in den Ingenieurswissenschaften (2013).

[BL02] Boyer, K. K., Lewis, M. W.:

Competitive priorities: investigating the need for trade-offs in operations strategy. Production and operations management 11 (2002), H. 1, S. 9-20.

[BLM14] Bogner, A., Littig, B., Menz, W.:

Interviews mit Experten: eine praxisorientierte Einführung. : Springer-Verlag, 2014.

[Bo10] Bo, Z.:

Mathematical modeling of poly (ethylene terephthalate) air drawing in spunbonding nonwoven process (2010).

[BSM+14] Bauer, W., Schlund, S., Marrenbach, D., Ganschar, O. (2014): "Industrie 4.0—Volkswirtschaftliches Potenzial für Deutschland; BITKOM und Fraunhofer–Institut für Arbeitswirtschaft und Organisation: Berlin, Germany, 2014,"

[CGK+07] "Knowledge Based Process Control System to Optimize Needle Performances for High Added Value Needle Punched Nonwovens," (2007)

[CMG+17] Cloppenburg, F., Münkel, A., Gloy, Y., Gries, T.:

Industry 4.0–How will the nonwoven production of tomorrow look like? MS&E 254 (2017), H. 13, S. 132001.

[Con16] Conway, R.:
Technical textile finishing.
Handbook of Technical Textiles. : Elsevier, 2016, S. 189-210.

[CPR18] Chaudhari, D., Patil, T., Raichurkar, P.:
Gearing-Up Automobile Industry with Technical Textiles (2018).

[ČS08] Čiukas, R., Sadauskas, D.:
Control of the stability circular knitting process with passive yarn feeding. Mechanics 72 (2008), H. 4, S. 77-81.

[Dav98] Davies, B. A.:
Current and past technologies for headliners including acoustics, recycling and safety. SAE transactions (1998), S. 667-672.

[DCH99] De Araújo, M., Catarino, A., Hong, H.:
Process control for total quality in circular knitting
AUTEX Research Journal. I (1999), S. 21-29.

[FG08] Feldhusen, J., Gebhardt, B.:
Product Lifecycle Management für die Praxis: Ein Leitfaden zur modularen Einführung, Umsetzung und Anwendung. : Springer-Verlag, 2008.

[FGU11] Fatkić, E., Geršak, J., Ujević, D.:
Influence of knitting parameters on the mechanical properties of plain jersey weft knitted fabrics
Fibres & Textiles in Eastern Europe 19 (2011), H. 5, S. 88.

[FH00] Fung, W., Hardcastle, J. M.:
Textiles in automotive engineering. : Elsevier, 2000.

[FJ16] Fray, D., Jafferson, J.:
Solid-state gas sensors (2016).

[GS16] Gandhi, K., Sondhelm, W.:
Technical fabric structures–1. Woven fabrics.
Handbook of Technical Textiles. : Elsevier, 2016, S. 63-106.

[HA00] Horrocks, A. R., Anand, S. C.:
Handbook of technical textiles. : Elsevier, 2000.

[Hel11] Helfferich, C.:
Die Qualität qualitativer Daten (2011).

[HH06] Holbery, J., Houston, D.:
Natural-fiber-reinforced polymer composites in automotive applications
Jom 58 (2006), H. 11, S. 80-86.

[Ita16] Administration, I. T.:
Textiles Top Markets Report (2016).

[Jai13] Jain, V.:
Basics of process control in textile manufacturing.
Process Control in Textile Manufacturing.
: Elsevier, 2013, S. 3-13.

[JLI16] Jerusalem, M. A., Lin, S.-W., Irianto, D.:
A comprehensive model for process selection by considering offline and online quality control
Journal of Advanced Mechanical Design, Systems, and Manufacturing 10 (2016), H. 4, S. JAMDSM0065-JAMDSM0065.

[KB01] Kandachar, P., Brouwer, R.:
Applications of bio-composites in industrial products
MRS Online Proceedings Library Archive 702 (2001).

[Kon18] Koncar, V.:
Smart Textiles for in Situ Monitoring of Composites. : Woodhead Publishing, 2018.

[KPG17] Küsters, D., Praß, N., Gloy, Y.-S.:
Textile Learning Factory 4.0–Preparing Germany's Textile Industry for the Digital Future
Procedia Manufacturing 9 (2017), S. 214-221.

[KSC+07] Kuo, C.-F. J., Su, T.-L., Chiu, C.-H., Tsai, C.-P.:
Analysis and construction of a quality prediction system for needle-punched non-woven fabrics
Fibers and Polymers 8 (2007), H. 1, S. 66-71.

[Lim10] Lim, H.:
A review of spunbond process
Journal of Textile and Apparel, Technology and Management 6 (2010), H. 3.

[Mas95] Masson, J.:
Acrylic fiber technology and applications. : CRC Press, 1995.

[Mat08a] Matsuo, T.:
Automotive applications.
Polyesters and Polyamides. : Elsevier, 2008, S. 525-541.

[Mat18] Matt, D.:
KMU 4.0: Digitale Transformation in kleinen und mittelständischen Unternehmen. : GITO, 2018.

[Mcc13] Mccarthy, B. J.:
Polymeric Protective Technical Textiles. : Smithers Rapra, 2013.

[MDA+12] Majumdar, A., Das, A., Alagirusamy, R., Kothari, V.:
Process control in textile manufacturing. : Elsevier, 2012.

[MP99] Mukhopadhyay, S. K., Partridge, J.:
Automotive textiles
Textile progress 29 (1999), H. 1-2, S. 1-125.

[MPA13] Moyo, D., Patanaik, A., Anandjiwala, R.:

Process control in nonwovens production.

Process control in textile manufacturing. : Elsevier, 2013, S. 279-299.

[Onw97] Onwubolu, G. C.:

On and off-line quality control for product design and manufacturing processes

The South African Journal of Industrial Engineering 8 (1997), H. 2.

[PA09] Patanaik, A., Anandjiwala, R.:

Some studies on water permeability of nonwoven fabrics

Textile Research Journal 79 (2009), H. 2, S. 147-153.

[PM16] Patil, T. C., Momin, M. R.:

Impact of Relative Humidity on Loom Shed Efficiency

International Journal on Textile Engineering and Processes 2 (2016), H. 4, S. 7-1.

[RA06] Rawal, A., Anandjiwala, R.:

Relationship between process parameters and properties of multifunctional needlepunched geotextiles

Journal of Industrial Textiles 35 (2006), H. 4, S. 271-285.

[RS16] Russell, S., Smith, P.:

Technical fabric structures–3. Nonwoven fabrics.

Handbook of Technical Textiles. : Elsevier, 2016, S. 163-188.

[RT08] Russell, S., Tipper, M.:

Nonwovens used in automobiles

Textile advances in the automotive industry.(ed.) R. Shishoo, Woodhead Publ. Ltd. and CRC Press LLC (2008), S. 63-85.

[SB18] Schawel, C., Billing, F.:

Brainstorming.

Top 100 Management Tools. : Springer, 2018, S. 57-59.

[SBL04] Sparavigna, A., Broglia, E., Lugli, S.:
Beyond capacitive systems with optical measurements for yarn evenness evaluation
Mechatronics 14 (2004), H. 10, S. 1183-1196.

[SGB05] Štrumberger, N., Gospočić, A., Bartulić, Č.:
Polymeric materials in automobiles
Promet-Traffic & Transportation 17 (2005), H. 3, S. 149-160.

[Shi08] Shishoo, R.:
Textile advances in the automotive industry. : Elsevier, 2008.

[Shi97] Shishoo, R. L.:
Technical textiles—Technological and market developments and trends (1997).

[SMS+08] Stegmaier, T., Mavely, J., Schweins, M., Arnim, V., Schmeer-Lioe, G., Schneider, P., Finckh, H., Planck, H.:
Woven and knitted fabrics used in automotive interiors
Textile Advances in the Automotive Industry (2008), S. 43-62.

[SO18] Saricam, C., Okur, N.:
Polyester Usage for Automotive Applications
Polyester-Production, Characterization and Innovative Applications, 1st ed.; Camlibel, NO, Ed (2018), S. 69-85.

[TC05] Tsou, J.-C., Chen, J.-M.:
Case study: quality improvement model in a car seat assembly line
Production Planning & Control 16 (2005), H. 7, S. 681-690.

[www20a] https://www.lindenfarb.de/en/, Zugriff 03/11/2020

[www20b] www.ttandd.org, Zugriff am 03/05/2020

[www20c] https://www.mahlo.com/fileadmin/user_upload/PDF/Prospekte/Prozesskontrolle/Qualiscan_QMS-12_us.pdf, Zugriff am 31/08/2020

[www20d] https://www.produktion.de/trends-innovationen/so-werden-manager-fit-fuer-die-digitale-transformation-211.html, Zugriff am 29/09/2020

[www20e] https://techtextil.messefrankfurt.com/frankfurt/en.html, Zugriff am 26/08/2020

[www20f] https:// www.freudenberg-pm.com/markets/automotive, Zugriff am 23/05/2020

[www20g] https://www.datacolor.com/business-solutions/product-overview/datacolor-spectravision/, Zugriff am 22/09/2020

[www20h] https://www.mahlo.com/en/industries/nonwovens/details-en.html?tx_mahlodevices_femahlodevices%5Baction%5D=show&tx_mahlodevices_femahlodevices%5Bcontroller%5D=Sensoren&tx_mahlodevices_femahlodevices%5Bsensoren%5D=23&cHash=bb10401359e18126822e847e11986e49,Zugriff am 23/09/2020

[www20i] http://filcontrol.com/products/yarn-sensors/, Zugriff am 24/09/2020

[www20j] https://www.rfwireless-world.com/Terminology/Advantages-and-Disadvantages-of-Infrared-Sensor.html, Zugriff am 24/09/2020

[www20k] https://store.chipkin.com/articles/piezoelectric-force-sensor, Zugriff am 02/11/2020

[www20l] http://gtqhfvua.preview.infomaniak.website/wp-content/uploads/2013/12/XC2-F-UK.pdf, Zugriff am 02/11/2020

[www20m] https://www.yourelectricalguide.com/2017/12/capacitive-proximity-sensor.html, Zugriff am 02/11/2020

[www20n] https://www.gesamtmasche.de/download/die-deutsche-textil-und-modeindustrie-kurzfassung/, Zugriff am 26/10/2020

[www20o] https://lenzing-instruments.com/wp-content/uploads/2019/06/cis300_ll-1.pdf, Zugriff am 23/09/2020

[www20p] https://www.uster.com/fileadmin/user_upload/customer/customer/Services/Usterized/Member_Area_NEW/App_Rep_UT5_CMT5_Zweigle/SE-564_Comparison_of_the_capacaitive_and_optical_measuring_1.pdf, Zugriff am 06/10/2020

[www20q] https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/Operations/How%20we%20help%20clients/Capability%20Center%20Network/PDFs/DCC%20Chicago%20Brochure.pdf, Zugriff am 18/10/2020

[www20r] https://www.protechna.de/en/warping_machines/camscan-5203, Zugriff am 16/10/2020

[www20s] https://lenzing-instruments.com/wp-content/uploads/2019/06/nis300.pdf, Zugriff am 29/09/2020

[www20t] https://lenzing-instruments.com/wp-content/uploads/2019/06/invispec.pdf, Zugriff am 29/09/2020

[www20u] https://lenzing-instruments.com/wp-content/uploads/2019/06/nos300.pdf, Zugriff am 24/09/2020

[www20v] https://lenzing-instruments.com/wp-content/uploads/2019/06/bis200.pdf, Zugriff am 24/09/2020

[www20w] https://www.erhardt-leimer.de/produktsuche/,Zugriff am 27/08/2020

[www20x] https://cdn.nimbu.io/s/4j0nxju/channelentries/lw3vlv3/files/Hammer-IMS%20CASE%20M-Rays%20Thick%20nonwovens%20and%20coated%20textiles%20LR.pdf?d1ri7gr, Zugriff am 27/08/2020

[www20y] www.texdata.com Zugriff am 03/05/2020

[YW08] Yu, T., Wang, G., "Research of on-line process quality control system," 2008 IEEE International Conference on Automation and Logistics 2008).

# 9 Appendix

## 9.1 Quality control parameters

Tab. 9.1: Quality control parameters for woven, knitted and non-woven fabrics

| Woven fabrics | | |
|---|---|---|
| **Yarn parameters** | **Machine parameters** | **End-fabric parameters** |
| • Tensile strength<br>• Torsion of the threads<br>• Color<br>• Frequency of thread breakage incidents per bobbin<br>• Drape of the threads<br>• Diameter of the bobbins<br>• Frequency of weft breakage | • Machine temperature<br>• Machine speed<br>• Machine vibrations<br>• Rate of yarn feeding<br>• Yarn tension equal (left, middle, right)<br>• Temperature (external)<br>• Humidity (external) | • Width of output fabric<br>• Weft density<br>• Waviness (fiber crimp)<br>• breaking strength and elongation for dry and wet webbing,<br>• abrasion resistance<br>• shrinkage rate<br>• Color fastness |
| **Knitted fabrics** | | |
| **Yarn parameters** | **Machine parameters** | **End-fabric parameters** |
| • count<br>• unevenness (U%)<br>• strength<br>• twist<br>• elongation<br>• appearance<br>• coefficient of friction<br>• bending rigidity | • yarn input tension<br>• stitch cam setting<br>• take-down load<br>• rate of yarn feeding<br>• number of feeders<br>• yarn patterning in feeders<br>• needle gating | • loop length<br>• GSM<br>• courses per inch<br>• fabric width<br>• wales per inch<br>• fabric defects<br>• stitch density<br>• fabric tightness factor<br>• yarn count<br>• fabric construction<br>• yarn type |
| **Spun laid non-woven fabrics** | | |
| **Material parameters** | **Machine inline parameters** | **Machine offline parameters** |

| | | |
|---|---|---|
| • Fiber fineness<br>• Fiber orientation<br>• Fiber size<br>• Density of the fiber<br>• Web uniformity<br>• Web weight | • Primary air temperature<br>• Quench air rate<br>• Air suction speed and venturi gap<br>• Collection speed<br>• Through- put<br>• Bonding temperature and pressure | • Die hole size<br>• Die setback<br>• Web collection type<br>• Die hole design |
| **Dry laid & needle punched non-woven fabrics** | | |
| **Material parameters** | **Machine parameters** | **Needle parameters** |
| • Web uniformity<br>• Web thickness<br>• Web weight<br>• Air permeability | • Feed rate<br>• Stroke frequency<br>• Web speed<br>• Machine vibrations | • Needle punch density<br>• Depth of penetration<br>• Needling level<br>• Type of needle<br>• Shape of needle |

## 9.2 Questionnaire for the Expert Interviews

Tab. 9.2: Questionnaire for Expert interviews according to SPSS principle

| | Topic | Questions |
|---|---|---|
| Introduction | Organizational details | • Introduction of the master thesis<br>• Introduction of the expert (which job, which position, how long?) |
| General | General questions | • Which automobile end products are produced in your company?<br>• What is the sequence of processes from the beginning (raw material) till the manufacturing of the end product?<br>• What are the possible quality errors occurring during the various processes of manufacturing?<br>• What are the possible quality errors occurring in the intermediate products in-between the processes?<br>• What are the quality parameters that are monitored?<br>• What are the solutions to monitor and analyze the parameters/errors?<br>• How are the errors corrected or are the defected product rejected?<br>• How much of the quality control is executed manually?<br>• How far is the digital transformation of quality control?<br>• Do you work with IoT solutions or MES system?<br>• What are the reasons for not bringing complete digital transformation in quality control yet?<br>• How much of digital quality control is involved according to you?<br>• Do you collect data from each of the machines/processes for further data mining or predictive maintenance or condition monitoring with sensors?<br>• how and which data/parameters are understood?<br>• Is it stored? Shared in the departments?<br>• Is it processed or analyzed?<br>• Is it used to generate improvement measures for the future? What is your opinion, what are the potential of improvement in the quality control processes?<br>• What are your suggestions about the measures for improvement?<br>• How much financial loss through reasons such as lack of automation or still stand of machines because of the quality errors is incurred? |

| | | |
|---|---|---|
| **Non-woven** | **Air-laid Web formation** | - **Opening of fiber bales and Sandwich mixing**:<br>• Which quality parameters of the fibers and the environment/surroundings need to be considered before beginning the process?<br>• What are the quality problems faced while opening and mixing the fiber bales?<br>- **Spraying antistatic conditioning**:<br>• How is the process of spraying monitored?<br>- **Carding**:<br>• Opened and fixed fibers combed into a web. What role does the quality of the fiber play in the overall quality control?<br>• Which web parameters need to be considered for quality control?<br>- **Web building on a cross lapper**:<br>• Swing speed and conveyer speed control the web thickness or web weight. How are they adjusted?<br>• What role does the Length of fiber play in regard to Quality control?<br>• How are these parameters monitored?<br>- **Web formed:**<br>• How is the quality of the web formed examined before going through web bonding processes?<br>• Which are the general quality errors occurring during web formation and what are their consequences?<br>• Which technological solutions are used to monitor the quality defects/parameters during web formation?<br>• What are the consequences of the general quality errors occurring during web formation?<br>• What consequences do environmental factors such as humidity and temperature have?<br>• How much financial loss through reasons such as lack of automation or still stand of machines because of the quality errors is incurred? |

| | | |
|---|---|---|
| | **Spun-laid Web formation** | - machine/online variables:<br>• primary air temperature: Fiber diameter is known to decrease with increase in temperature of the primary air<br>• quench air rate: The drawing effect resulting from the air-drag force leads to the polymer molecular orientation. The quench air velocity controls the attenuation, while its temperature controls the cooling effect<br>• air suction speed: The speed of the suction air draws the filaments causing fibers to be finely attenuated. By increasing the suction speed of the air, the anisotropy of the filament distribution decreases within the structure from enhanced alignment in the machine direction<br>• Venturi gap: A larger Venturi gap yields finer fibers<br>• throughput: The amount of the molten polymer forced through the metering pump per unit time. When throughput is increased, the fiber diameter of the resultant fibers also increases. At lower throughput rates, finer fibers are produced<br>• collection speed: The speed at which the conveyor belt moves controls the final lay-down of the multi filaments after the initial drawing and electrostatic filament separation<br>• bonding temperature and pressure – increases tensile properties, stiffer fabric.<br><br>- offline variables- The fiber diameter is mainly influenced by the die hole size, die hole design parameters and die setback. The poor die design results in a non-uniform web<br><br>- material variables: spun bonding process requires polymers with higher molecular weight and a broad molecular weight distribution to produce uniform webs |

| | | |
|---|---|---|
| | **Needle punching Web bonding** | - **Non-woven formation by needle punching**:<br>• How is the mass density between the two stages: pre-needling line and a finish needling line monitored and corrected?<br>- **Web parameters**:<br>• Some of the web parameters are **feed rate** and **stroke frequency**. What quality errors can occur through these parameters? How are these monitored?<br>• What other quality parameters exist?<br>• Which Problems could occur when the parameters are not tackled appropriately?<br>- **Machine parameters**:<br>• What are the various machine parameters crucial in quality control?<br>• How are the **frequency of the strokes and linear speed** of the web balanced?<br>• The key parameter representing the entanglement of fibers is known as penetration per square inch (PPSI). PPSI is directly proportional to the density of the needles on the needle board and to the frequency of strokes, but inversely proportional to the speed of the web. How is it monitored?<br>• How is **needle punch density** and **depth of needle penetration** monitored?<br>• Needling level and depth of penetration should be also best fit with the required weight of car carpet, because excessive needling may also weaken the nonwoven fabric.<br>• What quality errors can occur through these parameters?<br>- **Needle parameters**:<br>• Some of the parameters are needle type, shape, arrangement and number of barbs etc. How are they monitored?<br>• Which quality problems occur due to these parameters?<br>• What are the other quality parameters?<br>• How is the amount of needling varied and monitored?<br>• **The main factors that influence needle damage** are non-alignment of needles, fiber quality (waste, regenerated or unopened fiber tufts), needle punching condition (e.g. if the speed of the web per stroke is too high it results in sideways deflection of needles by the fabric), needles penetrating a thick web too aggressively and encountering high friction between needles and fibers, deep barbs that increase the load on the needle during penetration, machine vibrations during operation, and improperly |

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| | | designed hole sizes in the bed and stripper plates, needle penetration force, stitch density<br>• How are these monitored and corrected?<br>• How much time is lost and what financial lost is incurred due to needle breakage?<br>- **Structure needling and curing in stenter:**<br>• What are the quality parameters involved in structure needling?<br>• Some of the parameters are<br>  - Position of the fork in the needle board<br>  - Penetration side of fork needle must be on the same side of finish needling to obtain improved velour effect<br>  - Penetration depth<br>• How are these monitored? What errors occur during structure needling and how are they corrected?<br>• How is the temperature controlled during curing in stenter?<br>• How is the material speed controlled?<br>• What errors occur during curing in stenter? |
| **Woven & Knitted** | **Fiber/ Yarn- Extrusion** | - Product parameter:<br>• Tensile strength<br>• Torsion of the threads<br>• Color<br>• Which other product parameters are monitored?<br>- Process parameter:<br>• The shape, size and number of holes determine the fiber cross section, fineness and number of filaments in the yarn.<br>How are they monitored?<br>• Following extrusion, the filament yarns are gathered together, dried or cooled in an air flow, then wound onto bobbins for subsequent process.<br>How is the temperature monitored?<br>• What other process parameters are monitored? |
| | **Warping** | - Process Parameter:<br>• Frequency of thread breakage incidents per bobbin<br>• Drape of the threads<br>• Temperature (machine)<br>• Temperature (external)<br>• Humidity (external)<br>• Light-intensity<br>• What other process parameters are monitored?<br>- Product parameter:<br>• Diameter of the bobbins<br>• What other process parameters are monitored? |

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| | **Weaving** | - Process parameter:<br>• Yarn tension equal (left, middle, right)<br>• Frequency of weft breakage<br>• What other process parameters are monitored?<br>- Product parameter:<br>• Width of output fabric<br>• Weft density<br>• Waviness (fiber crimp)<br>• breaking strength and elongation for dry and wet webbing,<br>• abrasion resistance<br>• What other process parameters are monitored? |
| | **Knitting** | - Are the yarn checked and tested for parameters such as count, unevenness (U%), strength, twist, elongation, appearance, coefficient of friction, bending rigidity?<br>- Are the machine parameters such as yarn input tension, stitch cam setting, take-down load, rate of yarn feeding, number of feeders, yarn patterning in feeders, needle gating, tucking and floating arrangements controlled and monitored?<br>- Are the parameters for the Knitted fabrics such as loop length, GSM, courses per inch, fabric width, wales per inch, fabric defects, stitch density, fabric tightness factor, yarn count, fabric construction (design), yarn type controlled? |
| | **Coating/ Thermosetting** | - Process parameter:<br>• Tension of input fabric<br>• Pressure (machine)<br>• Humidity (machine)<br>• Temperature (machine)<br>- Product parameter:<br>• Width of output fabric<br>• Weft density<br>• Shrinkage rate<br>• Humidity of fabric<br>• Number of smirches<br>- Potential errors: Shifting of yarns of the fabric under stress |

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| | **Printing/ Cutting** | - Process parameter:<br>• Tension of input fabric<br>• Temperature (machine)<br>• Humidity (machine)<br>- Product parameter:<br>• Printing: gaps and overlaps<br>• Color space<br>• Length of print design<br>• Color fastness to light<br>• Color fastness to rubbing<br>• Color fastness to sweat |

## 9.3 Summary of the Expert Interviews:

### 9.3.1 Yarn manufacturer:

**Product**: Weaving Yarn from synthetic and natural fiber for woven fabrics in automobile branch. However, Weaving yarn and Knitting yarn have similar manufacturing process.

**Manufacturing Process**:

- Purchase of raw material:
  - Purchase of synthetic and natural fiber from supplier
  - Natural fiber, the quality is simply a little more diversified than it is with synthetically produced fibers. In the case of natural fibers, they have a higher scope of testing through a control for the incoming goods inspection. They have a control sheet where it is precisely defined who has to do what at which stage and The parameters to be tested are also defined there. This is filled out accordingly in the purchasing department. And then the sample of the incoming goods is sent to quality assurance (QA). In QA then follows the inspection of the defined parameters. And in QA then follows the article-related release.
  - All randomly tested in laboratory because it is a destructive test
- Manufacturing after release:
  - The production areas that this passes through- the spinning mill, cone mill and the twisting mill behind it are installed, and for the entire individual departments, important parameters must be observed. Practically every article has its own production regulation so that the responsible employees in the production area know exactly how to set up the machine accordingly. The default fineness, the yarn count, the yarn twist and then also the machine Technical detail
  - PDA software is under development
  - Like the incoming goods inspection plan, there is also an intermediate inspection plan, where it is precisely defined what quality aspects of this particle/worsted yarn are to be inspected individually. This is offline

between processes at the moment where the control sheets for the individual areas are filled out by the responsible persons.

- They also have a dyeing factory, always depending on how the article looks like they have the possibility to stop at the dyeing factory and start comb dyeing there. Then the combed top would go to the Vorwerk. There they are always further refined, mixed, parallelized. Based on the wool and through the combing, one gets a more even and firmer yarn. In the out-plant either dyeing comes from a well-known dyeing factory or one can also stop with the raw widths of the goods inputs, depending on the customer's task. After Vorwerk comes the spinning mill. There I can simply spin yarn, compact yarn or elastic yarn. There we also have different machines, which are used in the different ring spinning mills with the corresponding modifications or classifications. From the spinning mill, the yarn then goes from there to the winding mill, which is also known as the cone mill. the yarn is then cleaned again according to the given classifications, which is simply a necessity or which the customer has as standard.
- General errors:
    - From raw materials - in the wool the straw parts, packing remainders or other foreign fibers.
    - From the production dyeing are normal or usual faults - first of all the color accuracy of the pattern, the color fastness play a role.
    - From the other spinning technical areas there are deep confusions - different orders with other orders may be contaminated. There you simply have to pay attention to the appropriate cleanliness and distance.
- These are random inspections that are monitored manually by employees.
- The only permanent monitoring that takes place in our winding department is the cleaning. An optical sensor that permanently records the yarn. It is then still required to be monitored by the manager.
- Machine-technical cotton spinning mill is higher digitized measurement methods attached to the machines. Unfortunately, the wool range is not very developed. At the moment there is no continuous quality monitoring.
- Cotton spinning mills have been highly digitalized over a very long period of time and they all produce the same quality over weeks or months. With the interviewed company it's different. “We tend to be smaller, and we don't have any articles ranging in size from a hundred kilos to 5 tons. Whereas one ton is more or less the average size. And in many different qualities, in different mixtures. We process wool. We process silk, we process where linen, hemp as a natural color examples, cotton, then we process PAN, polyester, various technical fabrics, dyes antistatic, metal- It is very diverse making it difficult to digitalize.”
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### 9.3.2 Company A - woven fabric industry

**Contact person: Plant Manager**

**Products:**

- Reinforcement tapes, binding, loop straps
- Elastics and sealings
- Panorama roofs

**Manufacturing Process:**

- Purchase of Raw yarn:
  - No quality check at all. Defects are detected in the latter process of weaving which leads to loom stoppage.
  - Such defects occur very often: on weekly basis
- Warping and Weaving:
  - Temperature and Humidity controlled for weaving
  - Major problem is Sustainability such as shrinking of fabric. Change in Ratio of width and thickness.
  - Elongation of fabrics is also a problem.
  - Width, thickness and Elongation are the only parameters measured offline manually.
  - Weft density, waviness(fiber crimp) are not measured.
  - The yarn tension is monitored on the looms. if a yarn breaks, the loom stops.
  - Currently, all checks are carried out manually. This means that the weavers have their test protocol and have to check every two hours for changes in intermediate products, according to the test protocol, test plan and documentation.
  - Early identification of weaving errors to avoid transfer of defected fabrics for further processes. Identification, sorting and simultaneous action!
- Dyeing:
  - Hall based Temperature and humidity not present.
  - Defined recipe for colors. Manual control of fabric color with color matrix measuring system by employees.
  - Depending on the standard, there are standardized light sources, which are also maintained and serviced.
  - Color fastness and Abrasion resistance is tested in labs.
  - Outsourcing of a lot of lab tests to external companies depending on the requirements and test standards of the automotive companies.
- Finishing:
  - Shrinkage is a problem
  - Using wrong Chemical agent for finishing is a problem
  - The making/mixing of chemical agent is controlled with 4 eyes principle manually.
  - Wrong temperature and wrong speed of conveyer belts are also common problems.

- Elongation properties of band might be damaged during the process.
- Camera based inspection for surface defects still in validation phase

**Improvement potential:**

- Inline quality control everywhere, where possible!
- “if I could I would create an inline test in the web machine per gear. I would. I would test ever gear for sustainability and elongation, an inline elongation measurement. Specially Inline Sustainability and elongation (not sure if possible) measurement.“
- Continuous Measurement and immediate actions/readjustment of deviations.

### 9.3.3 Company B - woven fabric industry

**Contact person: Plant Manager- Production and Development**

**Manufacturing process:**

- Purchase of Raw yarn:
- Yarn is bought. Controlled on a small volume randomly. Reliance on suppliers
- Warping and weaving:
- Temperature, humidity, light intensity in the partially air-conditioned. The temperature is at the strict specifications for these things, which we of course present and also check according to the data sheet.
- There are sensors that constantly measure the temperature during the weaving process
- General errors: Start-up marks and faults due to dust/contamination
- Continuous manual Visual monitoring
- Automatic visual monitoring with ML-based solutions cannot be used economically. That's why these solutions aren’t introduced.
- Coating:
- Online measurement with regard to the basis weight, i.e. the coating application measure- current drawing measurement
- Tension controls correspond if necessary fabric tension can adjust and measure tension. Everything online during the process!
- Printing/dyeing:
- Visual disassembly process, our color measurement can be compared with the given standards and the goods are re-shelved or re-colored accordingly. So that the color specifications can be adhered to.
- We can measure the color both visually and spectrophotometrically.
- Use of camera inspection: In the rejection area there is a hybrid camera technology, which does not detect defects, but only the position of the weft thread.
- Improvements:
- profitability is still a problem!

- 100% monitoring by automatic recognition by means of camera optics, so that one can quickly intervene on errors and take countermeasures to counteract them. It has to be scientifically possible, cost-effective, and efficient.

### 9.3.4 Company C- Knitted fabric industry

**Contact person: Team leader R&D**

**Knitted fabrics:** Mainly scrim production-A multiaxial scrim technique

**Products:** Sports car- B pillars, bonnets, roofs, under floor protection materials, battery covers from carbon fibers. For normal cars with glass fibers, since carbon is too expensive.

**Raw materials**: glass fiber, carbon fiber, aramid fiber, partly thermoplastic fibers

**Manufacturing process:**

- Purchase of yarn:
  - Basically specifically for the automotive industry, they rely on the measurement of the supplier, a specification is agreed with the supplier. They send the measured values that has been recorded. It is then checked with the specification and then release the material for production
  - Only on Customer requirement sometimes random measurement such as checking the fineness of the glass fibers.
  - "Trucks with fibers arrive at our premises, and if we now randomly check the fineness, we take one of many bobbins down and check a few meters. Doesn't tell us if the whole lot is okay. The amount is too small."
- Preparation of yarn:
  - Documentation of fibers such as how long does the fiber last. Whether the fiber has expired.
  - Barcode scanners help select Which pallet is taken now, how does it get to the plant and so on. All this is automatically guaranteed to be the right material that is on the line. Alarm is raised when the wrong material is taken.
  - Then there is a production map, where it is defined how we manufacture the articles. How many threads do I have to feed in, how do I get the threads in, how do I sew it with and which sewing method, with which materials. There is the checklist. This means that when production is started, the machines are set up for the line according to these production specifications. Checklist controlled manually.
- Knitting:
  - Manual control of material and process by a machine operator
  - Defined rules- when the errors are limited to a certain amount- cut and modified instead of rejection
  - Depending on customer requirements the camera based inspection is used. The employees monitor it manually.

  - “Machine learning based camera inspection under development since years. Problem: it is always difficult. If you had one article, for example, you could use it safely. We have 3000 different articles. I would have to adjust the settings for each article so precisely. And that doesn't make sense. Some customers need that and some don't.”
  - Due to the complexity, it is actually thought that since the machine operators have the proper training, they will have a much better eye for that than to let it be done automatically.
  - Temperature and humidity is controlled in the hall
  - Everything else is measured offline. The breaking of yarn and other errors are identified after the process.
  - The settings of machine and the properties of the material is measured at the beginning of the process by producing the first meters.
  - General errors: missing sewing thread, missing reinforcing thread, gaps in the scrim in the different layers, contamination
  - Contamination due to broken needle can be identified with metallic objects detector.
- Powder reduction:
  - Temperature and humidity inline controlled
  - Camera inspection possible
  - General errors: gaps in the scrim in the different layers, contamination, powder accumulations

**Improvement measures:**

- It would make sense to get that human aspect out. Solution to identify for example when is a gap in the scrim tolerable and which value onwards is it an error. Automation of the process to identify errors.
- Inline measurement wherever possible
- Problem:
  - Inline measurement leads to gathering of a huge amount of data-Big data handling! Lack of knowledge regarding data evaluation is a huge problem.
  - “In the textile industry- non-woven, woven fabric and scrim manufacturers. The structure of each technology is different -very interdisciplinary, so every company has to work on it for itself to get the best results. I need a person who is super familiar with all this work. I need someone who knows about informatics. I just need to know What does my sales representative want to have for evaluation or what do you want to have as a customer? I think that's what makes it so difficult to bring these interdisciplinary things together”

### 9.3.5 Company D- Knitted fabric industry

**Contact person:**

- **Quality manager-** responsible for both operational quality and management

**Products:**

- Our customers are Tier 1 manufacturers of panoramic roofs, interior fittings such as headliners, pillars cladding

**Manufacturing Process:**

- Purchase of Yarn:
  - "We buy already warped yarns and chemicals essentially from the same manufacturers and suppliers and only in exceptional cases do we check the technical values against the specification list/acceptance test certificate of the suppliers."
  - Either when customer requirement compels to perform the control tests
  - Or when there are complaints or problems in production that cannot be assigned.
- Knitting:
  - Each article has predefined machine parameters, which are then set up before release by an operator, shift supervisor checks it and finally it is released before starting the process.
  - Yarn tension is not measured individually because we use large CPMs. When you have a thousand yarns lined up next to each other. But all the machine parameters are of course monitored. They are set electronically with a tear-limit window. The machine independently monitors these parameters and corrects and regulates them.
  - Self-developed PDA Software- The machine is coupled with production data acquisition PDA, standard machine parameters recorded inline so that you can track speed, from when to when it has run, including when trucks need to be replaced.  Then the human must come to evaluate, judge and start again. Afterwards we have the OEE of the plant- how is the quality?, Data for this are all in PDA software. Also they have predefined stop reason mechanisms to track the reasons for stoppage continuously. Monitoring of key operating figures on a daily basis.
  - The hall is climatized and the environmental parameters are monitored.
  - Typical errors: Stripes and Missing Stitches
  - Stripes: the strips are very difficult to evaluate. The problem often occurs at the very end of the process, when the material is dyed and finished. If you see the visual stripes at the end of the process, they can be disturbing in the car and then possibly lead to rejection or reworking of the material.
  - Missing stitches: When knitting, stitches do not work 100 % and in one or the other case stitch is lost. Visual defect during final inspection.
  - Test requirement: The sample is dyed in a commercial washing machine. We use blue as a color, in order to be able to evaluate

afterwards by real light, whether or not the surfaces, the bad optical conspicuousness. To be able to evaluate stripes. On the one hand, this method is fast, but on the other hand it has the disadvantage that it does not have the same quality and significance as final inspection at the end.

- Manual Visual Camera Inspection: Experienced employees who have enormous knowledge, who monitor this themselves and find out the problems and with camera via monitors.
- ML based camera inspection: They have a pilot project. A machine manufacturer is currently developing a camera inspection in his own machine and we are available as development partner. So it is a cooperation, where the solution is developed, tested and validated at their premises. The camera systems must be able to improve themselves by a logic. For the most part, it works well, but it still needs these experienced employees from experience and who give the programs the finishing touches, because there are many different articles or materials.
- If the camera inspection is not introduced during the knitting process, this is of course also due to the fact that both of these typical faults are not visible to the human eye. One of the key statements of the camera setting is that what the eye cannot see, the camera cannot see as well. This means that we only use the camera for the things that I can see optically, either in the fabric itself or against a watch pattern that the camera then compares with.  But if the strips of the knitted fabric is not noticeable at all, the camera system doesn't help me at that point. This means that there possible promising potential of research would be to make faults that the human eye cannot see detectable with the cameras automatically.

- Dyeing:
  - Have their own color recipes.
  - Automatic quality Control with photo spectral solution which compares the color with the sample. There are tolerances. If the sample moves within the tolerances and within the range as it should, then the material is released for the next steps.
  - Additional Fiber processing
- Finishing:
  - Providing the technical properties on the fabric that the customer expects.
  - For example, the topic of flame protection. We have the vast majority of our products somewhere in the car interior worldwide. What is permissible, what is not permissible? In the case of flame retardants, chemicals are added. There is also a recipe for this, similar to color. The chemicals are added manually via automated processes, but employees determine the recipe step by step with an automated

manual. That means they get all the instructions about what exactly they have to do.

- End quality control:
  - Now the product is finished - so here comes goods inspection. First The visual evaluation of the fabric for visual defects, is not based on technical values, but purely optical defects. There are 2 variants:
    1. that means we have automated fabric inspection wherever possible, that means the material is photographed by cameras from different angles. The software background compares the images with the defect catalogue, which is created parallel to the roll with the textile defect file, defect map.
    2. We have then the possibility to use the manual inspection, which is coupled with the defect catalogue, to target the defects that the automatic inspection has detected and then we can confirm or correct one defect after the other if we want to. and what we have to do in any case, it is agreed with customers, that the defects are only marked if the customer does not want us to cut out the defects, so that he can sort out the defects in his process without much effort. Most customers cut their own.
  - Automatic inspection wherever possible and manual inspection only for marking of defects and packing.

**Motivation**: “We produce in Germany for our customers worldwide, mainly in the automotive industry, and of course at an extremely high level to become more and more efficient. And if you only rely on employees, that is not enough. I will do something wrong when I say I am satisfied. a quality manager is never satisfied.”

### 9.3.6 Company E- Non-woven industry

**Contact person: Quality Manager**

**Nonwovens Products**:

- Automotive headliners and boot liners
- Automotive carpets
- Tuft backing for automotive carpets
- Underbody panels and wheel liners
- Air filter and cabin filter

**Manufacturing process** (depends on end-products and customer requirements):

- Manufactured fibers from suppliers:
- Supplier checks/tests the parameters and sends a specification list along with the goods
- Random quality control of fiber parameters such as diameter, weight, mechanical properties such as elasticity, tensile strength etc.
- Web Formation: Air laid with carding and Spun laid
- Inline QC- only temperature

- Offline quality test for product parameters such as thickness, surface weight by weighing(gm/$m^2$), tensile strength etc. after the process.
- No QC for machine online parameters such as quench air rate, air suction speed and venturi gap, collection speed, throughput, bonding temperature and pressure and also die hole size (influences product thickness)
- Process initially needs time for stabilization which usually always leads to initial scrap.
- Web Bonding: Mechanical (needle punching) and thermal (calendaring)
- Quality inspection with camera:
- Camera systems which look at the surface of the nonwoven and which can, for example, detect contamination or discoloration, stains. Often such a contamination or stain is of course unattractive, but in the end it has no great influence on the function. But there are often or the customer must be able to see himself optically and say, there is dirt on it, I don't want that. Many of the problems we have with our material, quality problems have to do with the dirt. Contamination that comes from the process, changes somewhere the fibers, they get stuck somewhere, they get dirty perhaps with the time over dust or also over temperature and simply become hot and then dark
- Manual marking of defects, either total rejection or cutting the defected part depending on the amount of defects. Manual Inspection on monitor
- Radioactive measuring instruments with x-ray principle for inspecting surface weight and thickness Continuously Inline.
- The employee is presented on a screen, can see whether the material is getting thicker or thinner or whether it is changing thickness from left to right. One can always take countermeasures directly.
- Offline quality tests
- Scrape rate less than 1%

Improvement scope:

Inline Quality control through better statistical process control. Monitoring quality influences during the process to gather the information rather than reworking afterwards. Early recognition and countermeasures!

### 9.3.7 Company F- Non-woven industry

**Contact person:**

- **Quality Control Manager**
- **Production Quality Manager**
- **Laboratory team leader**

**Products:**

- Parcel shelves/trunks

- Dashboards
- Door/side panels
- Underbody panels
- Roof linings/ABC pillars
- Velour Carpets
- Bonnets

**Manufacturing Process:**

- **Purchase of yarn:**
  - The raw materials such as fibers or powder or even films are purchased and then processed.
  - There are goods receipt inspections of fibers, where we do optical and moisture tests for viscose fibers.
  - Otherwise, random checks are carried out if something is particularly noticeable and otherwise factory test certificates from the respective manufacturers.
  - A complete visual check of what is inside the individual bale is not done. But you can bypass everything from the outside and see if you can see obvious dirt, if the film is badly damaged or so on and is manually monitored by employees. No use of a camera or anything else.
  - Typical mistakes: mold formation for example, soiling of any kind from metal to foreign fibers.
  - “Basically, we have treated this incoming inspection in the past a little bit neglected. We had problems with the equipment due to moisture, which is visible through the discoloration, and we said Okay, we have to take a closer look at the incoming goods inspection. That's why this inspection was practically created. They say, now we discover this error already in the incoming goods department of the plant since then. Now I have almost no more problems.#2
  - We currently have no more problems with wet material. Pollution? Yes and no, because you can only see from the outside. Sometimes there are even overdried in it, which we can then see with the bale on top.
  - “How the moisture is measured: We have two different methods. We have one with an integrated scale without built-in drying and one with actual moisture meters for bales, i.e. two sample bars are screwed in. And then the electrical voltage is used to measure how much resistance is present. On the basis of the material, it is then possible to draw conclusions about how moist the material is. There is an agreement with the supplier about how moist the material may be. We know that too. And if the moisture is above that then we have a problem.”
- **Web building (air laid) and Web formation (needle punching and waterjet):**
  - Inline:
  - This is a camera system manufactured by ISRA VISION. There is a purely theoretical self-learning algorithm behind. It is then able to classify defects independently and can also label them. fully automated! You set your width, a width of non-woven fabric, then you set the length. Then an error

catalogue, for example, is learned from our customers. And then you say directly What is a critical error? What is a non-critical error? This number will be printed on a label and also attached to the roll. This is all automated, without the influence of employees except for writing it on the label afterwards. Everything else is fully automated. You actually have to look at these errors regularly. If there are errors that cannot be assigned. You might have to look at the part. For example, if you then discover that there's a mistake, I can't assign it, somehow completely new. If necessary, you would have to unwind the roll again and then look at the point where the error appeared to see what it is."

- The camera is located after the hardening and finishing processes and that just before the cutting block
- One of the most important inspection systems we use is metal detection, because during needle hardening, these needles also tend to tend to break off. Yes exactly, because we have a metal detection system inline on every machine. So when a metal part is detected, then the system basically turns on and we were stored filled. The employee then also has a siren. The employee must then find this piece of needle and mark it or push it out.
- Problem: The number of rejects is thus significantly reduced. Unfortunately, it is not possible to avoid 100 per cent that we have no defects at all. This is not possible with any nonwoven fabric. The plants are much too large for that. You can't avoid that some particles or oil stains are not on the material.
- In the hot chamber we also have a constant temperature in the hot chamber where the material is refined. This is how we store. With the ovens I can, I don't know now, if something like that is stored as well. But we have temperature control on every furnace. And the distribution is also displayed. It is always manually controlled via monitor
- Offline:
- And there is the additional laboratory test, where the test plan is followed by additional random tests. Length, width, grammage, thickness, strength. In the end, as already mentioned, there are also tests in production, straight length, width, weight and thickness. So we try to set ourselves up on a broader basis. We can also take over the train test, but it is currently carried out in the laboratory. Both tests and then all further tests.

- **Improvement measures:**
  - Automated thickness, fiber orientation, web guidance and width measurements: the width is currently measured manually. If you measure it somehow via laser. do not know what other methods are possible. That would of course also be helpful.
  - If we don't have a constant climate in the halls, the fibers in the carding machines in the needle machines have a worse running characteristic, which can then also be seen
  - What we don't have yet- No error checking for bad edge cutting with knives. It always has to be done manually. That is, if the knives are not set properly or if they don't cut properly.

### 9.3.8 Company G Non-woven industry

**Contact person: Managing director**

**Manufacturing Process:** air-laid thermal web bonding

- **Purchase of yarn:**
  - No quality control for the purchased yarn
- **Web formation and bonding:**
  - ML-based automatic camera inspection only at the calendar machine where foreign particles, machine faults and deformities are detected and classified
  - Magnetic metal detector to identify broken needles during the process
  - Machine parameters are not recorded inline and are manually set and controlled by the employees
- **Improvement measure:**
  - Wishes an uniform structure and surface of the nonwoven.
  - It also wishes radioactive or laser based measuring instruments for inspecting surface weight and thickness continuously inline

## 9.4 Quality control solutions and measuring principles

Tab. 9.3: Complete overview of the problems and solutions in woven, knitted and non-woven industry

| Woven Fabrics | | |
|---|---|---|
| | **Problems** | **Solutions and measuring principles** |
| **Warping** | Yarn breakage (input) | Capacitive sensors |
| | | Optical sensors |
| | | Electromechanical sensors |
| | Yarn breakage (output) | Piezo-electric sensors |
| | Foreign fibers in yarn | Optical sensors |
| | Environmental influence | Temperature sensors |
| | | Humidity sensors |
| | **Problems** | **Solutions and measuring principles** |
| **Weaving** | Incorrect loom setting | Digital assistance system |
| | Machine vibration | Piezo-electric sensors |
| | Machine temperature | Temperature sensors |
| | Environmental influence | Temperature sensors |
| | | Humidity sensors |

| | Problem | Solution and measuring principles |
|---|---|---|
| **After weaving** | Fabric errors | Machine learning based automatic camera inspection |
| | **Problems** | **Solutions and measuring principles** |
| **Dyeing and Finishing** | Wrong temperature setting | Digital assistance system |
| | Wrong usage of chemical agent | |
| | Wrong speed setting of conveyer belt | |
| | Environmental influence | Temperature sensors |
| | | Humidity sensors |
| | **Problems** | **Solutions and measuring principles** |
| **End inspection** | Faulty fabric color | Spectrophotometer |
| | Fabric error | Machine learning based automatic camera inspection |
| **Knitted Fabrics** | | |
| | **Problems** | **Solutions and measuring principles** |
| **Prior to Knitting** | Yarn breakage | Capacitive sensors |
| | | Optical sensors |
| | | Electromechanical sensors |
| | | Piezo-electric sensors |
| | Foreign fibers in yarn | Optical sensors |
| | Environmental influence | Temperature sensors |
| | | Humidity sensors |
| | **Problems** | **Solutions and measuring principles** |
| **Knitting** | Incorrect machine setting | Digital assistance system |
| | Machine vibration | Piezo-electric sensors |
| | Machine temperature | Temperature sensors |
| | Environmental influence | Temperature sensors |
| | | Humidity sensors |
| | **Problems** | **Solutions and measuring principles** |

| | | |
|---|---|---|
| **After Knitting** | Broken needles | Metal detector |
| | Stitching fault | Image processing techniques |
| | Fabric errors | Machine learning based automatic camera inspection |
| | **Problems** | **Solutions and measuring principles** |
| **Dyeing and Finishing** | Wrong temperature setting | Digital assistance system |
| | Wrong usage of chemical agent | |
| | Wrong speed setting of conveyer belt | |
| | Environmental influence | Temperature sensors |
| | | Humidity sensors |
| | **Problems** | **Solutions and measuring principles** |
| **End inspection** | Faulty fabric color | Spectrophotometer |
| | Fabric error | Machine learning based automatic camera inspection |
| **Non-woven Fabrics** | | |
| | **Problems** | **Solution and measuring principles** |
| **Purchase of fiber (before manufacturing)** | Poor quality of fiber | Infrared sensor |
| | Moisture content in fiber | Capacitive measuring gate |
| | Environmental influence | Temperature sensors |
| | | Humidity sensors |
| | **Problems** | **Solutions and measuring principles** |
| **Web formation and bonding** | **Web parameters** | |
| | Surface temperature of web | Infrared sensor |
| | Moisture content in web | Infrared sensor |
| | | Microwave resonance measurement |
| | Fiber orientation | High resolution camera with an specifically developed algorithm |
| | Web weight | M-ray |

| | | |
|---|---|---|
| | | Gamma backscatter |
| | | x-ray |
| | | Beta gauge |
| | | Infrared sensor |
| | Web thickness | M-ray |
| | | x-ray |
| | | Beta gauge |
| | | Infrared sensor |
| | | Laser |
| | Web width | Infrared sensor |
| | **Machine parameters** | |
| | Web guidance | Electromechanical sensor |
| | | Infrared sensor |
| | **Environmental parameters** | |
| | Environmental influence | Temperature sensors |
| | | Humidity sensors |
| | **Problems** | **Solutions and measuring principles** |
| **End inspection (after manu-facturing)** | Broken needles | Inline metal detector |
| | Faulty fabric color | Spectrophotometer |
| | Fabric error | Machine learning based automatic camera inspection |

**Working principle of the sensors:**

Capacitive sensors are used to detect magnetically and electrically conductive objects. The sensors work contact-free. They monitor the tension variations produced by the electrical charges into the yarn in linear motion. [Pro17, Fil20]

Electromechanical sensors are also used to detect the breakage of the yarn. They monitor the strength of the running yarn and mechanical changes in the strength due to yarn breakage are transformed into electrical signals. [Pro17, Fil20]

Piezo-electric sensors can be used to monitor the final yarn output. It measures the vibration of the yarn and identifies the deviations leading to defects promptly. [Pro17, Fil20]

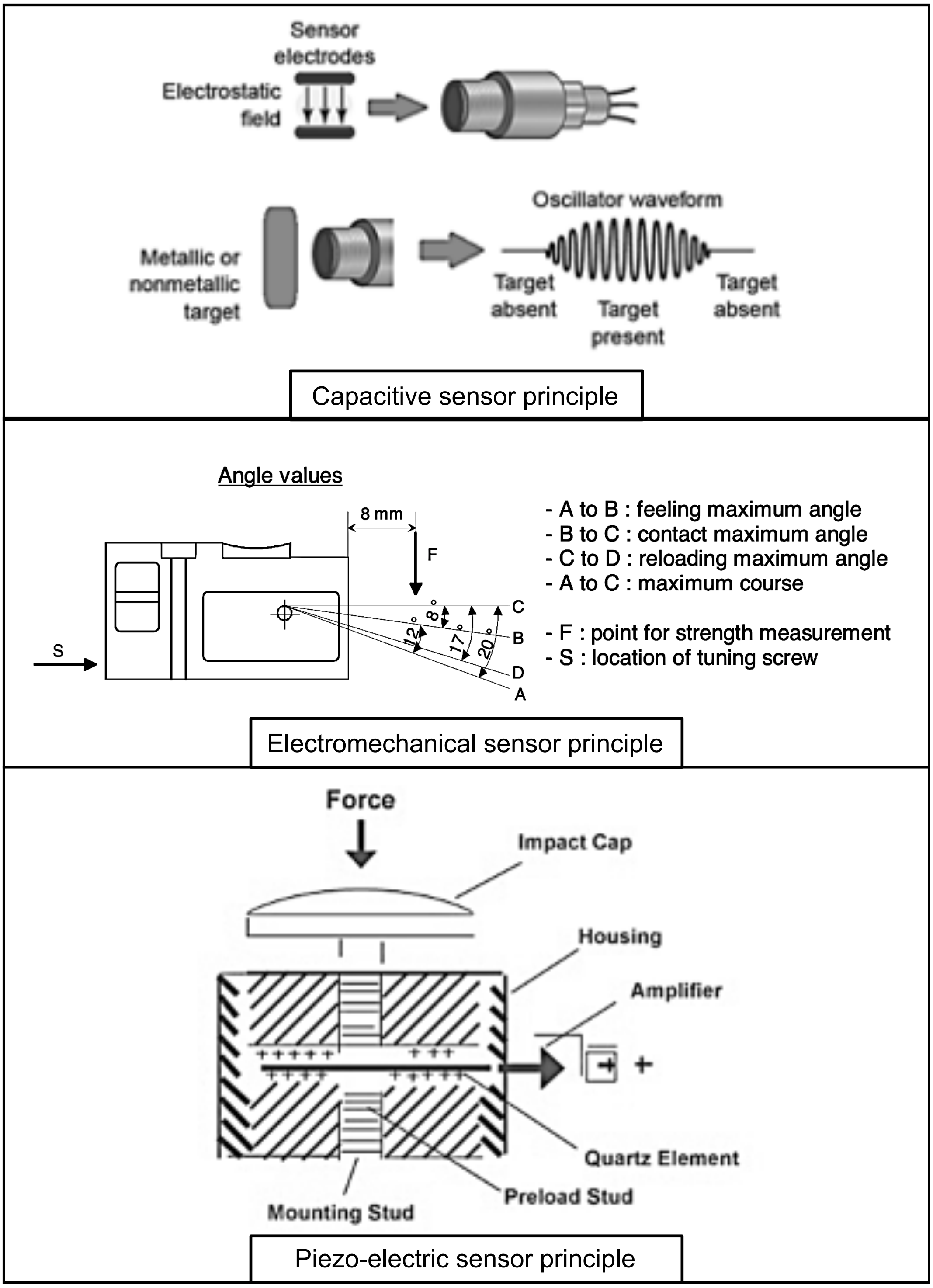


Fig. 9.1: Working principles of sensors for woven and knitted fabrics [www20k, www20l, www20m]

The principle of x-ray can be used to measure the weight of the web depending on the weakening of the intensity of the x-ray passing through the web. Similar, different isotopes can be used to generate beta rays and the weakening in the intensity of the beta rays passing through the web can be used to determine the weight. The weight of the web can also be measured with infrared sensors with the principle of infrared transmission and reflection. Reflection of laser on the web material from both sides and by taking the distance of laser from the web material into account, the thickness of the web can be measured. [www20c, www20x]

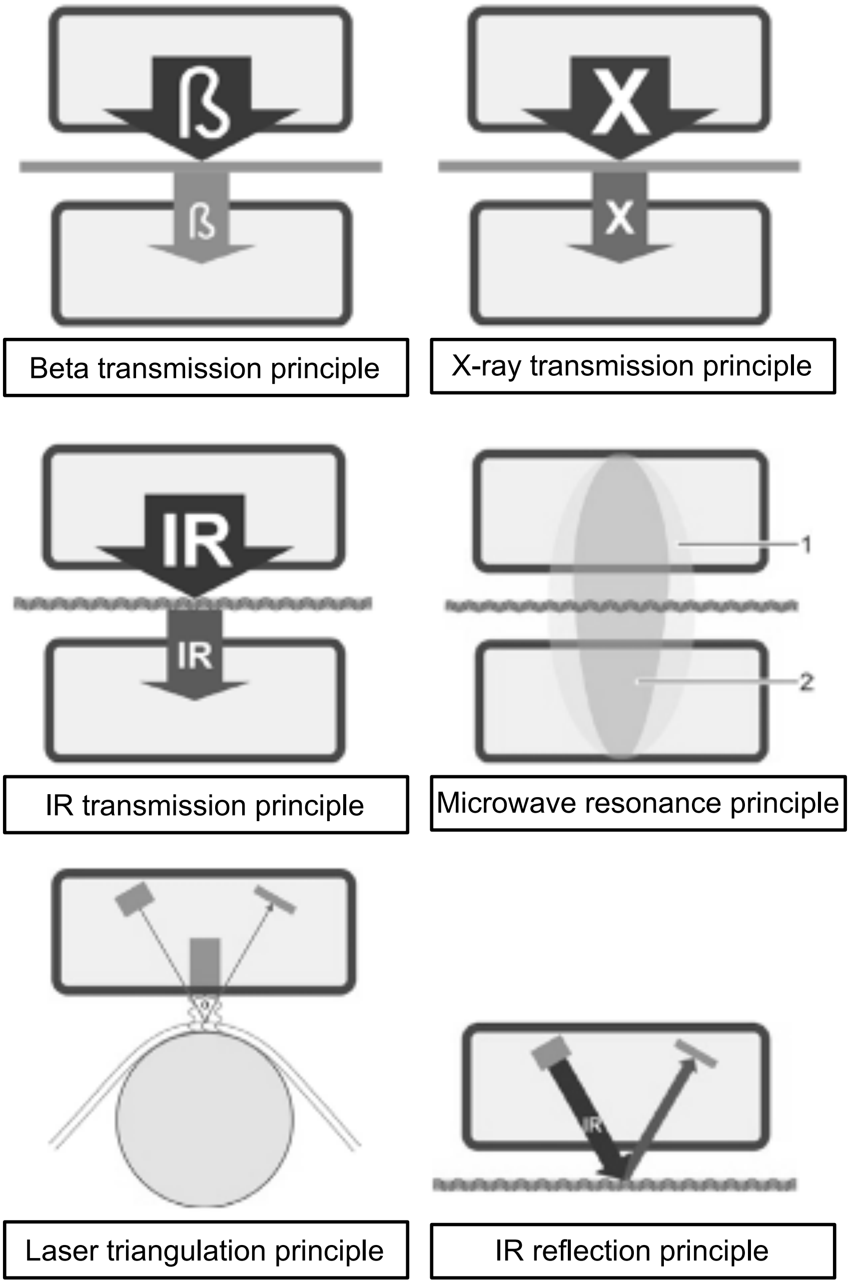


Fig. 9.2: Working principles of sensors for non-woven fabrics [www20c, www20x]

# 10 Erklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbständig angefertigt habe. Es wurden nur die in der Arbeit ausdrücklich benannten Quellen und Hilfsmittel benutzt. Wörtlich oder sinngemäß übernommenes Gedankengut habe ich als solches kenntlich gemacht.

Ort, Datum

Unterschrift

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