

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

System-based Analysis to Implement a new Data Collection Product for the Textile Industry

João Pedro Ferreira de Brito



Mestrado em Engenharia Mecânica

Supervisor: Joaquim Gabriel Magalhães Mendes

Co-supervisor: Frederico Alves Lima

July 28, 2023

System-based Analysis to Implement a new Data Collection Product for the Textile Industry

João Pedro Ferreira de Brito

Mestrado em Engenharia Mecânica

July 28, 2023

Abstract

This dissertation was developed in a corporate environment at **Smartex**, a company that has developed a quality inspection system using cutting-edge Artificial Intelligence technology, Machine Learning, and Computer Vision to reduce defective production in the textile industry.

The project consisted of three key stages for implementing data collection Hardware. In the first stage, it was expected that an in-depth analysis of a new sector from the Textile Supply Chain was performed, as well as the problems not yet assessed by Smartex were mapped out. In the second stage, it was expected that a suitable data-collection technology to tackle the problems discovered during the research stage was selected, as well as a system-based analysis for implementing it was carried out. In the last stage, it was expected that feasible solutions were proposed, tests were performed, open issues were mapped out, a first prototype was implemented, and the next steps of development of a soon-to-be new Smartex product were planned

The market analyses showed that developing a similar technology to what Smartex already has for a new sector of the industry would be the best decision when the value-added parameter was considered. Therefore a study was carried out to identify which would be the new system specifications, as well as hardware and software requirements. In sequence, a product ideation moment was carried out for understanding which would be the potential approaches to meet those requirements. The most difficult specification to meet was related to the high machine throughput of the selected process to be inspected, which will require further analyses and research to effectively tackle the problem.

This work serves as a backbone for sustaining the development of a new product in the following years, as well as a benchmark for other possible new solutions that Smartex might want to explore within this sector of the industry.

Keywords: System, Hardware, Software, Artificial Intelligence, Product Ideation,

Resumo

Esta dissertação foi desenvolvida em um ambiente empresarial na **Smartex**, uma empresa que desenvolveu um sistema de inspeção de qualidade utilizando tecnologia de Inteligência Artificial de ponta, Aprendizado de Máquina e Visão Computacional para reduzir a produção defeituosa na indústria têxtil.

O projeto consistiu em três etapas-chave para implementação de hardware de coleta de dados. Na primeira etapa, esperava-se realizar uma análise aprofundada de um novo setor da Cadeia de Suprimentos Têxteis, bem como mapear os problemas ainda não avaliados pela Smartex. Na segunda etapa, esperava-se selecionar uma tecnologia adequada de coleta de dados para enfrentar os problemas descobertos durante a fase de pesquisa, além de realizar uma análise baseada em sistema para implementação. Na última etapa, esperava-se propor soluções viáveis, realizar testes, mapear questões em aberto, implementar um primeiro protótipo e planejar os próximos passos para o desenvolvimento de um novo produto Smartex em breve.

As análises de mercado mostraram que desenvolver uma tecnologia similar ao que a Smartex já possui para um novo setor da indústria seria a melhor decisão considerando o parâmetro de valor agregado. Portanto, foi realizado um estudo para identificar quais seriam as novas especificações do sistema, bem como os requisitos de hardware e software. Em seguida, foi realizado um momento para conceptualizar o produto e compreender quais seriam as potenciais abordagens para atender a esses requisitos. A especificação mais difícil de atender estava relacionada às altas velocidades de processamento da máquina onde o sistema seria instalado, o que exigirá análises e pesquisas adicionais para enfrentar efetivamente o problema.

Este trabalho serve como base para sustentar o desenvolvimento de um novo produto nos próximos anos, além de servir como referência para outras possíveis soluções que a Smartex possa querer explorar dentro desse setor da indústria.

Keywords: Sistema, Hardware, Software, Inteligência Artificial, Idealização de Produto

Acknowledgements

This dissertation marks the end of my journey in academia, although it's not quite the end, and the beginning of a new chapter as a young professional, which is also not quite the beginning. Without further ado, I would like to express my gratitude to every single person who made these years possible.

Crossing the Atlantic as a teenager in search of this opportunity was both exhilarating and challenging. I owe a special thanks to my family for their support and encouragement. Starting a new life in a foreign country is not easy, and I am grateful for my friends who made it a walk in the park.

Finding a good job, especially when you are just starting out in the field, can be a difficult task. I am immensely grateful to the Smartex family for these amazing two years of growth and learning. Continuously challenging ourselves in the workplace while having fun is a rare and valuable experience. For making it possible, I would like to thank my colleagues on the Product team.

Facing health issues that required me to pause and reassess my life was scary. For easing the suffering, I would like to thank the doctors who have provided exceptional care during this journey. For helping me not lose my mind during the pandemic and other difficult periods, I would like to thank my therapist.

A big thank you to the Smartex family, in special the DevOps, Embedded, Hardware, ML, Product, R&D, and Service Eng. teams. I would also like to thank the PJDA, SN, PDG, DL+ROCA, families for their love and support.

Last but not least, I would like to thank all of the following people. None of this would be possible without any of you! André Brito, Andréa Ferreira, António Rocha, Bruna Medeiros, Catarina Violante, Carolina Napolitano, Chanalisa Salvi, Claudia Castro, Cornélio Lacerda, Eduardo Pereira, Fernanda Tormin, Frederico Lima, Gabriela Tavares, Gilberto Loureiro, Joaquim Gabriel, João Alves, Ligia Ogata, Ludmila Guedes, Paula Carneiro, Paulo Ribeiro, Rafael Lima, Rennan Damiani, Ricardo Ferreira, Ricardo Fernandes, Rita Bugalhão, Rita Miragaia, Rui Rodrigues, Tânia Carvalho, Tiago Gonçalves, Tiago Santos, and Tiago Pinto.

João Pedro Ferreira de Brito

*“It’s like our dear investor always says; if you’re not ashamed of the first version of your product,
you took way too long to launch it”*

António Rocha, a.k.a. ToJobs

Contents

1	Introduction	1
1.1	Background and motivation	1
1.2	Smartex overview	2
1.3	Dissertations Objective Key Results (OKRs)	3
1.4	Document structure	4
2	State of the Art	5
2.1	Systems Engineering Method	7
3	Smartex.ai technology	15
3.1	Hardware	15
3.1.1	Heavy Module (HM)	15
3.1.2	Light Modules (LM)	16
3.1.3	Master Module (MM)	16
3.1.4	AI Booster	16
3.1.5	Finis Module	16
3.1.6	Tablet	16
3.2	Software	17
3.2.1	Sensing Service	17
3.2.2	Core Service	18
3.2.3	Machine Learning Service	18
3.2.4	Machine Service	18
3.2.5	Services Network	19
3.3	System	19
4	Industry assessment and Preliminary tests	23
4.1	Textile Industry characterization	23
4.2	Discovery sessions	25
4.2.1	Processes, Workflow, and Challenges	26
4.2.2	Opportunities Evaluation and Technology Selection	29
4.3	Preliminary tests	32
5	Product Ideation and System Modifications	39
5.1	Requirement analysis	39
5.1.1	System Requirement Specifications	40
5.1.2	Hardware Requirements	40
5.1.3	Software Requirements	43
5.2	Partnership selection	43

5.3	Product ideation	44
5.3.1	Using USB 3.0 cameras	44
5.3.2	Using multiple MM	45
5.3.3	Using the cameras in streaming mode instead of trigger mode	46
5.3.4	Rotating all modules 90° and use the cameras' HFOV as if it was the VFOV	48
5.3.5	Using multiple camera bars on a single system	48
5.4	Mechanical design	48
5.4.1	Machine assessment	49
5.4.2	Clamps design	50
5.4.3	Solidworks Assembly	50
5.5	Modifications	52
5.5.1	Hardware modification	52
5.5.2	Software modification	54
6	Workflow Documentation and Discussion	57
6.1	Workflow Documentation	57
6.2	Prototype Implementation	60
6.3	Open issues and Further work	60
7	Conclusion	65
	Appendices	67
	Appendix A PRD Template	69
	References	75

List of Figures

1.1	Woven fabric production back in 1970 and 2020. Picture from Smartex resources collection	2
2.1	Visual representation of a system with its boundaries, environment, input, and output	5
2.2	Schematic representation of the waterfall model	9
2.3	Schematic representation of the spiral model	10
2.4	Schematic representation of the v-model	11
2.5	Schematic representation of the Scrum methodology	13
3.1	Smartex's Software modules and respective Hardware where they run, if applicable	17
3.2	Simplified scheme of Smartex Network. In purple are the main Embedded SW Services and in green are the module through which the operators can interact with the Smartex system.	19
3.3	Smartex system. (a) Smartex equipped Open-width CKM with open doors, (b) Smartex equipped Open-width CKM with closed doors, (c) Schematic showing a Smartex equipped CKM.	20
3.4	Schematic for the Rapport analogy	21
4.1	Standard method for marking rolls. (a) The material used (b) A roll being marked for further identification	25
4.2	Textile and Fashion industry stages and impact direction. Image from Smartex repository	25
4.3	Example of a typical Dyehouse workflow for knitted fabrics	28
4.4	Opportunity tree with potential solutions for each pain point	30
4.5	Defect number 122762-01-1: knitted fabric with ink stain - (a) Original defect sample; (b), (c), (d), and (e) are pictures taken with different parameters by the Smartex system	34
4.6	Defect number 128034-OL: woven fabric with ink droplets - (a) Original defect sample; (b), (c), (d), and (e) are pictures taken with different parameters by the Smartex system	35
4.7	Defect number 127334-A, sample 1: knitted fabric with ink stain - (a) Original defect sample; (b), (c), (d), and (e) are pictures taken with different parameters by the Smartex system	36
4.8	Defect number 127334-A, sample 2: knitted fabric with ink droplet - (a) Original defect sample; (b), (c), (d), and (e) are pictures taken with different parameters by the Smartex system	37
4.9	Defect number 124815IF: knitted fabric with silicon stains - (a) Original defect sample; (b), (c), (d), and (e) are pictures taken with different parameters by the Smartex system	38

5.1	Internal parts of a Heavy Module highlighting the RJ45 pano mount 8 pieces . . .	45
5.2	Two MM connected to one another via a Master-Slave technique through an Ethernet cable	47
5.3	Machine assessment (a) Plane of interest (b) Tapped holes to be used for designing the structural parts	49
5.4	Simplified model of the Stenter Machine on Solidworks where the holes and shafts of interest are represented	49
5.5	Clamp design (a) Flattened clamp (b) Clamp after folding	50
5.6	System assembly showing FOV. (a) Perspective view (b) Parallel-to-fabric view (c) System-cut view	51
5.7	Disassembled MM for modification showing the location where the hole will be drilled and the RJ45 pano mount to be assembled on the hole	52
5.8	HM with USB 3.0 cameras	53
5.9	Modified HM - 4 HM with flipped PCBAs, 2 non-flipped HM, 2 HM without female DB9s after desoldering	54
5.10	Modifications on Network Settings (a) Modifications performed on the MM (b) Modifications performed on the Finis Module	55
6.1	Command given for setting a fake RPM value for the IMU in installation 577 . .	58
6.2	(a) Command given on the first terminal to monitor all the Sensing Service logs (b) Command given on the second terminal to monitor only the critical logs (b) Command given on the third terminal to monitor only the warning logs	59
6.3	Final installation (a) System mounted on the Stenter Machine, (b) Master Module on top of the right side clamp, (c) Tablet and server cabinet	61
6.4	Tablet showing white pictures due to Camera Version and Vision SW incompatibility	62
6.5	Tablet showing pictures with wrong exposure	63

List of Tables

2.1	System Functional Elements	6
2.2	System Components	7
4.1	Dyehouse’s stages, their descriptions, and associated processes	26
4.2	Processes, machines where then can be performed, and a short description of why they are performed	27
4.3	Defects observed on the Stenter machine since January 1st, 2023.	31
5.1	System requirements	41
5.2	Hardware Requirements and the System Requirement it derived from in parentheses	42
5.3	Software Requirements and the System Requirement it derived from in parentheses	43

Abbreviations

AI	Artificial Intelligence
BCG	Boston Consulting Group
BMS	Battery Management System
CKM	Circular Knitting Machine
CV	Computer Vision
DB	Database
DB9	D-subminiature 9-pin
DIN	Deutsches Institut für Normung
ERP	Enterprise Resource Planning
FNI	Fabric Not Inspected
FOV	Field of View
FW	Firmware
GHG	Greenhouse Gas
HFOV	Horizontal Vertical Field of View
HM	Heavy Module
HW	Hardware
IMU	Inertial Measurement Unit
IT	Information Technology
LAW	Light Attenuator Window
LCA	Life Cycle Assessment
LED	Light Emitting Diode
LM	Light Module
ML	Machine Learning
MM	Master Module
MoE	Measures of Effectiveness
OEKO-TEX	Ökologisch Textil
OKR	Objective Key Result
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
Rbw	Required Bandwidth
RFID	Radio Frequency Identification
RPi	Raspberry Pi
RPM	Revolutions per Minute
RJ45	Registered Jack 45
SAC	Sustainable Apparel Coalition
SSH	Secure Shell

SW	Software
SyRS	System Requirements Specification
UI	User Interface
UX	User Experience
VFOV	Vertical Field of View
WD	Working Distance
WRAP	Worldwide Responsible Accredited Production
ZDHC	Zero Discharge of Hazardous Chemicals

Chapter 1

Introduction

Due to the growing worldwide trend on optimal use of natural resources, as well as the rising concerns towards climate change, different industries started a sprint to find efficient solutions for their current sustainability-related problems. In the last years, the search for environmental-friendly technology was busted either by internal or external factors. Some enterprises took part in this endeavor for marketing strategy purposes - such as the ones described by Fuxman *et al.* [1] -, but the vast majority only do it to comply with Environmental, Social, and Governance (ESG) goals imposed to them by pure top-down pressure from international treaties, major legislation, and local policies [2].

1.1 Background and motivation

The efforts towards less environmentally hazardous production are increasing day by day, but some industries, such as the Textile and Fashion industry, still lag in this regard. According to a report released in early 2021 by the World Economic Forum in collaboration with the Boston Consulting Group (BCG), the Textile and Fashion industry ranks #3 among the big eight supply chains responsible for global emissions [3]. In concrete numbers, this industry is responsible for 5% of global Greenhouse Gas (GHG) emissions [3] and 20% of global clean water pollution [4]. Furthermore, the defective production rates reach up to 5% of total production, which translates into a \$30+ Billion loss [5]. One of the root causes of these negative numbers stems from the fact that the manufacturing processes throughout the supply chain have hardly changed over the past 50 years as shown in Figure 1.1.

This macro scenario drives the industry's stakeholders to an incessant search for mechanisms that allow them to first track their production impact and then reduce it. On the other hand, in the absence of quality data, the fashion sector usually relies on certifications, labels, and voluntary industry initiatives, such as the Higg Index and Sustainable Apparel Coalition (SAC), bluesign, Ökologisch Textil (OEKO-TEX), Cradle to Cradle, Ellen MacArthur Foundation, Textile



Figure 1.1: Woven fabric production back in 1970 and 2020. Picture from Smartex resources collection

Exchange, The Microfibre Consortium, Zero Discharge of Hazardous Chemicals (ZDHC), Worldwide Responsible Accredited Production (WRAP), and the EU Ecolabel [6]. However, these initiatives do not accurately predict their impact since they are based on human input and average values of the industry to calculate their metrics, leading to major greenwashing scandals, as exemplified by the Higg Index incident in June 2022 [7].

Given the context, it is clear that there is a giant window of opportunities for those who want to build disruptive technology to accurately assess the industry impact, as well as monitor production data to increase quality and reduce waste. Smartex is an example of that. Founded in 2019, Smartex has already become one of the major innovators worldwide in this industry, pushing the boundaries for sustainable and efficient textile production. This project is evidence that Smartex keeps innovating in the field, continuing its endeavor of collecting reliable production data of all sorts of granularity to prevent waste, reduce impact, increase quality, and bust productivity in all of its clients.

1.2 Smartex overview

Smartex's main solution is based on Computer Vision (CV), Machine Learning (ML), and Artificial intelligence (AI), along with a customized hardware system, capable of detecting defects during the production phase. This solution consists of an easily integrable system for Circular Knitting Machines (CKMs), capturing and analyzing 100% of the production in real-time for the presence of defects, and having the ability to intervene in the production line, preventing production failures and waste generation. Compared to existing solutions in the market, it stands out as

unique and revolutionary due to its capacity to safeguard all production images, enabling traceability in the supply chain. The solution also enhances the operational management performance of the company itself, providing an intuitive interface for accessing production statistics.

In 2022, Smartex focused on increasing the maturity level of its inspection system that detects defects in real-time on textile production. In this regard, besides the continuous development of the system integration with open-knit CKMs, the company also started a large-scale development process for integrating its systems on tubular CKMs. Naturally, by adapting the inspection system to a larger variety of machine types, Smartex contributes to a positive environmental impact in the textile sector and reduces waste.

Given the circumstances and the business strategy of the company, it is time to take the next step toward Smartex's vertical expansion. This project aims to analyze the industry scenario, map the current opportunities and come up with the first drafts of a new data-collection product to be inserted into the company portfolio

1.3 Dissertations Objective Key Results (OKRs)

This dissertation aims to address three main tasks using a multidisciplinary approach. It will draw upon the skills acquired during both the Bachelor's and Master's degrees in Mechanical Engineering, as well as concepts of System Engineering. The three tasks are:

1. Perform an in-depth analysis of a new sector from the Textile Supply Chain and map out the problems not yet assessed by Smartex
2. Select a suitable data-collection technology to tackle the problems discovered during the research stage and perform a system-based analysis for implementing it.
3. Propose feasible solutions, perform tests, map out open issues, and plan the next steps of development of the soon-to-be new Smartex product.

The first stage has a research-oriented approach. It comprises client discovery visits, internal staff interviews, specialist interviews, and a literature review. After performing all of these activities, it is expected that a detailed workflow map of the industry sections of interest is created, along with an opportunity tree including concrete examples of all the problems discovered. In addition, the opportunity tree is also expected to provide some potential solutions for each problem encountered.

The second stage, in turn, encompasses both analytical and creative activities in their nature. It involves ranking the possible solutions identified in Stage 1 based on their added value, conceptualizing these solutions, assessing their feasibility, evaluating their alignment with the company's main goals, performing preliminary tests, deciding on the implementation of a specific solution, and gathering all the requirements for its development.

The final stage entails typical engineering and product development tasks composed of machine assessments, custom parts design, off-the-shelf hardware modifications, tests in controlled environments, iterations on the Hardware design, and finally testing the final prototype *in loco*.

1.4 Document structure

Most of the work done throughout the months was documented in this report, making a good compromise between both the business-sensitive information that must be undisclosed, and the commitment to the academia with the required transparency and clarity upon scientific documents. Having this disclaimer in mind, this document is organized into 6 main sections, one of them being the introduction - Chapter 1.

Chapter 2 presents the state-of-the-art concepts on multiple fronts that were key for this project. Further on, Chapter 4 reports the industry assessment and preliminary tests that were performed to validate the first ideas. Chapter 5, in turn, reports the requirement analysis performed, the product ideation sessions, the mechanical design of custom parts, as well as some Hardware and Software modifications that were carried out. Chapter 6 presents the workflow documentation, the prototype implementation, and a section with both open issues & future work. To finish it up, the conclusions will be addressed in chapter 7.

Chapter 2

State of the Art

In the mid-20th century, researchers from various fields formulated systems theory to address challenges posed by complex systems [8]. The term *System* has a global meaning and can be defined as a generic term for bridging details and indicating identified links, structures, objects, and other elements. It encompasses a wide range of natural and artificial systems, including biological, physical, mechanical, thermal, chemical, electrical, political, economic, and conservative systems, among others. Examples of systems include the periodic system of elements, zoological system, messaging system, and political system [9]. In short, a system can be defined as a collection of interacting and interconnected elements or components that work together to perform a specific function or achieve a particular goal [10].

According to the Deutsches Institut für Normung (DIN) 19226 for Control Engineering, a system, as seen in Figure 2.1, is a configuration of mutually interacting elements. It encompasses a set of interconnected components that interact with each other and are separated from their environment by an enveloping surface. This enveloping surface forms the system boundary and intersects the links between the system and its environment. The norm also states that a system can receive inputs from the environment and produce outputs that affect the environment. Additionally, systems can be composed or subdivided to form larger or smaller systems [11]. It is important to

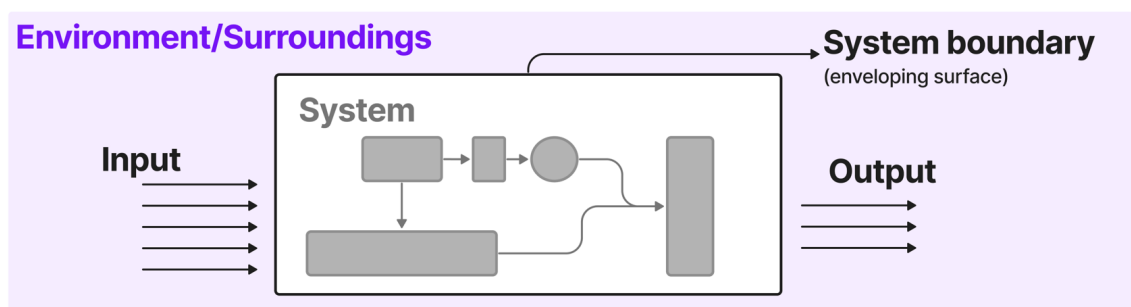


Figure 2.1: Visual representation of a system with its boundaries, environment, input, and output

note that a system is always a subsystem, implying the existence of a larger system within which it operates.

In System Engineering, there are two fundamental dimensions considered when analyzing and designing complex systems: the functional dimension and the physical dimension. The functional dimension of a system refers to its behavior, operations, and the functions it performs to achieve its goals. There are 4 types of functional elements¹, namely *Signal*, *Data*, *Material*, and *Energy* as shown in Table 2.1 [10]:

Table 2.1: System Functional Elements [10]

Class function	Element function	Applications
Signal – generate, transmit, distribute, and receive signals used in passive or active sensing and in communications	Input signal Transmit signal Transduce signal Receive signal Process signal Output signal	TV camera FM radio transmitter Radar antenna Radio receiver Image processor
Data – analyze, interpret, organize, query, and/or convert data and information into forms desired by the user or other systems	Input data Process data Control data Control processing Store data Output data Display data	Keyboard Computer CPU Operating system Word processor Printer
Material – provide system structural support or enclosure, or transform the shape, composition, or location of material substances	Support material Store material React material Form material Join material Control position	Airframe Shipping container Autoclave Milling machine Welding machine Servo actuator
Energy – provide and convert energy or propulsive power to the system	Generate thrust Generate torque Generate electricity Control temperature Control motion	Turbojet engine Reciprocating engine Solar cell array Refrigerator Auto transmission

On the other hand, the physical dimension also referred to as components, deals with the tangible parts of the system, i.e. the hardware and software that constitutes the system. Table 2.2 shows the existing types of components, their functions, and applications. Hardware elements of a system include physical devices, equipment, and materials that perform specific functions within the system, whereas Software elements refer to the programs, instructions, and data that control and coordinate the operation of hardware components within the system [10].

¹It is important to notice that both Signal and Data elements can be placed under the umbrella of the basic system-constituent entity *Information*

Table 2.2: System Physical Elements, also referred to as System Components [10]

Category	Component	Functional element(s)
Electronic	Receiver	Receive signal
	Transmitter	Transmit signal
	Data processor	Process data
	Signal processor	Process signal
	Communications processors	Process signal/data
	Special electronic equipment	Various
Electro-optical	Optical sensing device	Input signal
	Optical storage device	Store data
	Display device	Output signal/data
	High-energy optics device	Form material
	Optical power generator	Generate electricity
Electromechanical	Inertial instrument	Input data
	Electric generator	Generate electricity
	Data storage device	Store data
	Transducer	Transduce signal
	Data input/output device	Input/output data
Mechanical	Framework	Support material
	Container	Store material
	Material processing machine	Form/join material
	Material reactor	React material
	Power transfer device	Control motion
Thermomechanical	Rotary engine	Generate torque
	Jet engine	Generate thrust
	Heating unit	Control temperature
	Cooling unit	Control temperature
	Special energy source	Generate electricity
Software	Operating system	Control system
	Application	Control processing
	Support software	Control processing
	Firmware	Control system

2.1 Systems Engineering Method

The System Engineering Method refers to a structured engineering approach to developing complex systems. The process consists of a series of steps or phases for developing the systems in an organized, consistent, and uniform way until its full materialization, leading to the creation of a fully engineered model that meets operational requirements reliably and within budget [10, 12]. The Systems Engineering Method relies on four pillars as shown below:

1. **Requirements analysis:** it involves collecting and structuring clear and measurable statements that specify the necessary operational and functional design features or limitations for

the system to be considered acceptable [13]. According to Brooks [14] *"The hardest single part of building a system is deciding precisely what to build. No other part of the conceptual work is as difficult as establishing the detailed technical requirements"*, therefore it is essential to perform a thorough analysis of the requirements before moving toward the next steps of the engineering [10, 12].

2. **Functional definition:** this step refers to the process of translating requirements into specific functions that the system needs to perform, i.e. identifying the actions or tasks that the system must accomplish. After that, one must divide or allocate the requirements into different functional building blocks [10, 12].
3. **Physical definition:** this phase involves selecting a preferred design approach for implementing the required functions. To select the design, one can use predefined criteria e.g. Measures of Effectiveness (MoE), which could include factors like performance, risk, cost, and schedule. The design is then elaborated to a detailed level [10, 12].
4. **Design validation:** this stage comprises the process of ensuring that the design meets the requirements and its acceptance criteria. This validation is carried out through various activities that can include creating models of the system environment for simulating or testing the selected design. [10, 12].

The following subsections present a few widely-used system development frameworks, namely the Waterfall model, Spiral model, V-model, and the Agile methodology, more specifically the Scrum framework. These frameworks incorporate the four pillars described above within the system life cycle.

2.1.0.1 Waterfall model

The Waterfall Model is a sequential development approach that divides the process into distinct, non-overlapping phases. Firstly, the Requirement Gathering stage involves gathering detailed requirements from the client. The Design Stage focuses on planning the technical aspects, such as programming language selection and high-level project details. The Built Stage involves coding the software based on the design. In the Test Stage, the software is thoroughly tested to ensure compliance with client specifications. The Deployment stage involves deploying the application in the intended environment, and during the Maintenance stage, any necessary code changes are implemented based on customer requests. Figure 2.2 displays a schematic of the model and its phases [10, 15].

Some of the main advantages of this model include the fact that it offers a clear and structured approach, ensuring stability and predictability. It emphasizes the importance of thorough requirement analysis and encourages progress documentation through tangible deliverables. However, it also has some limitations. It lacks flexibility, often resulting in long development times and a higher risk of failure. Therefore, the waterfall model is best suited for projects with stable requirements, shorter timelines, predictable environments, and sufficient availability of trained resources.

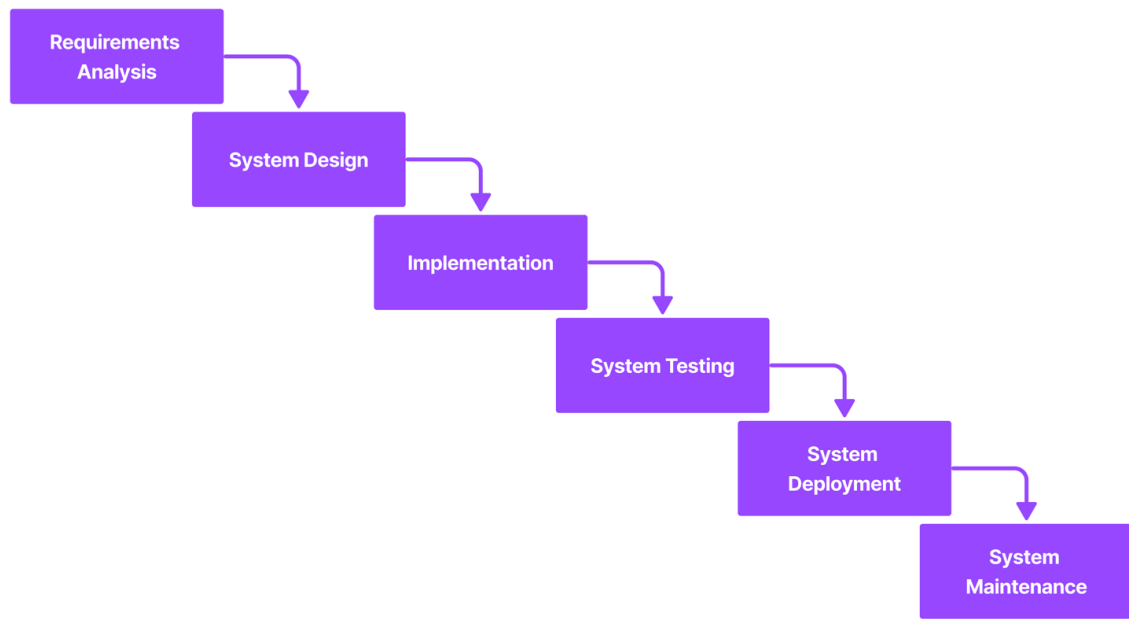


Figure 2.2: Schematic representation of the waterfall model Adaptation from [10, 15]

2.1.0.2 Spiral model

The spiral model, introduced by Barry Boehm, is a development approach that builds upon the concepts of the waterfall model. It is a flexible framework that follows an iterative process consisting of several activities. These activities include determining objectives and constraints, evaluating alternatives, identifying risks, and resolving risks by assigning priorities to them [10, 16].

The model emphasizes the development of prototypes for the identified risks, starting with the highest risk. Each prototype development follows a waterfall model, which means it goes through sequential phases like requirements gathering, design, implementation, testing, and deployment. After resolving a risk, the results of the cycle are evaluated, and planning for the next iteration takes place. If a certain risk cannot be resolved, the project may be terminated immediately. The spiral model allows for iterative refinement and risk management throughout the development process, making it suitable for projects with evolving requirements and inherent risks [10, 16–18].

The main advantages of this model rely on the fact that as the work progresses, the estimates for budget and schedule become more realistic, allowing for better project planning. Besides that, the engineers can begin working on the project at an earlier stage, enabling faster development. Additionally, the spiral model is well-suited for managing changes during development, making it easier to accommodate evolving requirements. However, the spiral model also has some disadvantages. Due to its highly customized nature, it limits reusability since each application requires a different adaptation of the model. Furthermore, estimating the budget and time at the beginning of the project can be challenging, as the requirements evolve throughout the process. This increases the risk of not meeting the initial budget or schedule [10, 16–18].

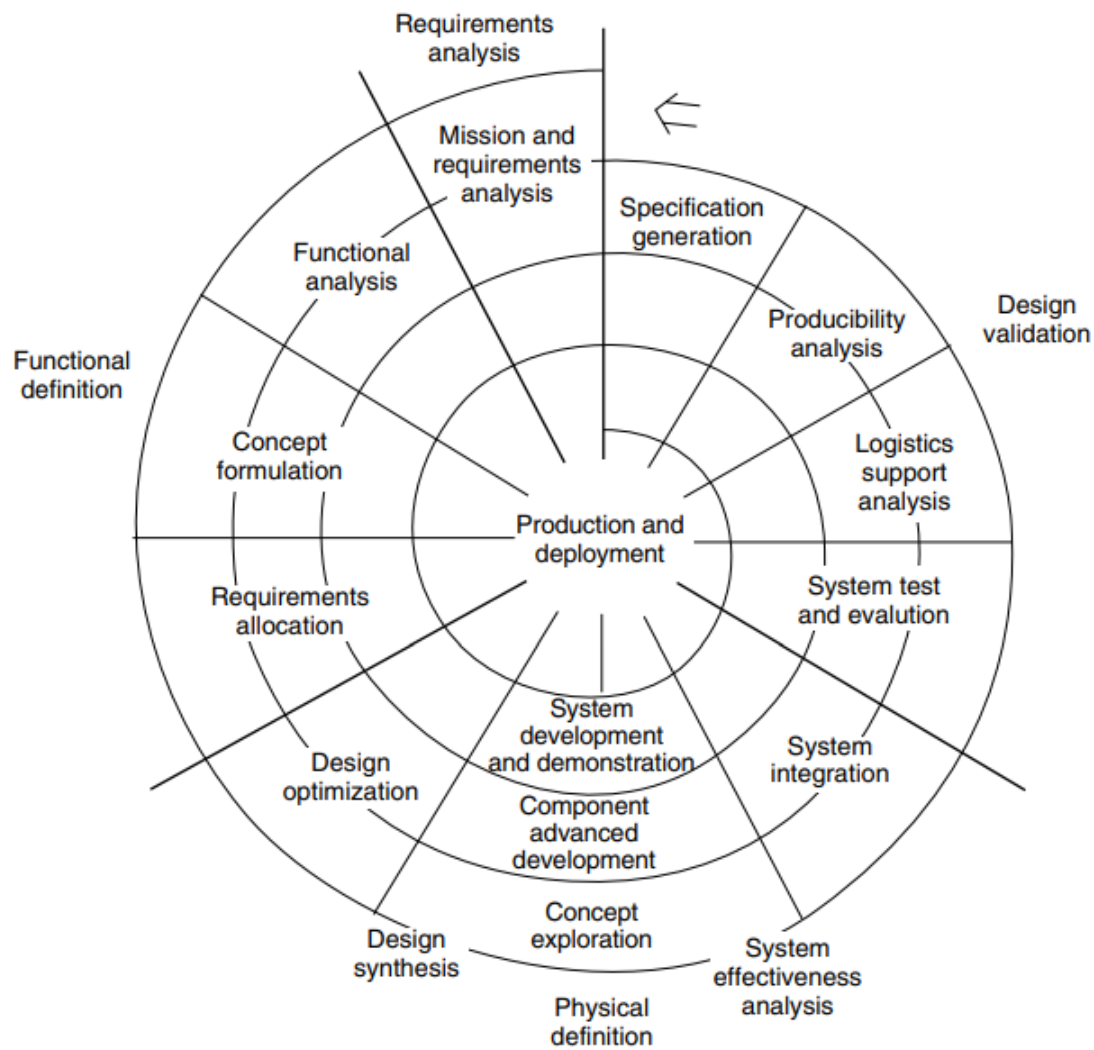


Figure 2.3: Schematic representation of the spiral model [10]

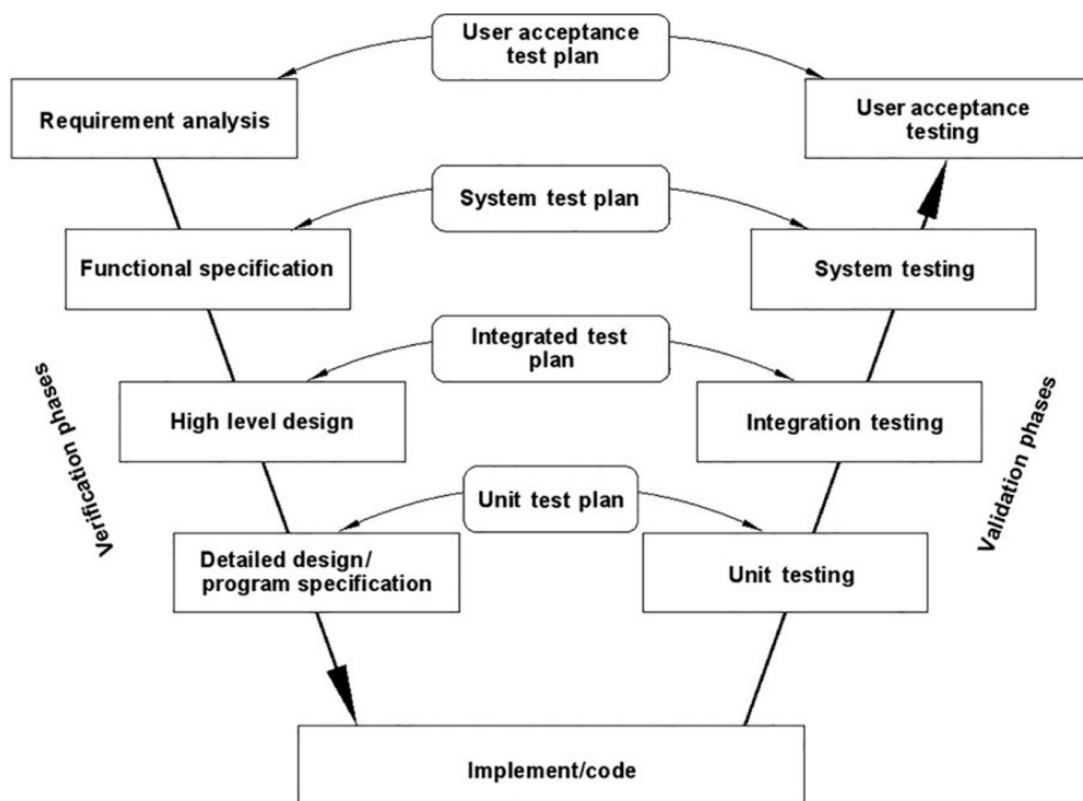


Figure 2.4: Schematic representation of the v-model [19]

2.1.0.3 V-model

The V-Model is an internationally recognized development standard for Information Technology (IT) systems. It provides a structured approach that defines the tasks to be performed, the methods to be used, and the tools required for carrying out the development process.

The V-Model, shown in Figure 2.4, is used in various applications, including serving as a basis for contracts. It ensures that the scope of hardware/software delivery and documentation completeness are clearly defined. Additionally, it functions as a guideline and instruction manual for system development, providing detailed descriptions of activities and documents. Moreover, the V-Model serves as a communication basis, facilitating mutual understanding and reducing frictional losses between stakeholders, such as customers, users, contractors, and developers. Overall, it is a comprehensive framework that offers guidance and standardization for IT system development, fostering clear communication, effective documentation, and well-defined project deliverables [19–21].

2.1.0.4 Agile methodology

In 1994 the Standish Group published a report named The Chaos Report where the traditional project management framework was evaluated. The report identifies issues such as unclear re-

quirements, lack of end-user involvement, and frequent changes as common causes of project failure. Its goal is to highlight the challenges faced by traditional project management approaches [22]. Further on, in 2021, a group of software development experts who sought to address the limitations of traditional project management approaches formulated the Agile Manifesto. The manifesto emerged from discussions and collaborations among these experts, who shared a common desire to find a more effective and flexible way of developing software [23, 24]. This new methodology is guided by four core values, namely:

1. **Individuals and Interactions over Processes and Tools:** This value emphasizes the importance of focusing on people and effective collaboration within a project. It recognizes that the success of a project is greatly influenced by the interactions and communication among team members.
2. **Working Software over Comprehensive Documentation:** Agile prioritizes the delivery of functional and usable software over excessive documentation. While documentation has its place, the primary focus is on creating working software that provides value to the customer.
3. **Customer Collaboration over Contract Negotiation:** Agile promotes active involvement and collaboration with customers throughout the development process. It values ongoing customer feedback, understanding their needs, and adapting to changing requirements rather than relying solely on fixed contracts or initial specifications.
4. **Responding to Change over Following a Plan:** Agile embraces change as an inherent aspect of software development. It emphasizes the ability to quickly respond and adapt to changes in requirements, technology, or market conditions. Agile methodologies prioritize flexibility and iterative planning to deliver the best possible outcome.

One of the most widely used Agile frameworks for managing and organizing complex software projects is named Scrum. It provides an approach to software development that emphasizes iterative and incremental delivery, collaboration, and adaptability. In Scrum, there are three key roles: the Scrum Master, the Scrum Team, and the Product Owner. The Scrum Master plays the role of a facilitator, bridging the gap between management and the project. They ensure that the Scrum values and practices are followed and act as a coach and moderator for the Scrum Team. The Scrum Team, in turn, is composed of cross-functional members, typically 5-10 people, including Quality Assurance (QA), Developers, and User Experience (UX) & User Interface (UI) designers. The Scrum Team collaborates and self-organizes to deliver the defined tasks for each sprint. The Product Owner represents the voice of stakeholders and is responsible for idealizing product features and managing the product backlog. Usually, a product manager prioritizes and determines the sequence of development tasks. These roles work together to facilitate effective communication, foster self-organization, and deliver valuable products in a Scrum project.

The development cycle in Scrum follows an incremental logic that repeats itself after each iteration. The iterations are called Sprints and usually last from 1 to 4 weeks. Prior to the sprint, the

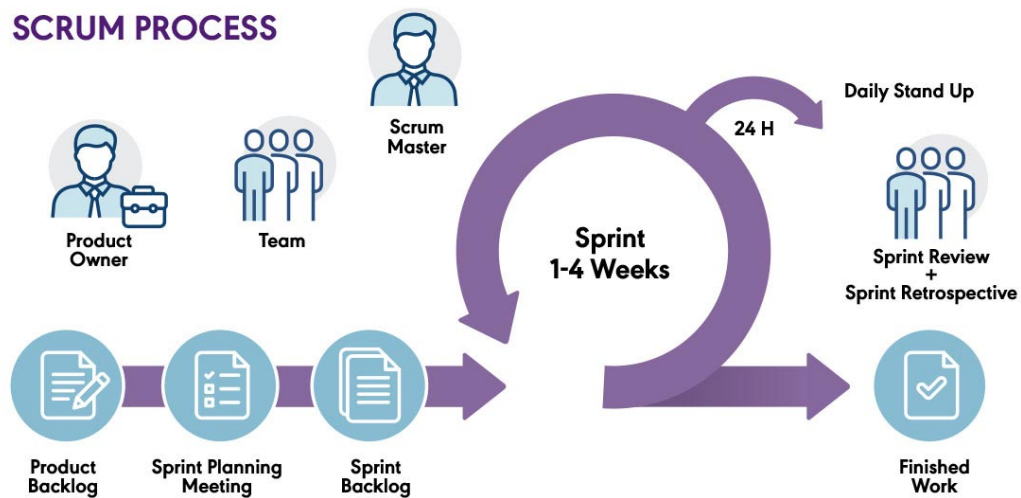


Figure 2.5: Schematic representation of the Scrum methodology [26]

Product Owner is supposed to perform their product discovery sessions and define which features will be developed for the product. These features will be then divided into small tasks that must not require more than 16 hours to be done. These tasks will be written from the perspective of the end user, originating the so-called User Stories. All the User Stories are placed on the Product Backlog, where they will be waiting until they are selected to be developed in one Sprint. Prior to each Sprint, a Planning meeting is held with all the members of the Scrum Team. The Team then select which tasks they will perform during that period taking into consideration the priorities and level of difficulty of each task. These tasks are then performed throughout the Sprint [25].

To better track the development cycle during the Sprint, Daily Stand-Up meetings are held where each team member shortly explains which tasks they are tackling that day. Other strategies for tracking the Team performance during the Sprint are the Burn-Down Charts and the Scrum Board. The Burn-Down is a visual tool that shows the remaining work or backlog items on the vertical axis and the time on the horizontal axis. As the project progresses, the chart visually depicts how the remaining work decreases over time. It helps the team and stakeholders understand if they are on track to complete the work within the desired time frame. The Scrum board, also known as a Kanban board, is another visual representation of the team's work during a sprint. It typically consists of columns representing different stages of work, such as "To Do," "In Progress," and "Done." Each work item is represented by a sticky note or card, which is moved across the board as it progresses through the stages. The Scrum board provides transparency and visibility into the team's workflow, making it easy to track and manage the status of tasks and identify bottlenecks or issues that need attention. Figure 2.5 shows the Scrum cycle in a visual-friendly way.

Chapter 3

Smartex.ai technology

As mentioned in [1.2](#), Smartex technology combines CV, ML, and AI in a customized hardware-based system to identify defects during knitted fabric manufacturing. In the following subsections, the Smartex system will be explained in detail from a Hardware, Software, and System standpoint. Understanding how this technology works is key for comprehending the adaptations performed on it throughout the following chapters of this document.

Firstly a Hardware overview will be showcased, presenting all the main HW pieces and Modules. After that, the Smartex Software will be presented, with a focus on the Local-based SW modules. To wrap it up, the System will be explained, showcasing how HW and SW interact with each other in order to perform the desired tasks

3.1 Hardware

The system consists of 6 devices, namely Heavy Module (HM), Light Module (LM), Master Module (MM), AI booster, Finis Module, and Tablet. These modules are mounted on the machine via a metallic structure that supports them in a correct position within the Circular Knitting Machine (CKM).

3.1.1 Heavy Module (HM)

The Heavy module is a device that contains a Printed Circuit Board Assembly (PCBA) with Light-Emitting Diodes (LEDs), one camera, and one D-subminiature 9-pin (DB9) connector on each side - a female on the left and a male on the right. This PCBA is placed inside a custom-made aluminum extrusion that has a hole on the top where a Registered Jack 45 (RJ45) connector is mounted, and a gap on the front where an acrylic display is placed.

The Working Distance (WD) of these modules is defined by the type of camera and lenses used. The amount of HMs used on an installation depends on the CKM where it will be installed, varying between 4 and 8 modules. The HMs are placed side by side on the assembled structure and connected to one another via DB9.

3.1.2 Light Modules (LM)

The Light Modules have a similar construction to the Heavy Modules. The main difference between these devices is that the LMs do not have a camera on them, which makes them simpler and smaller.

Similarly to the HMs, the LMs are also placed side by side on the assembled structure and connected to each other by their DB9 ports. The number of LMs used on an installation is equal to the number of HMs used.

3.1.3 Master Module (MM)

The Master Module is where the Sensing Service¹ runs. In short, it is responsible for gathering, preparing, and sending all the data collected by the HMs to the AI Booster, as well as triggering the cameras whenever the pictures must be taken. Each installation has one single MM which is placed inside the CKM alongside the HMs and LMs.

This device is composed of a custom-made PCBA inside of a metallic structure. It contains some external connectors, namely a female DB9, connector mod jack with 8 RJ45 connectors, USB 3.0, and a DC supply port. This device is responsible for pre-treating the data and sending it to the AI Booster.

3.1.4 AI Booster

The AI booster is where both the Core and ML services² run. In short, this device is responsible for treating the data, evaluating it using Machine Learning algorithms, deciding whether to intervene in the production or not, and triggering the Finis if needed.

3.1.5 Finis Module

The Finis Module is installed on the static part of the CKM and it runs the Machine Service³. It is responsible for stopping the CKM whenever the Finis Module is triggered by the Core Service.

3.1.6 Tablet

The tablet is a device the operators can use as means to interact with the Smartex system. Through the Tablet, any operator can define thresholds, see the identified defects, and have an overview of the roll that is being manufactured in that CKM.

¹Further explained on the Smartex's Software section

²Further explained in the Smartex's Software section

³Further explained in the Smartex's Software section

3.2 Software

The Smartex Software (SW) is extensive and, analogously to the HW, modular. Some parts of it are Cloud-based modules, whereas some are Local-based. The scheme in Figure 3.1 presents all the SW modules and the respective HW where they run, if applicable.

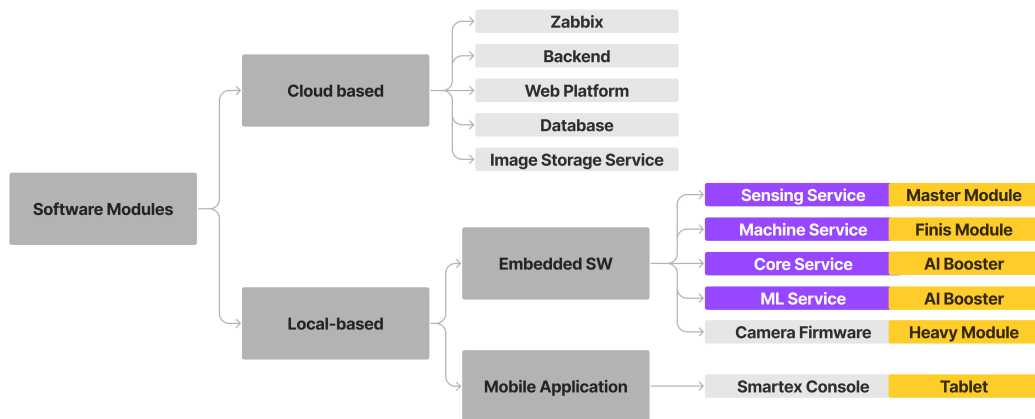


Figure 3.1: Smartex's Software modules and respective Hardware where they run, if applicable

In order to comprehend how the Smartex system works, it is essential to understand the Smartex Embedded Software, hereinafter referred to as Vision SW or just Vision. Vision comprises four services, namely Sensing, Core, Machine Learning, and Machine services. Each one of them will be explained in subsections

3.2.1 Sensing Service

The purpose of the Sensing Service is to take pictures of 100% of the fabric produced in a CKM with multiple light types and placements while communicating with the Core Service. The Sensing Service runs on the Master Module and comprises the following tasks:

- Detect, load, and calibrate cameras
- Load sensors
- Load settings from the backend
- Take pictures
- Pre-treat, and send pictures to Core Service
- Notify Core Service of CKM speed changes

3.2.2 Core Service

The purpose of the Core Service is to maintain the system state (current roll, production info, defects, stops, etc), intermediate the system communication, and send data gathered to the backend. The Core Service runs on the AI Booster and comprises the following tasks:

- Load settings from Backend and sync settings with Smartex Console
- Receive images from Sensing Service and send them to ML Service
- Process ML response, check both the current thresholds and stoppage criteria heuristics
- Trigger Finis Module if needed
- Fetch data acquired via sensors by both the Sensing and Machine Services
- Send updated information to the backend

3.2.3 Machine Learning Service

The purpose of the ML Service is to detect defects in images received from Core Service. The ML Service, like the Core service, also runs on the AI Booster and comprises the following tasks:

- Load settings from Backend
- Load ML model selected in settings
- Pre-process data
- Perform transformations to images to be fed into the ML model
- Run ML model on transformed images and return classifications to Core Service

3.2.4 Machine Service

The purpose of the Machine Service is to collect humidity data, collect temperature data, stop the machine, lock the machine, and unlock the machine. The Machine Service runs on the Finis Module and comprises the following tasks:

- Load settings from Backend
- Load sensors
- Read sensor values, lock, and unlock the machine
- Communicate the values fetched to Core Service

3.2.5 Services Network

As mentioned before, all these services communicate with each other and with the cloud. Some of them do via Ethernet cable connection, and others via wireless protocols. Figure 3.2 shows a simplified scheme of the Smartex network showing how the main Embedded SW Services, the Console, and the Backend communicate among themselves. Although the Smartex system is constantly communicating with the cloud, it is able to run offline. This allows the system to infer the images and have good performances even in challenging network environments.

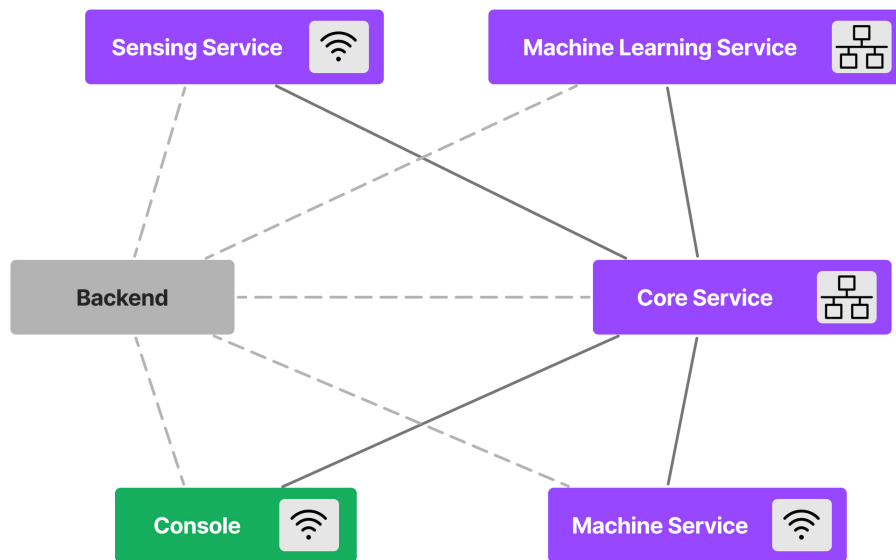


Figure 3.2: Simplified scheme of Smartex Network. In purple are the main Embedded SW Services and in green are the module through which the operators can interact with the Smartex system.

3.3 System

The combination of the HW and SW modules previously mentioned results in the system shown in Figure 3.3. The camera bars with HM and LM are installed on the CKM takedown⁴. To guarantee the correct positioning of the system, CKM assessments are carried out prior to the installation.

When the Smartex system starts inspecting the fabric, all the services mentioned in section 3.2 are fully operational. The Sensing Service will trigger the cameras, the images are then sent to the Core Service and redirected to the ML Service where the ML model will infer the quality of

⁴Region of the machine where the produced textile is located.

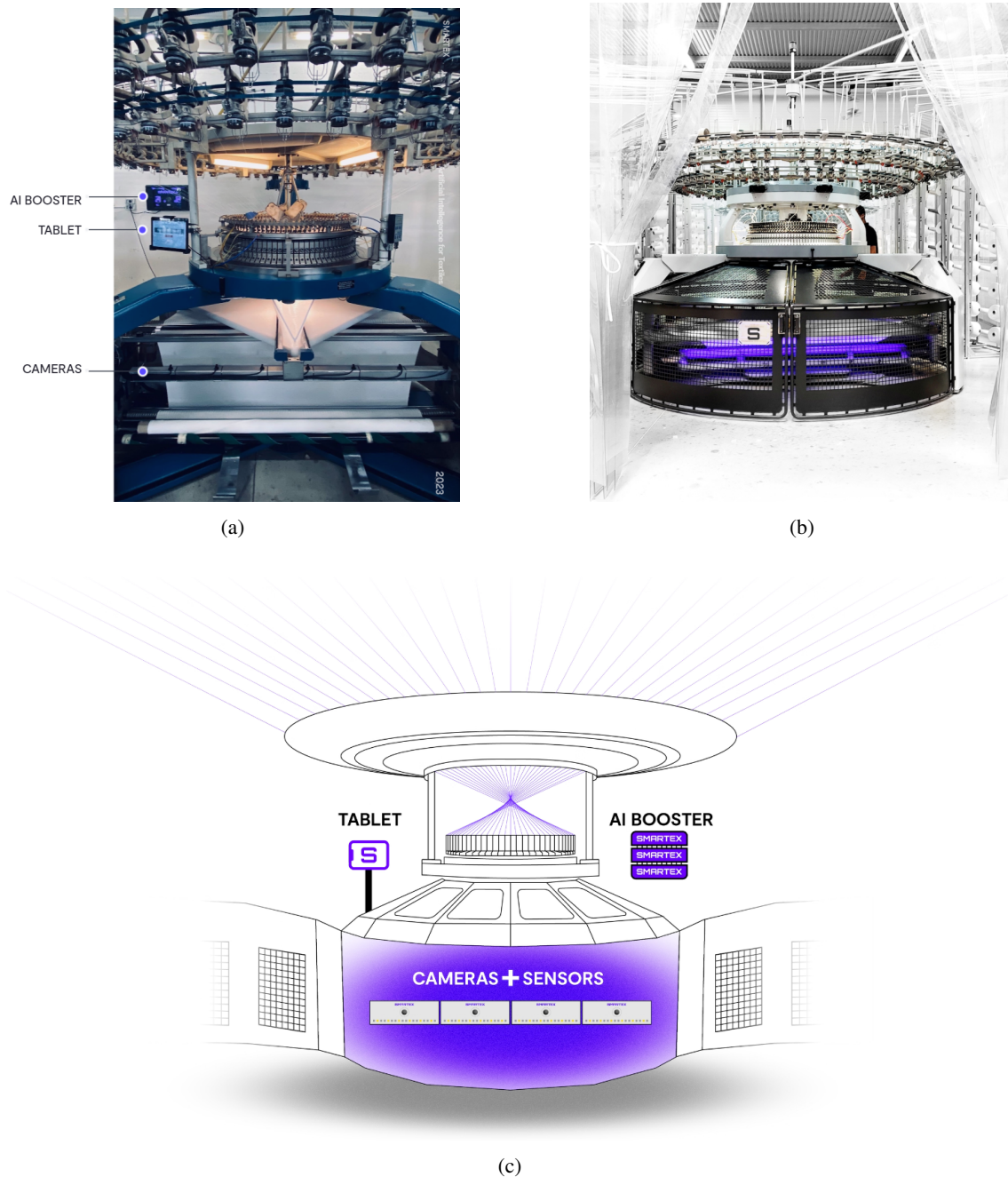


Figure 3.3: Smartex system. (a) Smartex equipped Open-width CKM with open doors, (b) Smartex equipped Open-width CKM with closed doors, (c) Schematic showing a Smartex equipped CKM.

the textile shown in the pictures, as well as give them a couple of scores and labels. The scores are then sent back to the Core Service which will compare the scores to the current threshold and stoppage criteria heuristics. A stop command is then sent to the Machine service if needed. This cycle repeats indefinitely as long as the system is running.

All the pictures taken overlap with the other pictures to guarantee 100% inspection. For the cameras to take the pictures at the correct time, guaranteeing the desired overlap, the system considers 3 different parameters: the cameras' Vertical Field of View (VFOV), the fabric Rapport⁵, and the machine rotations per minute (RPMs). The best analogy for understanding the concept of rapport is imagining that a person is painting one single yarn thread that is fed to the CKM. If that were the case, a spiral pattern would be seen in the fabric. The distance of these lines is the Rapport, i.e. the Rapport is the period of the manufactured fabric. Figure 3.4 presents a schematic for this analogy.

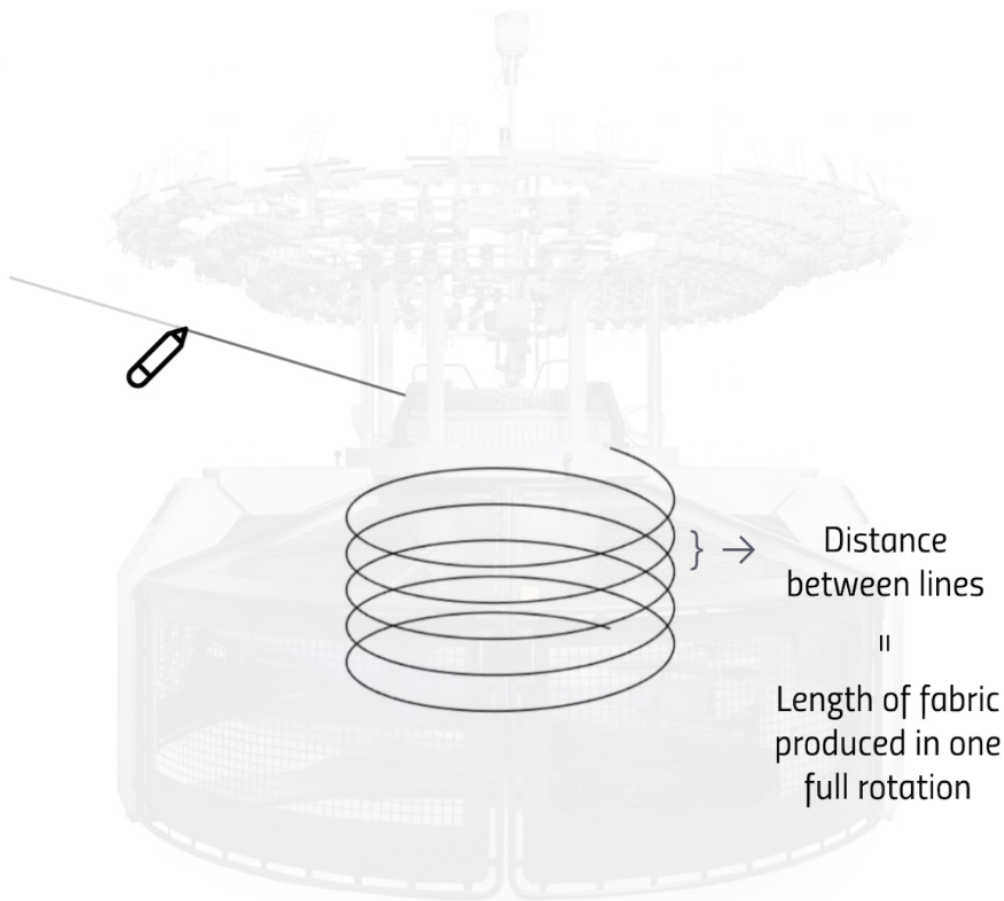


Figure 3.4: Schematic for the Rapport analogy

⁵amount of fabric produced per full CKM rotation.

Chapter 4

Industry assessment and Preliminary tests

Developing a new product for an industry begins with a comprehensive analysis of the industry as a whole. This research serves as the foundation for generating and evaluating innovative solutions to address industry challenges. It is crucial to assess the feasibility of implementing these solutions, taking into account factors such as available resources, complexity, and their impact on both the clients and the business. Furthermore, it is essential to ensure that the new technology aligns with the company's overall business goals. Balancing these considerations is key to successfully developing and implementing a new product.

This chapter provides the results of the industry assessment conducted during the initial stages of the project, which included discovery visits and both an industry specialist and Smartex's staff interviews. The key outcomes of these activities include a detailed workflow map of the relevant industry section, an opportunity tree that illustrates the problems identified, and potential solutions, if any.

4.1 Textile Industry characterization

The Textile & Fashion is \$2.4 Trillion Industry, accounting for more than 2% of global GDP [27]. It encompasses a wide range of activities related to the production of fabrics, garments, and other textile products. Although it figures among the most relevant industries worldwide, it has stopped in time in certain aspects, such as digitalization, quality control mechanisms, and traceability. These aspects are some of the contributors for this industry to rank #3 among the Big 8¹ most polluting Supply Chains.

The textile industry has an extensive supply chain that spans from cotton farmers to retailers, involving traders, spinners, knitting and weaving companies, importers, dyeing and finishing

¹Eight supply chains responsible for more than 50% of global emissions.

companies, and garment manufacturers. This chain is highly fragmented, making it challenging to trace and monitor the conditions under which textiles are produced and processed. This lack of transparency contributes to major environmental issues, labor exploitation, and unsafe working conditions scandals, which have plagued Fashion brands. Here follows a couple of testimonies presented to Smartex throughout the years that illustrate this scenario:

Example 1: *A major company that produces knitted fabrics using organic cotton faced a significant issue. They had to discontinue sourcing yarns from spinners supplied by Indian cotton fields due to a major scandal, involving the sale of regular cotton being misrepresented as organic cotton.*

Example 2: *A leading company specializing in knitted fabrics encountered an issue related to swapped textiles during the outsourcing of dyeing processes. Within the garment manufacturing sector, it is usual for companies to procure finished fabrics from specialized knitting companies, which often outsource the finishing processes. However, this particular company noticed a recurring problem where the rolls they sent for outsourcing did not match the ones they received back.*

Example 3: *A leading fashion brand is concerned about potential involvement in scandals because they lack information about labor outsourcing within their supply chain. The company is unaware of whether the companies in their supply chain engage in labor outsourcing, and if they do, this fashion brand does not know the working conditions under which this outsourced labor occurs*

One of the reasons for the lack of transparency and traceability throughout the supply chain is the lack of digitalization, making it almost impossible to create trustful mechanisms to assess any desired parameter. Figure 4.1 showcases the worldwide standard method for marking rolls and exemplifies how analog the industry is. Moreover, the standard method for logging production data consists of using countless notebooks and paper sheets for writing down every parameter used for manufacturing and processing textiles, which is extremely inefficient and prone to error.

The textile industry is known for its traditional and resistant approach to technology adoption. This perception is based on various factors. The first of them is that the industry has a long-standing history and heritage that values traditional techniques and processes. This emphasis on preserving established methods makes it difficult for the industry to embrace new technologies that may disrupt or replace them. Additionally, the reliance on manual labor combined with the lack of mechanisms able to tackle the specificities of the industry has created a mindset that resists automation and digitization. Moreover, the high cost associated with investing in advanced technologies and the required training and infrastructure upgrades poses financial challenges, particularly for companies from the first stages of the supply chain due to their low-profit margins. Additionally, a significant portion of the textile industry comprises family-owned factories that



Figure 4.1: Standard method for marking rolls. (a) The material used (b) A roll being marked for further identification

have been passed down through generations. The strong attachment to traditional methods and the resistance to deviate from established practices are deeply linked to this phenomenon, making it even more challenging to embrace new technologies and innovations. Nevertheless, the increasing pressure to enhance efficiency and sustainability, as well as comply with new-coming legislation is gradually pushing the industry to adopt innovative technologies, though at a slower pace compared to other sectors.

4.2 Discovery sessions

The Textile industry can be divided into five stages, as illustrated in Figure 4.2. Currently, Smartex technologies are present in the first half of Tier 2, in the Knitting stage. Therefore, a thorough analysis of the following stage of the industry - Dyeing - was carried out.

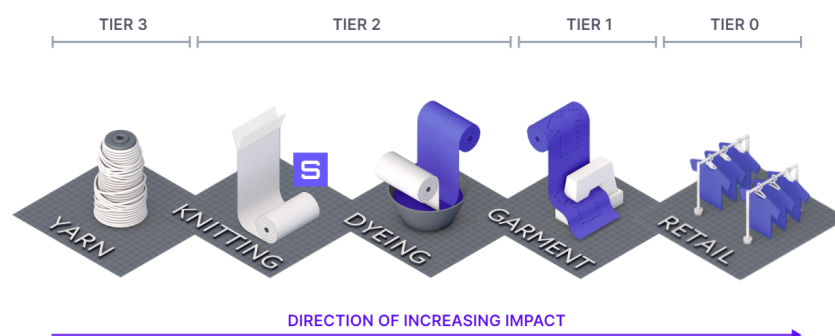


Figure 4.2: Textile and Fashion industry stages and impact direction. Image from Smartex repository

It is essential to map out the processes, understand the challenges these companies face daily, and ensure that the analysis remains unbiased, without favoring any specific stakeholder. During the discovery phase, the focus should be on understanding the overall sector scenario rather than

delving into the specific details of each player. Therefore, five different northern Portuguese Dye-houses were selected for the analysis. In each one of those companies, a series of people were interviewed, including the chiefs of production, chiefs of quality, planning assistants, chiefs of sectors, and shopfloor operators.

The Jobs-to-be-done [28] framework and guidelines were used in the assessment, resulting in interactions with a very specific structure. These visits typically ranged from 4 hours to a whole day, and in some cases, additional follow-up visits were conducted to validate the findings. The results of the assessments were further validated by consulting with industry specialists, engaging internal Smartex staff members with expertise in Dyehouses, and reviewing relevant literature. The outcomes of the discovery sessions will be organized in the following subsections:

- (i) Processes, Workflow, and Challenges
- (ii) Opportunities Evaluation and Technology Selection
- (iii) Preliminary tests

4.2.1 Processes, Workflow, and Challenges

Dyehouse processes consist of three stages: Pre-treatment, Colouration, and Finishing. Each stage may involve chemical and mechanical processes, depending on the desired outcome for the textile. Table 4.1 provides a brief description of these stages and lists the processes involved in each stage.

Table 4.1: Dyehouse's stages, their descriptions, and associated processes. Adapted from [29].

	Pre-treatment	Coloration	Finishing
Description	Pre-treatment is done before a dyeing and printing process. Its main purpose is to clean the fiber and make the dyeing or finishing step more efficient	Coloration is the application of dyestuff on textile materials such as fibers, yarns, or fabrics with the goal of achieving color with desired color fastness	In textile finishing a treatment is applied to a textile to give it a specific desirable quality or functionality, making it more suitable for its intended end use
Processes & Functions examples	Singeing, Scouring, Bleaching, Mercerization, Carbonization, Heat Setting, Drying	Dyeing (Batch or Continuous), Printing (Traditional & Digital). Note: Different dye types are used for different fibers	Mercerization, Softening, Carbonization, Coating, Brushing or Raising, (De)Sizing

Table 4.2 provides a brief description of key Dyehouse processes and the machinery required for their execution. It's important to note that these processes are not strictly sequential and may vary depending on factors such as fabric structure, composition, and desired outcome.

Figure 4.3 illustrates a typical Dyehouse workflow as an example. It is worth noting that many companies do not openly share this information, as the processes, their specifics, as well as the parameters set on the machines, are key factors that differentiate their services from the competition.

The main challenges identified during the discovery sessions in the Dyehouses are related to three key areas: transparency and communication between stakeholders, mechanisms for reporting on the quality of finished rolls, and methods for measuring impact. These three problems are very well illustrated in the following examples:

Table 4.2: Processes, machines where then can be performed, and a short description of why they are performed. Adapted from [30][29]

Process	Machine	Description
Singeing	Singeing machine	Responsible for burning the hairiness and fluff off of the surface of the fabric
Scouring	Jet machine	Responsible for removing the impurities from the textile that could interfere with further processes
Bleaching	Jet machine	Responsible for uniform the color of the fabric. Usually only performed in natural in textiles with natural fibers
Mercerization	Mercerizing machine	Usually performed to give a silk-like luster and increase strength, moisture absorbency, color yield of the fabric
Carbonization	Carbonizing machine or Carbonizing oven	Usually performed in wool fabric to get rid of potential residual impurities after scouring
Heat setting	Stenter machine	Only performed in fabrics with synthetic fibers to provide dimensional stability and shape retention for the textile
Dyeing	Jet machine	Performed to give color to the fabric. It usually is the only non-continuous process of them all
Printing	Traditional or Digital printing machines	Performed to give specific color patterns to the fabric
Squeezing	Squeezing machine	Responsible for getting rid of the excessive water on the fabric before drying
Dryeing	Stenter or Drying machine	Responsible for uniformly drying the textile after wet processes
Softening	Stenter or Tumbling machine	Responsible to enhance the softness and make the fabric more comfortable to the touch
(De)sizing	Stenter machine	Altering both the final width and density of the fabric
Coating	Stenter machine	Responsible for uniformly applying a thin film of any specific chemical on the textile surface
Brushing or Raising	Raising machine	Scrapping and pulling the fabric surface to loosen the fibers and developing a fuzzy texture
Anti-pilling	Singeing or Tumbler machine	Performed to get rid of the pilling, specially if the fabric will be submitted to printing processes

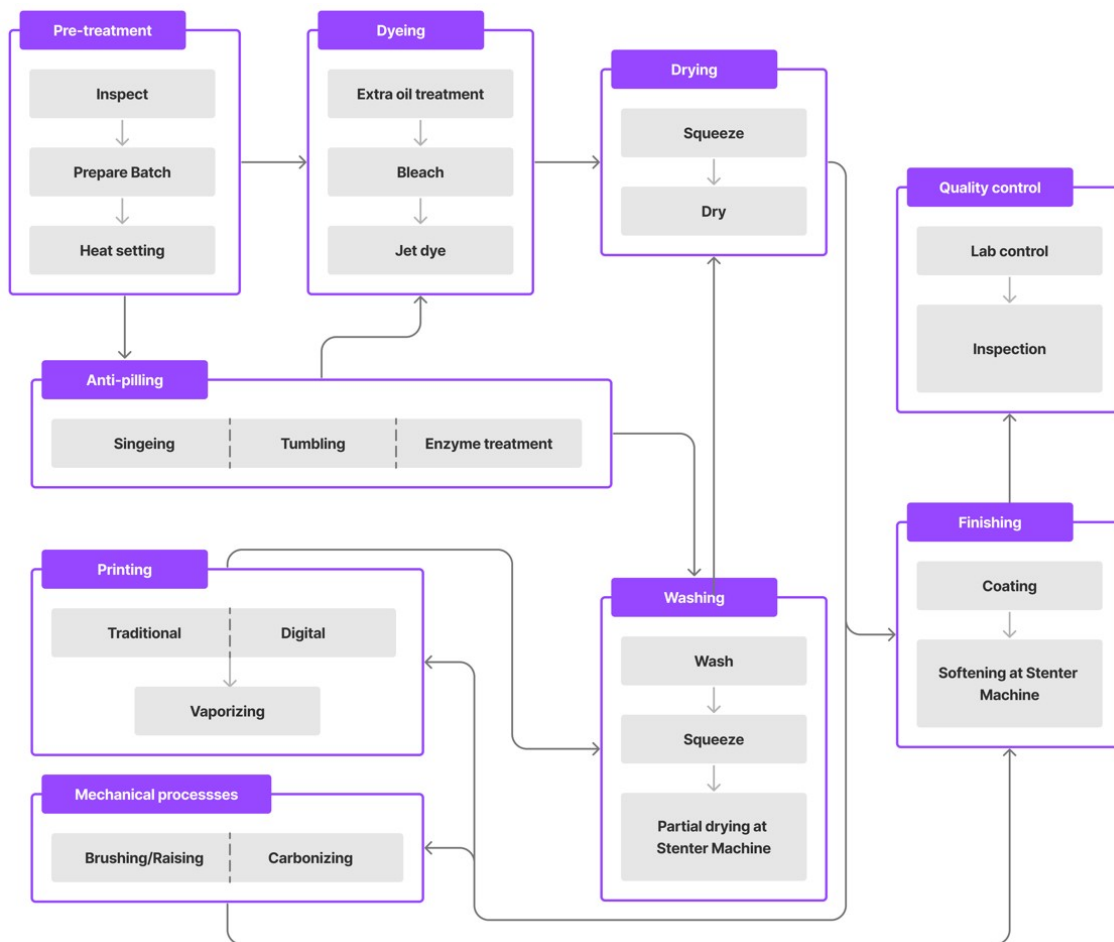


Figure 4.3: Example of a typical Dyehouse workflow for knitted fabrics

Example 1 - Lack of visibility on greige rolls' quality due to poor transparency and communication between stakeholders: A Dyehouse processed 600kg of knitted fabric, but after completing all the necessary processes, vertical oil lines were discovered on the fabric. Despite reprocessing it multiple times with stronger oil-treatment chemicals, the defect remained. The company that knitted the fabric did not take responsibility for the issue. As a result, the Dyehouse incurred a loss of 20,000€ on this service order

Example 2 - Poor Quality reporting mechanisms for finished fabrics: A Knitting company produced 150 rolls and subcontracted to a Dyehouse to perform the Dyeing and Finishing processes for them. Somehow midway through the Dyehouse processes, the rolls were contaminated with oil, resulting in several oil stains. At the quality inspection at the end of all processes, the Dyehouse realized there were some stains in those rolls and tried to charge the Knitting company to reprocess the whole batch. As the Knitting company is equipped with Smartex's inspection system, they were able to access Smartex's platform and prove those oil stains were not caused during the knitting stage. The Dyehouse was then responsible for covering the reprocessing costs.

Example 3 - Absence of methods to measure impact: *A vertical Knitting and Dyeing company is working with Higg Index and FibreTrace to compile as many data points as possible about their production. Also partnering with faculties to perform Life Cycle Assessments (LCAs) on their processes and they are still not satisfied with the results since none were able to deliver trustworthy data for them.*

By tackling these problems, the Dyehouses could have better visibility on the quality of the rolls that arrive on its premises, making the planning process easier. Besides that, a system similar to what Smartex has on CKMs could make it easier for the operators to pinpoint problematic results during the Dyeing & Finishing processes, allowing them to act fast and reduce the waste of resources and time.

4.2.2 Opportunities Evaluation and Technology Selection

Based on the information gathered during the discovery session, an opportunity tree was designed as seen in Figure 4.4. The purpose of this tree is to clarify the industry gaps that can be addressed with new technology, as well as to facilitate the product ideation process.

Based on the opportunity tree and after some analysis, it was defined that the technology to be used would be an inspection system analog to the ones Smartex already has for CKMs. The next step is to determine in which process it would be implemented. After further discussion with Smartex's staff and industry experts, it was determined that the Stenter Machine would be the ideal location for implementing this system. The decision is based on the following reasons:

1. Typically, almost all of the production undergoes this machine at least once during the Dyehouse processes.
2. Most textiles undergo processes in the Stenter Machine several times, allowing a proactive rather than a reactive approach toward defective production. In other words, this would allow the operators to identify defects early on instead of just spotting them at the final quality control stage.
3. Typically, the textiles undergo the Stenter Machine one last time at the end of all processes, also allowing a full final scan of the fabric before shipping.
4. The machine is designed in such a way that provides easy-to-access fabric planes, facilitating the implementation of a mechanical solution for the Hardware.
5. Many typical Dyehouse defects are only visible after the textiles go through this machine, making it ideal to identify them early on.

To gain deeper insights into the specific challenges encountered during the processes conducted on the Stenter Machines, a collaborative study was conducted in partnership with a northern Portuguese dyehouse. The study involved compiling all reported defects since January 1st,

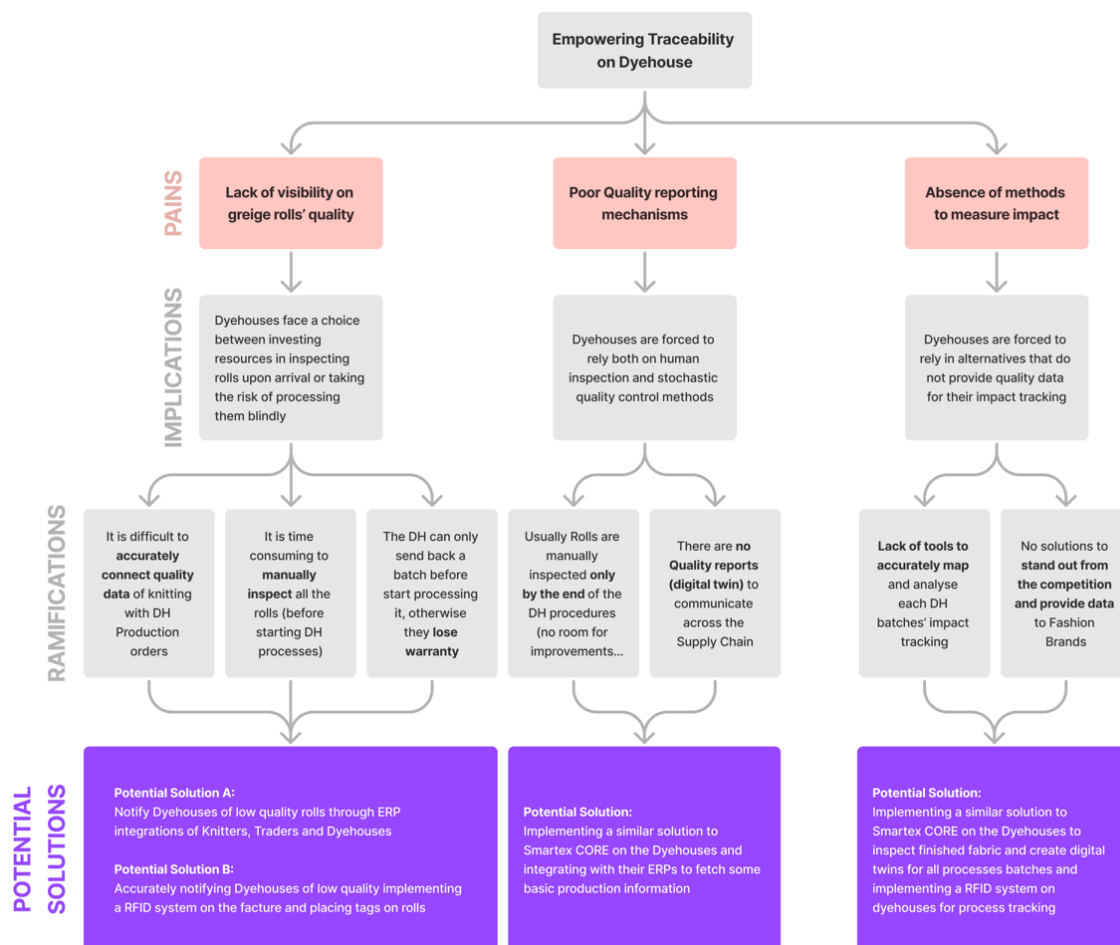


Figure 4.4: Opportunity tree with potential solutions for each pain point

2023, resulting in Table 4.3. The table reveals that Smartex's current technology allows for the identification of over 50% of the listed defects. However, upon further investigation and considering one of the major issues that affect the Dyehouses, particularly the lack of quality reporting mechanisms for finished fabrics, it became apparent that this data might not be entirely accurate. The Chief of the sector has consistently referred to some recurring defect that does not appear in the table: off-shade fabrics and shrinking. This suggests that the listed defects are only those easily identifiable by the operators during their routine tasks, while more complex issues requiring closer attention may have been overlooked.

Table 4.3: Defects observed on the Stenter machine since January 1st, 2023.

Defect spotted on the stenter machine	Quantity	Prevalence	Is it replicable?	Already detectable by Smartex?
Holes	12 341	47.24%	✓	✓
Needle defect	3 883	14.87%	✗	✓
Sewed lines	2 867	10.98%	✗	✗
Dirt	1 459	5.59%	✓	✗
Pilling	965	3.69%	✗	✗
Contamination	815	3.12%	✗	✓
Stains	689	2.64%	✓	✗
Barré	653	2.50%	✗	✓
Other	612	2.34%	✗	✗
Pinching	598	2.29%	✓	✗
Oil stain	488	1.87%	✓	✓
Ink droplets	427	1.63%	✓	✗
Hairiness	90	0.34%	✓	✗
Lycra dash	85	0.33%	✗	✓
Oxidation	80	0.31%	✓	✗
Permanent crease	71	0.27%	✓	✗
Total:	26 123	100%	Analysis period:	01/01/22 - 31/03/23

4.3 Preliminary tests

Now that the scope of this potential new product is defined, it is essential to conduct preliminary tests to evaluate the level of confidence in this idea. In other words, these preliminary tests serve as a means of searching for evidence that the idea is viable and would work effectively. Therefore the following strategy was used:

1. Request defect samples to Dyehouses
2. Separate the defects into two groups: defects Smartex already detect and defects Smartex have never dealt with
3. Use the MiniPES - a piece of hardware that simulates some features of the complete Smartex system
4. Using our ML models to infer the quality of the fabric on those pictures
5. Evaluate the results

A total of 31 defect samples were gathered, 5 out of them were never photographed and inferred by Smartex systems. Therefore, these five defects were further tested on the MiniPES. To guarantee the MiniPES will work properly, it is necessary to ensure the camera's Working Distance (WD) is set accordingly to the required by the camera specifications, i.e. the distance between the HM and the fabric must be as required by the manual. The images gathered can be seen from Figure 4.5 to 4.9.

After photographing the fabric in a controlled environment with our system, some inferences were performed upon them by our ML models. As there was not an ML model trained specifically for those defect types & picture arrangements, One could expect as the output of these tests any of the following scenarios:

- (i) The ML models perform great labeling the pictures
- (ii) The ML models have a mediocre performance labeling the pictures
- (iii) The ML models perform poorly in labeling the pictures

If (i) happens, there is good evidence the system will work for these types of defects. If (ii) happens, there is still evidence the system might work. In case (iii) happens, it would require more effort for having a functional ML model that detects those defects.

The results exhibited a range of performance outcomes: three tests yielded excellent results, while two tests demonstrated poor performance. More specifically, the chosen ML model predicts the following:

- The Silicon Stain from Figure 4.9 is a defect - confidence of 99.5%
- The Ink Stain from Figure 4.5 is a defect - confidence of 94.9%

- The Ink Droplet from Figure 4.6 is a defect - Confidence of 92.8%
- No concrete prediction upon the Ink Stain from Figure 4.7
- No concrete prediction upon the Ink Droplet from Figure 4.8

These findings indicate the potential viability of the idea, though dedicated efforts in data collection and model training will be required. Now that there is some evidence this technology might work for the intended purpose, the ideation process can be carried out.

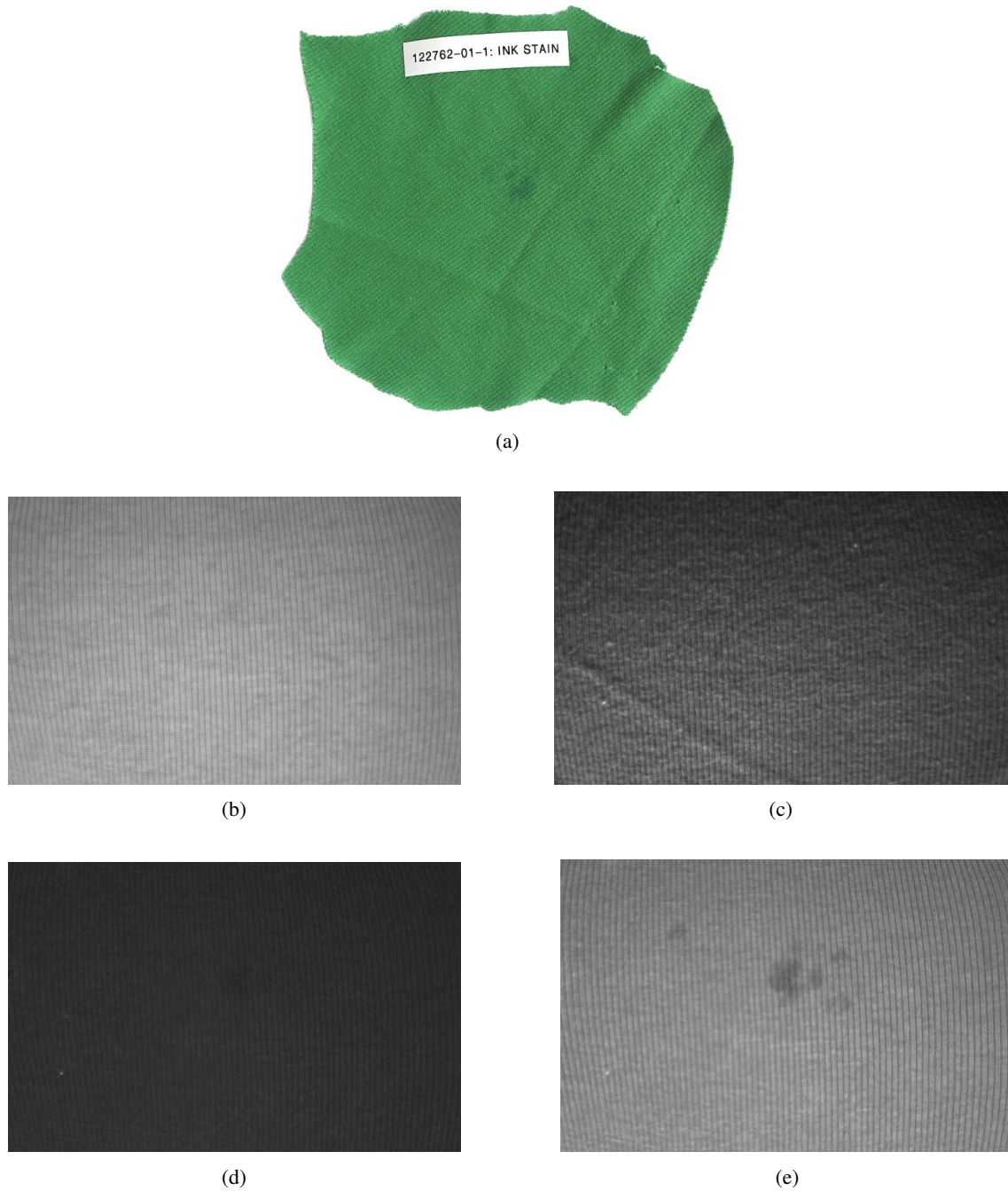


Figure 4.5: Defect number 122762-01-1: knitted fabric with ink stain - (a) Original defect sample; (b), (c), (d), and (e) are pictures taken with different parameters by the Smartex system

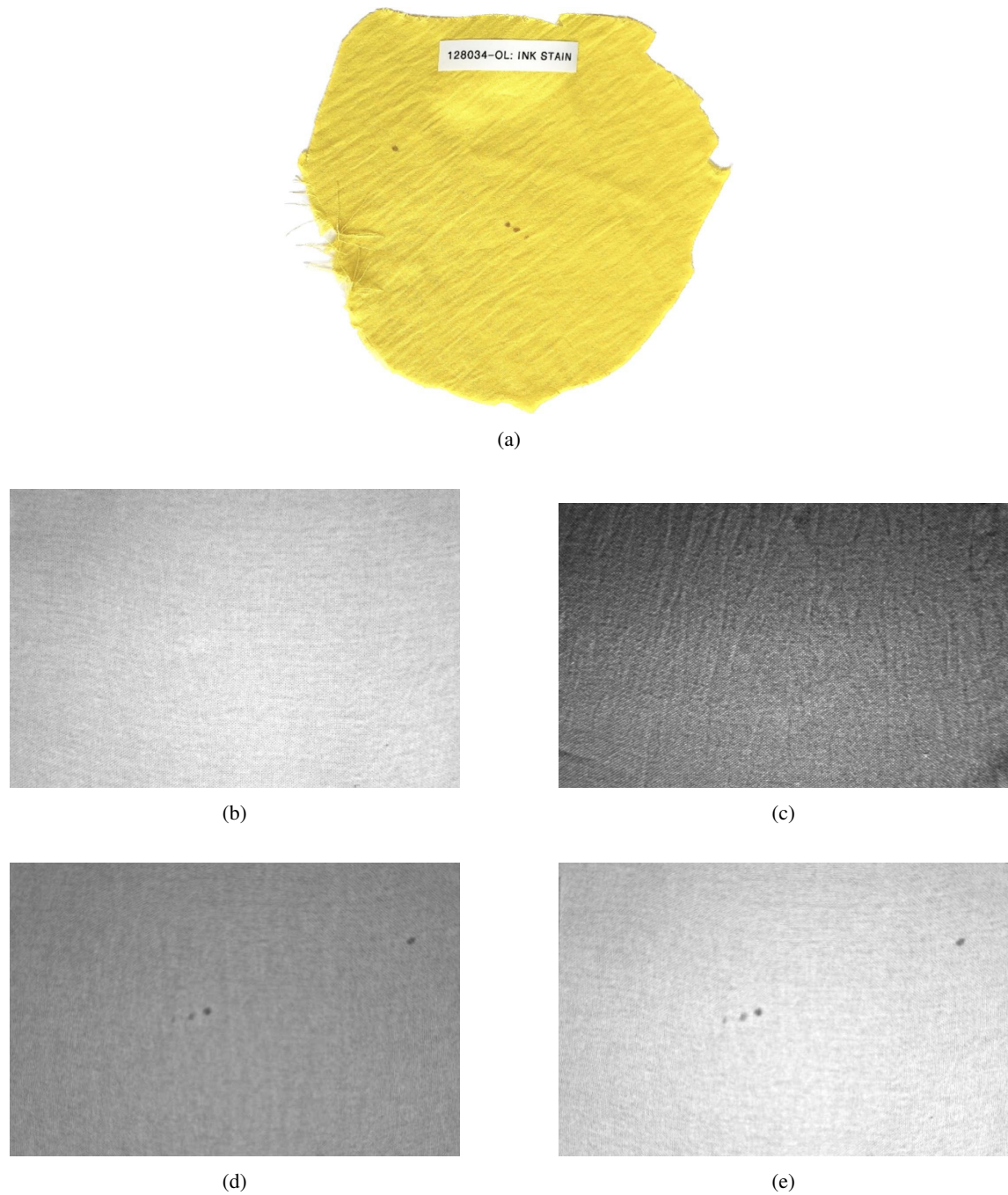


Figure 4.6: Defect number 128034-OL: woven fabric with ink droplets - (a) Original defect sample; (b), (c), (d), and (e) are pictures taken with different parameters by the Smartex system

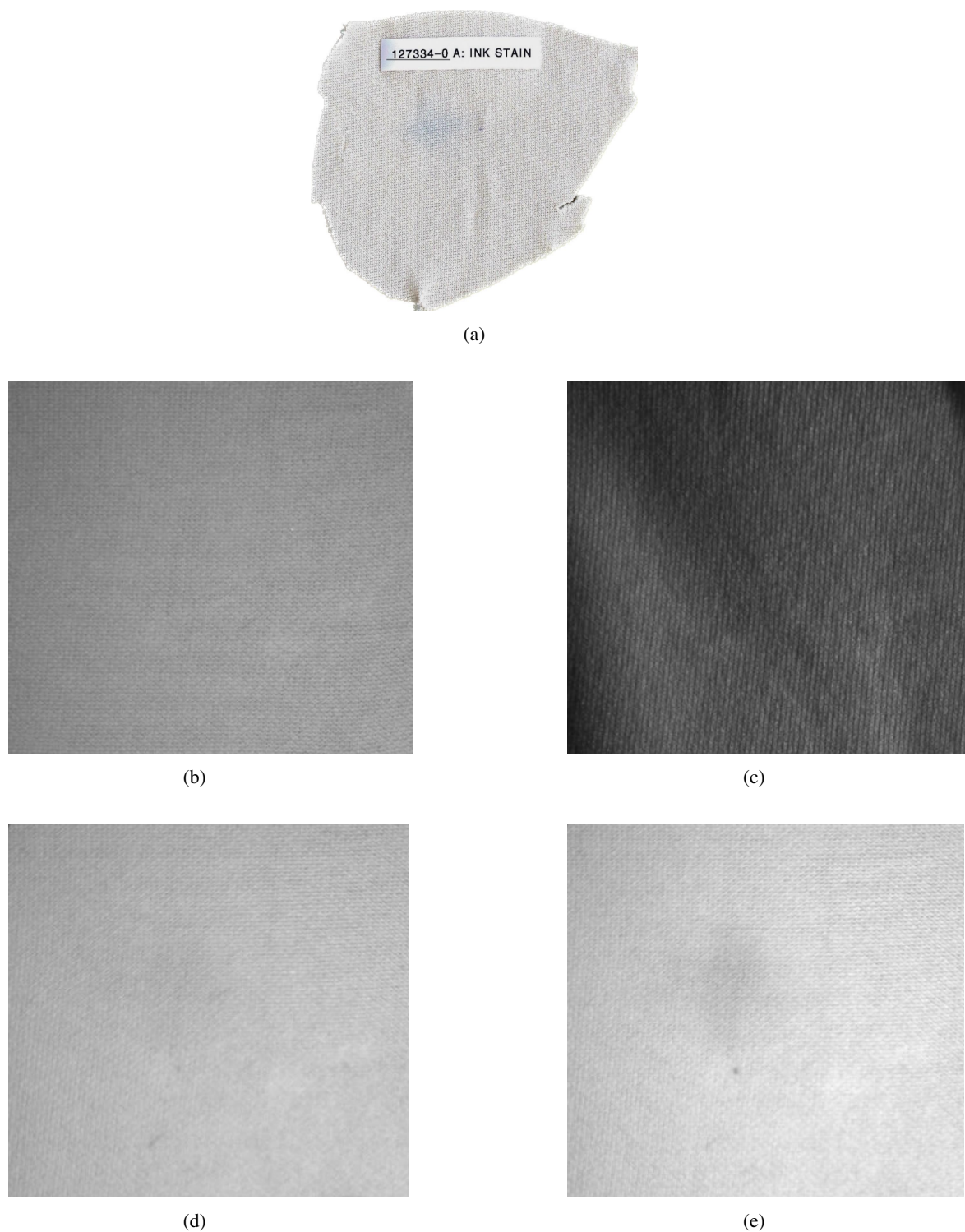


Figure 4.7: Defect number 127334-A, sample 1: knitted fabric with ink stain - (a) Original defect sample; (b), (c), (d), and (e) are pictures taken with different parameters by the Smartex system

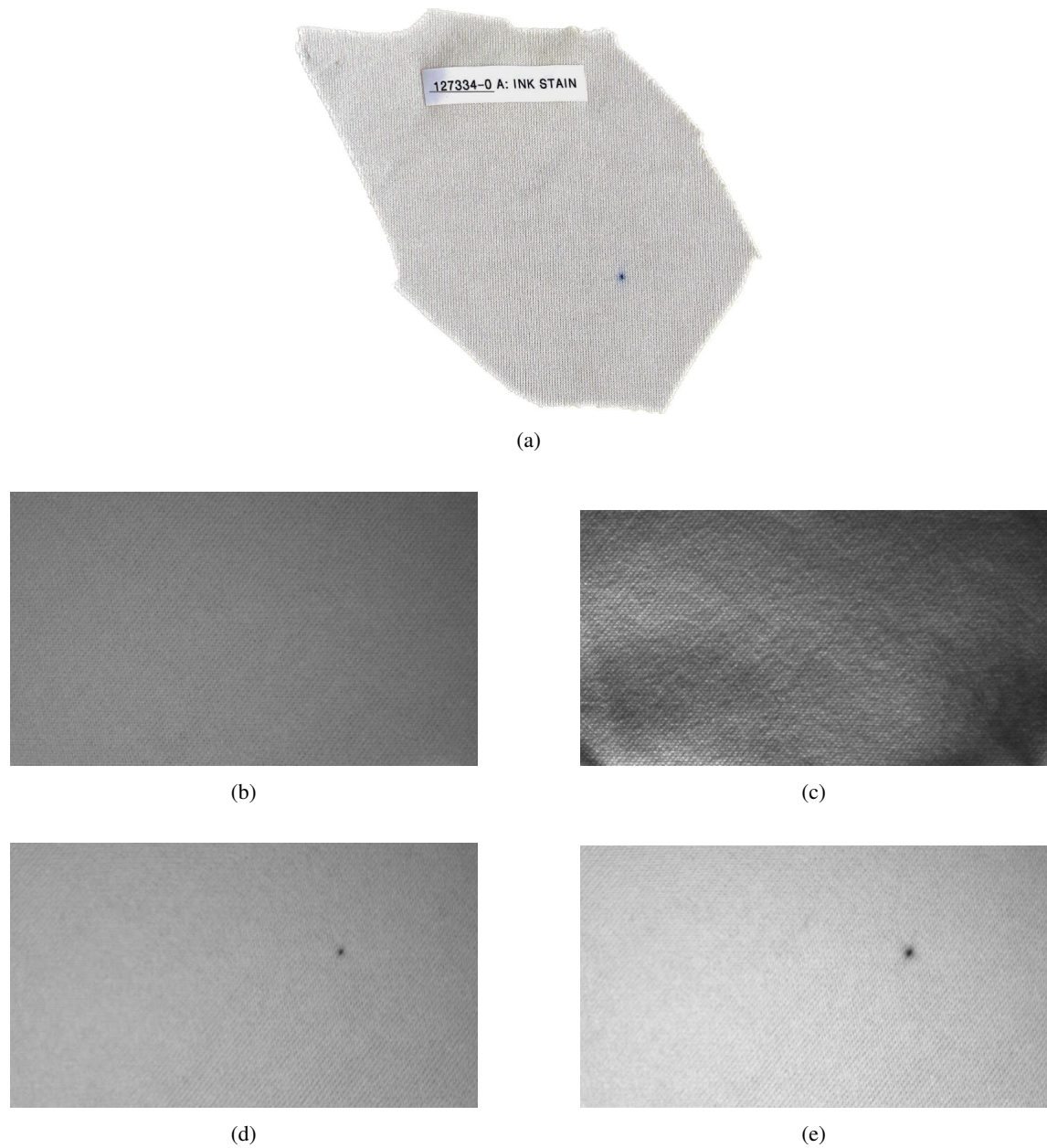
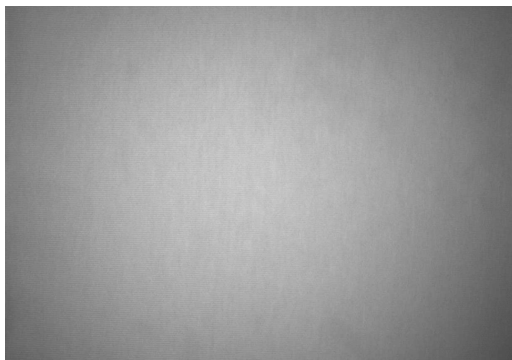


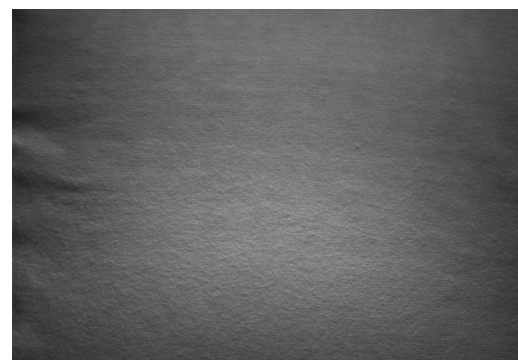
Figure 4.8: Defect number 127334-A, sample 2: knitted fabric with ink droplet - (a) Original defect sample; (b), (c), (d), and (e) are pictures taken with different parameters by the Smartex system



(a)



(b)



(c)



(d)



(e)

Figure 4.9: Defect number 124815IF: knitted fabric with silicon stains - (a) Original defect sample; (b), (c), (d), and (e) are pictures taken with different parameters by the Smartex system

Chapter 5

Product Ideation and System Modifications

The first step for formally starting the Ideation and System Modifications phase was choosing what type of System Engineering framework to use. As this is a project that includes iterations on both HW and SW, a hybrid System Engineering framework was used, including aspects from the Spiral model and the Agile methodology. The main reasons for that are:

1. As this is an exploratory project, it will require a series of iterations over time. Due to the possibility of rising requirements at later stages of the process, the Spiral model is the most suitable framework.
2. Any major SW modification must pass by the SW teams, which already use the Agile methodology¹. Therefore this same methodology will be used for SW iterations.

It is important to note that the purpose of this project is now to perform modifications on the current Smartex system and adapt it for another sector of the Supply Chain. This scenario could be faced as if Smartex's current technology was not a finished system, but an advanced prototype for this new sector. In this analogy, all the requirements gathered from now on could be faced as late-stage-rising requirements, forcing late-stage changes on the almost-deployed product.

5.1 Requirement analysis

Three different types of requirements were gathered². The first was the System Requirements Specifications (SyRS), which will derive into more detailed and specific HW and SW requirements - types 2 and 3 respectively.

¹The Agile framework used is SCRUM

²All requirements considered for developing the current Smartex system were excluded, i.e. only the new requirements will be presented in the following sections

5.1.1 System Requirement Specifications

After deeply analyzing this industry sector and consulting the literature of reference, it became clear that the Stenter Machine throughput would be one of the main challenges for this project. The speeds at which it operates can go from 10 m/min for heavyweight fabrics to 110 m/min for lightweight ones [31]. This will be challenging from both an HW and SW point of view³.

The difference in nature from the Knitting processes to the Dyeing/Finishing processes is also a big challenge. The current mechanism used to calculate the moment a batch of pictures must be taken rely on three parameters: rapport, RPMs, and the camera VFOV, as explained in Section 3.3. In Dyehouses, characterizing the processes in RPMs is no longer logical. Therefore a new strategy must be adopted.

The system should be installed at a certain distance from the fabric to avoid any iteration on the light density provided by the LEDs on the PCBAs. The installation must also avoid any nearby motor, as well as be done in a way that does not disturb any of the current tasks performed by the operators in their daily routine. Besides that, the installation must not require any permanent modifications to the machine - including the power supply that must be done externally.

As this project consists of adapting one existing technology to another sector of the industry, it is recommended to install all the modules and devices from the system, even though some of them might not perform any task at the moment. The reason for this is to keep the debugging process as close to the standard debugging protocols as possible.

Having all of these aspects into consideration, Table 5.1 was created to better organize the main System Requirement Specifications gathered. Some other requirements might arise at later stages, though this is undesirable. In the next section, the Hardware Requirements derived from the system requirements are addressed.

5.1.2 Hardware Requirements

One of the requirements that derive from the requirement SyRS-01 shown in table 5.1 and discussed in section 5.1.1 is the necessity of increasing the communication bandwidth between HMs and MM. Nowadays each HM is connected to the MM via RJ45 cables, summing up 8 modules⁴ connected to an 8-piece connector mod jack. This connector mod jack then communicates with an USB 2.0 channel, which means all the data sent from the HM go through the USB 2.0 hub. This creates a bottleneck due to its reduced bandwidth. The theoretical maximum bandwidth of a USB 2.0 is 480 Mbps and the real-world sustained data transfer rate for USB 2.0 is typically around 280-320 Mbps. For having an idea of the minimum Required Bandwidth (Rbw) for a machine throughput of 20m/min, some conservative calculations were performed, resulting in the necessity of 306 Mbps.

³Further discussed in sections 5.1.2 and 5.1.3

⁴In case of being an 8 module system

Table 5.1: System requirements

System Requirements Specifications			
Ref.	Requirement	Reason	Type
SyRS-01	The system must be capable of keep up with a machine throughput of 20m/min	To guarantee 100% of the fabric would be inspected for most of the European market	Must
SyRS-02	The system must be able to work without the values from the IMU	The system will be static, therefore the system must be able to calculate the exact moment of taking the picture with other parameters	Must
SyRS-03	The system must be installed with the correct Working Distance specified by the supplier	To avoid both altering the light density on the PCBAs and refocusing the cameras from the standard system	Must
SyRS-04	The system should be installed without performing any permanent modifications on the Stenter Machine	Permanent alterations on partners machines for experimental projects should be avoided	Should
SyRS-05	The system must never stop the machine	If the stenter machine stops arbitrarily, the fabric inside of it can ignite	Must
SyRS-06	The system should be fully installed, even if some of the modules do not perform any function for now	The complete installation makes the debugging process easier since an already functional system is being used as basis for the iterations.	Should
SyRS-07	The system must be installed as further away as possible from any motors	This would avoid/decrease any Electrical-Magnetic Interference (EMI)	Must
SyRS-08	The system must not interfere on the operators daily routine	Adding a foreign device on a well-established working routine can disturb operators and lead to accidents	Must
SyRS-09	The system power supply must be done externally	The power supply of Smartex current systems is done by bypassing energy from the machine electrical board to the MM. Experimental projects must not follow this standard	Must
SyRS-10	The devices must be well-isolated	The Dyehouse environment are usually humid and full of cotton fluff, which could be harmful for electronic devices	Must

Table 5.2: Hardware Requirements and the System Requirement it derived from in parentheses

Hardware Requirements			
Ref.	Requirement	Reason	Type
HWR-01 (SR-01)	Increasing the communication bandwidth between HM and MM	The RJ45 hub found on the MM is connected to one single USB 2.0 port, creating a bandwidth bottleneck	Must
HWR-02 (SR-03) (SR-04)	Design and manufacture custom parts to hold the system in place	There are no current parts able to secure the system in the correct place since this is a new machine type never before explored by Smartex	Must
HWR-03 (SR-01)	A RJ45 connector should be added to the Master Module	Using cabled instead of wireless connection for the MM and AI Booster communication will increase the system performance and reduce inference time	Should
HWR-05 (SR-02)	Implementing a new sensor to measure the instantaneous machine throughput	Smartex technology needs to know the machine throughput in order to calculate when to send the next frame request	Should
HWR-06 (SR-05)	The Finis Module resistance must not be assembled on the Stenter Machine	By not assembling it, the Machine Service can run as it is and even if a stop request is sent, the machine will never stop	Must

Apart from increasing the communication bandwidth, some other strategies can be used to tackle requirement SyRS-01. For example, increasing the cameras' VFOV and using an Ethernet cable instead of Wi-Fi for data transfer between the MM and AI Booster can be effective approaches.

As Stenter Machines are completely different from the CKMs, there are no current structural solutions already designed by Smartex for positioning the system in place. Therefore a machine assessment followed by a structural project is required.

Instead of using the RPMs and Rapport to define when to take pictures, one HW-based solution for overcoming the SyRS-03 requirement could be using a contact wheel with an encoder to calculate the relative velocity between fabric and system. Another strategy could be using high-frame-rate cameras for this measurement.

As stated in SyRS-06, the Stenter Machine must never be stopped. The easiest way of achieving this requirement is not using the Finis Module. This would allow the Machine Service to run as usual, but whenever a stop request is sent to the Finis Module, nothing will happen to the machine.

Having all of these aspects into consideration, Table 5.2 was created to better organize the main Hardware Requirements gathered. Analogously to this section, the next one, section 5.1.3, will address the SW Requirements derived from section 5.1.1.

5.1.3 Software Requirements

One of the SW-strategy for increasing the system performance and coping with the high machine throughput, SyRS-01, is optimizing the Vision SW. In case new cameras are used for taking pictures faster, its FW and protocols must be integrated into the Vision SW, otherwise, the Sensing Service will not identify the cameras and will not be able to send the requests using the correct syntax.

There are two different approaches to tackling SyRS-03 from a SW perspective. On a long-term basis, the whole code must be redesigned to be RPM-free. On a short-term basis, one can force a manual RPM input on the SW and use this fake RPM to calculate the moment the new frame requests must be sent.

Having all of these aspects into consideration, Table 5.3 was created to better organize the main Software Requirements gathered.

Table 5.3: Software Requirements and the System Requirement it derived from in parentheses

Software Requirements			
Ref.	Requirement	Reason	Type
SWR-01 (SR-01)	Optimizing the Vision SW	Decreasing the inferring time-span	Must
SWR-02 (SR-02)	Altering the Sensing Service logic for calculating when to send the frame requests	The sensing service nowadays rely on RPMs, rapport and the IMU to calculate when to send the next frame request	Should
SWR-03 (SR-01)	Integrating new cameras FW and protocols	In case of using different cameras from the ones currently used, the new FW must be integrated to Vision SW	Must
SWR-04	Training new ML models for infering using pictures taken under the Visible spectrum	All current ML models are trained to infer using data from pictures taken under the UV and IR spectra	Must

5.2 Partnership selection

There are a series of criteria used for selecting a Company to start a partnership with for this exploratory project. This decision plays a key role in this project because it can easily influence the project's timeline. The criteria used were:

- **The company must be profiled as Innovators or Early-Adopters:** the company must be willing to experiment with new ideas and be comfortable with an iterative development cycle. If they do not have this profile, one of the parties will likely be frustrated during the process
- **The staff should be willing to cooperate with the development process:** an innovative mindset could speed up the implementation process
- **The Stenter Machines available must be easy to install on:** the easier the machine is to implement the system, the faster a running prototype will be installed
- **The company must be located in Portugal:** ideally, the premises should be located as close as possible to Porto to facilitate the commuting process

All of these criteria were taken into consideration and to evaluate the companies where the discovery sessions were held on. The final decision was in favor of performing the Proof of Concept (PoV) at a leading company in the north of Portugal.

5.3 Product ideation

Taking into consideration all of the requirements listed in section 5.1, as well as the discussions held with multiple Smartex teams, a couple of solutions were raised. In short, the potential solutions are:

- Using USB 3.0 cameras
- Using multiple MM
- Using the cameras in streaming mode instead of trigger mode
- Rotating all modules 90° and use the cameras' HFOV as if it was the VFOV
- Using multiple camera bars

It is important to note that these solutions may not work individually, and the final solution will likely involve combining two or more of them. The following sections will explain in more detail the strategy behind each solution and the extra requirements they introduce.

5.3.1 Using USB 3.0 cameras

One of the biggest bottlenecks found was the fact that the RJ45 hub - where all HM are plugged - is connected to one single USB 2.0 port. Therefore the first question that comes to mind is: *"Is it possible to get rid of this USB 2.0 and use USB 3.0, for example?"*. On a short-term basis, for PoC purposes, it is possible to find a workaround for the USB 2.0 bottleneck. On the other hand, a more definitive solution would require an entire PCB redesign.

The short-term solution consists of bypassing the RJ45 hub, shown in Figure 5.1, using two USB 3.0 hubs - one in each available USB 3.0 port -, and connecting a cable directly from the camera to the new hubs. The data transfer and power supply would then be handled by the new cable.

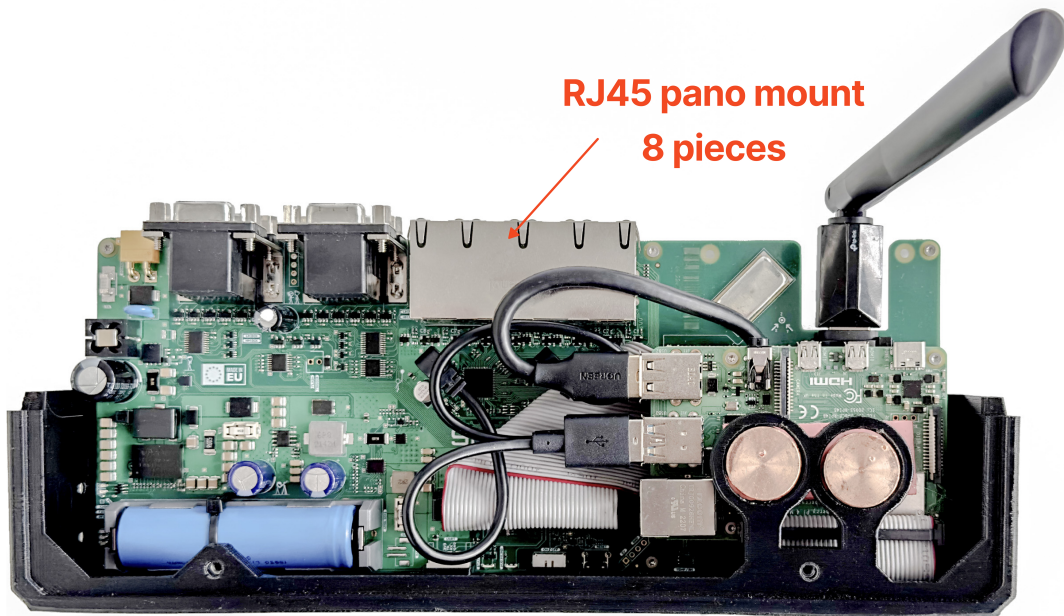


Figure 5.1: Internal parts of a Heavy Module highlighting the RJ45 pano mount 8 pieces

At first, this solution would add five extra requirements as listed below:

- Drill holes on the HM aluminum extrusion to pass the new cables
- Source USB 3.0 cameras. The camera's sensor should be the same as the ones currently used.
- Source USB 3.0 Hubs
- Source USB 3.0 cables. These cables must not exceed 2 meters and they should have the internal wires twisted to minimize electromagnetic interference (EMI) and radio frequency interference (RFI)
- Integrate the new FW and/or config files to Vision SW

5.3.2 Using multiple MM

Using multiple Master Modules on one single installation could also help to reduce the USB 2.0 bottleneck. By increasing the number of MM, the number of HM connected to it decreases. Therefore the data flux through the USB 2.0 port also decreases. There is a limitation in this

solution - each master module must have at least four HM connected to it at all times. Another point worthy of mention is that the more MMs used in one installation, the higher the Cost of Goods Sold (COGS) is.

There are two different strategies for using multiple MMs operating simultaneously. The short-term solution consists of having 2 parallel installations on the same machine, which is not desirable. The second strategy is using a Slave-Master technique to connect two MMs via an Ethernet cable as shown in Figure 5.2. For this strategy to work, some modifications must be performed on the Sensing Service.

One important thing to notice is that if this technique is used, the Ethernet port of both MM will be in use, therefore the wired connection to the Smartex network must be done differently. To overcome this obstacle, a USB 3.0 - Ethernet adapter can be plugged into the port that was previously used by the antenna. One must just alter some internal configurations on the MM so the device selects this connection form over the wireless connection.

The Master-Slave feature was designed for a certain specific type of CKM. In these machines, there are usually 2 camera bars working in parallel with 4 modules each. Therefore, each MM is connected to one unique camera bar. In the case of using both MM in the same camera bars, some extra modifications on the HW are required. All the new requirements originated from this solution are listed below:

- Alter the Sensing Service for it to allow this configuration
- Source USB 3.0 - Ethernet adapters
- Alter the MM network configurations for it to choose Ethernet via USB over Wi-Fi
- Drilling holes on the HMs
- Flipping HMs PCBA 180° for 4 different HMs.
- Eliminating the female DB9 connector from 2 HM - one standard and one flipped HM

5.3.3 Using the cameras in streaming mode instead of trigger mode

This potential solution can solve the problem of coping with the high machine throughput. By having the cameras on streaming mode, the cameras will create a video instead of taking multiple pictures.

This solution has a big constraint, this solution would require having mechanisms for recording while sending previous recordings to the ML Service to guarantee the inspection happens in real-time or with a short delay.

This solution introduces a couple of requirements as seen below:

- Developing an algorithm for exploding the video into frames and selecting only the good pictures for inference

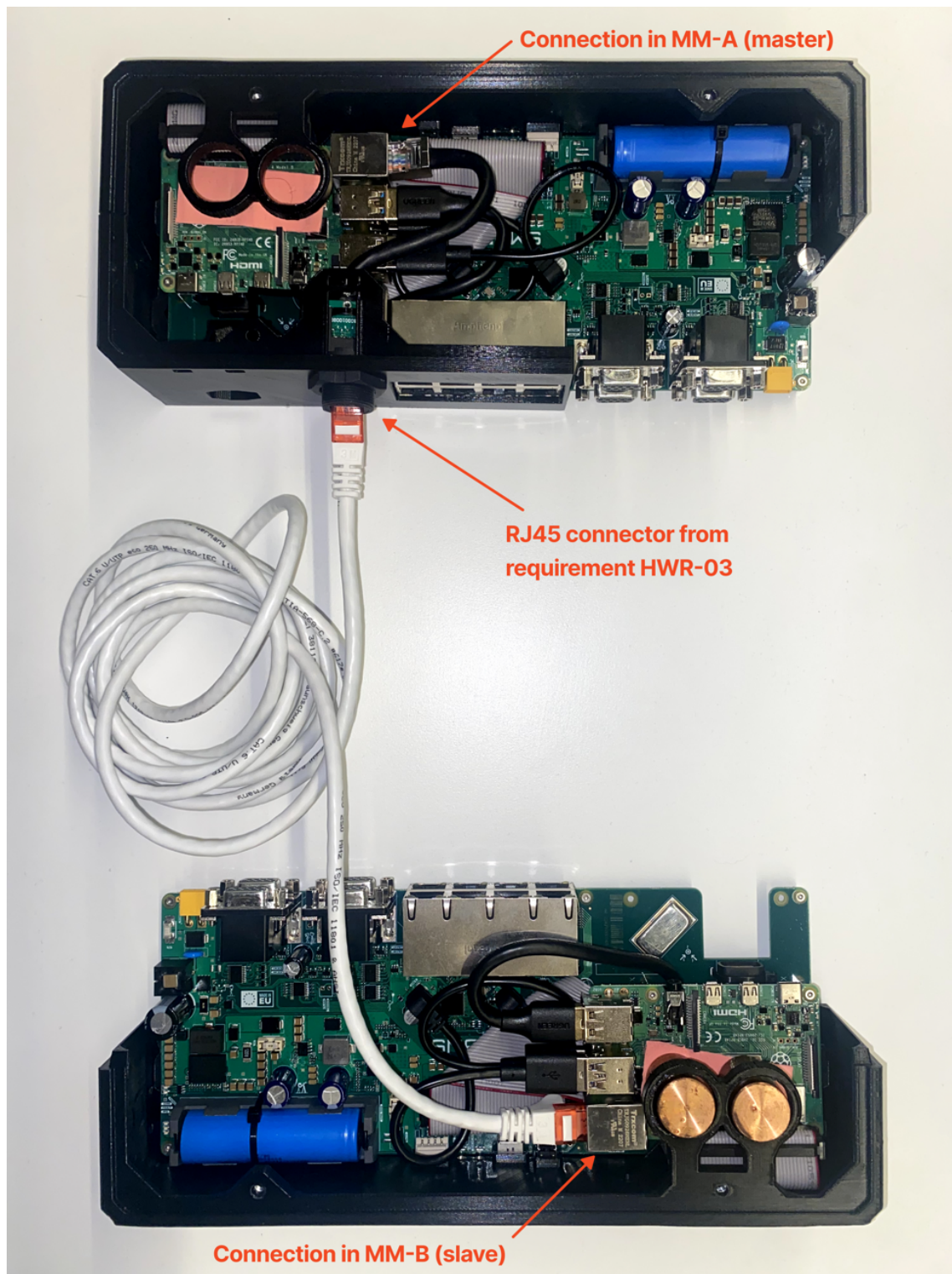


Figure 5.2: Two MM connected to one another via a Master-Slave technique through an Ethernet cable

- Integrating the new cameras FW and protocols to Vision SW
- Redesigning the Sensing Service

5.3.4 Rotating all modules 90° and use the cameras' HFOV as if it was the VFOV

This strategy could be interesting since it allows increasing the VFOV drastically without any major modifications to the cameras and other electronics. It consists of rotating all modules 90° and connecting them via DB9 cables. To implement this solution, major modifications would be required on the structure that supports the system, which would need to be completely redesigned.

Some modifications on the SW side would also be necessary. The main reason for that. To guarantee satisfactory ML performances, an algorithm that crops the image into multiple segments, and then recreates the image would be necessary.

In short, this solution introduces the following requirements:

- Complete redesign of the structure that holds the system
- Development of an algorithm for cropping the images into multiple segments

5.3.5 Using multiple camera bars on a single system

This potential solution is very interesting since it allows virtually increasing the VFOV by placing multiple camera bars along the machine. This could be faced as 2 distinct installations for short-term implementation or just one single installation - which would require the redesign of the Sensing Service.

The most important requirement for this solution to work is having enough space on the machine for placing all the systems and guaranteeing they will not contaminate one another with their own light sources. In case of needing to install the systems further apart, the sensing service should be able to send the frame requests in a synchronized manner to guarantee the pictures are taken in complementary ways. A list of the requirements introduced by this solution can be seen below:

- Redesign of the Sensing Service
- Guarantee the light sources of one system will not contaminate the other
- Finding a suitable place with enough space for installing the systems
- Synchronize frame requests for taking complementary pictures

5.4 Mechanical design

Now that the main design ideas were discussed, it is important to iterate on the system and perform the desired modifications so the system can be installed on the Stenter Machine. The first step of

this stage is performing a thorough machine assessment for designing the structure that will hold the system. Then, while the structural part is sent to production, all the other HW modifications can be performed.

5.4.1 Machine assessment

The Dyeing & Finishing processes are, in nature, continuous processes. Besides that, even though the Stenter Machine is the most common machinery in Finishing processes, it is typically limited to a couple of these machines per factory. These factors pose a significant challenge regarding its assessments: the machine never stops

The most important part of the assessment is characterizing the fabric plane about the point at which its structure will be mounted. This can be done by characterizing the shafts of interest - measuring their diameters, lengths, their relative position to each other, and the holes of interest, as shown in Figure 5.3. After assessing the machine, a simplified model of the machine was created on Solidworks, as shown in Figure 5.4.

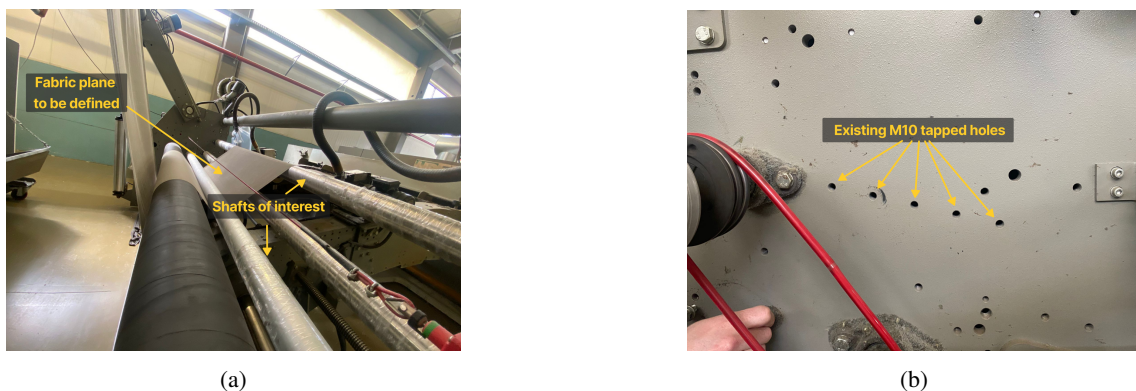


Figure 5.3: Machine assessment (a) Plane of interest (b) Tapped holes to be used for designing the structural parts

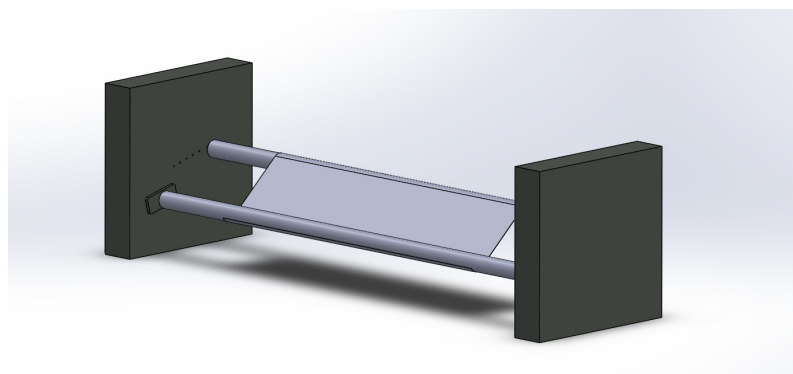


Figure 5.4: Simplified model of the Stenter Machine on Solidworks where the holes and shafts of interest are represented

5.4.2 Clamps design

Using as a basis the simplified machine model and the correct positioning of a regular system about the fabric plane, a clamp was designed. This custom-made part was created envisioning the tapped holes and three M10x16 screws as a means for fixing the structure.

This part was designed to be folded from a 4mm-thick metal sheet, more specifically the ANSI 304 steel. The bending radius, 5mm, was defined using a table of reference provided by the company that offers this service to Smartex. The clamp design can be seen in Figure 5.5

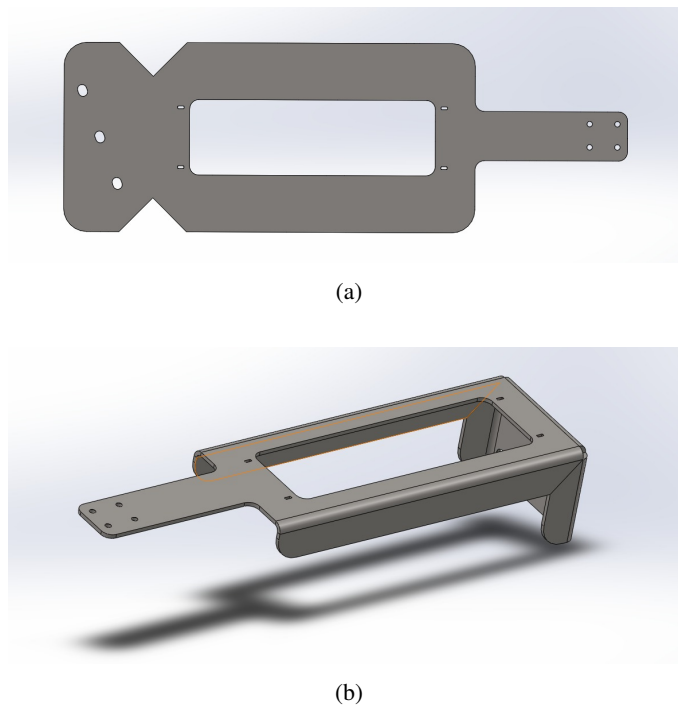
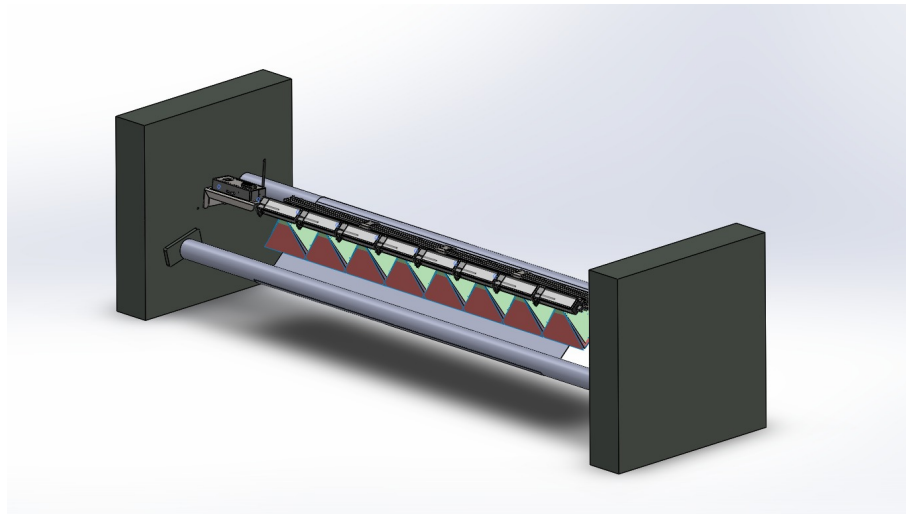


Figure 5.5: Clamp design (a) Flattened clamp (b) Clamp after folding

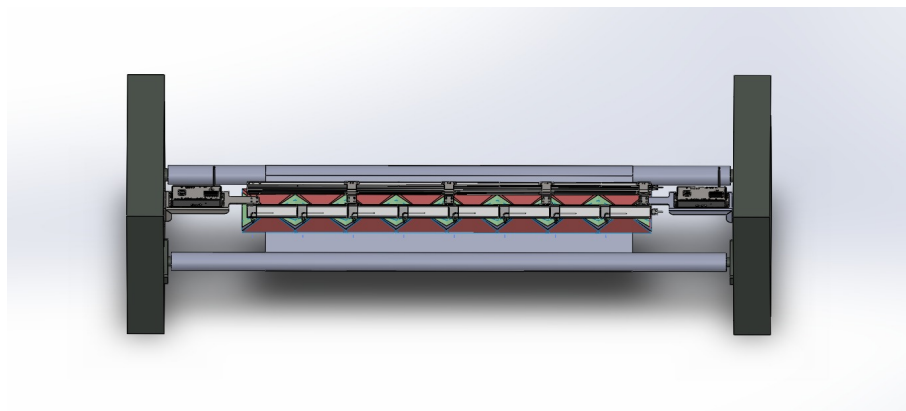
The first version of this clamp did not count with the hollow part in the middle and was slightly thicker - approximately 8mm. When the ANSI 304 steel was assigned to this 550-millimeter-long part and its mass properties were simulated, it reached 8.3kg, which is an outrageous value for this type of part. Therefore, a couple of strategies were taken to reduce its weight, starting with reducing its thickness to 4mm and creating the hollow part where the MM will be mounted. After adopting these strategies its weight was reduced to 2.3kg, which is still too heavy, but acceptable.

5.4.3 Solidworks Assembly

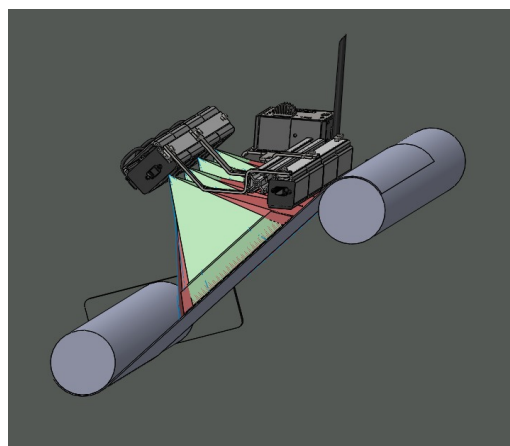
The final Assembly of a regular on the simplified Stenter Machine model using the custom-made clamps can be seen in Figure 5.6



(a)



(b)



(c)

Figure 5.6: System assembly showing FOV. (a) Perspective view (b) Parallel-to-fabric view (c) System-cut view

5.5 Modifications

To achieve the desired outcome in regards to proving the concept by creating a functional prototype, a couple of modifications were performed taking into consideration the System, Hardware, and Software requirements

Some of the strategies discussed on 5.3 were adopted for creating the prototype, namely using USB 3.0 cameras and using multiple MM.

The next subsections will address both the HW and SW modifications performed during this period. All of the problems and challenges faced will be later discussed in 6

5.5.1 Hardware modification

Some of the strategies discussed on 5.3 were adopted for creating the prototype, namely using USB 3.0 cameras and using multiple MM. Besides that, some modifications were performed to comply with one of the HW requirements listed in Table 5.1.2 - HWR-03

The first modification consisted of adding an RJ45 connector to the MM, as seen in Figure 5.7. To do so, the following steps were followed:

- Disassemble the MM
- Drill a 21mm hole next to the antenna using a step drill
- Assemble an RJ45 pano mount on the hole

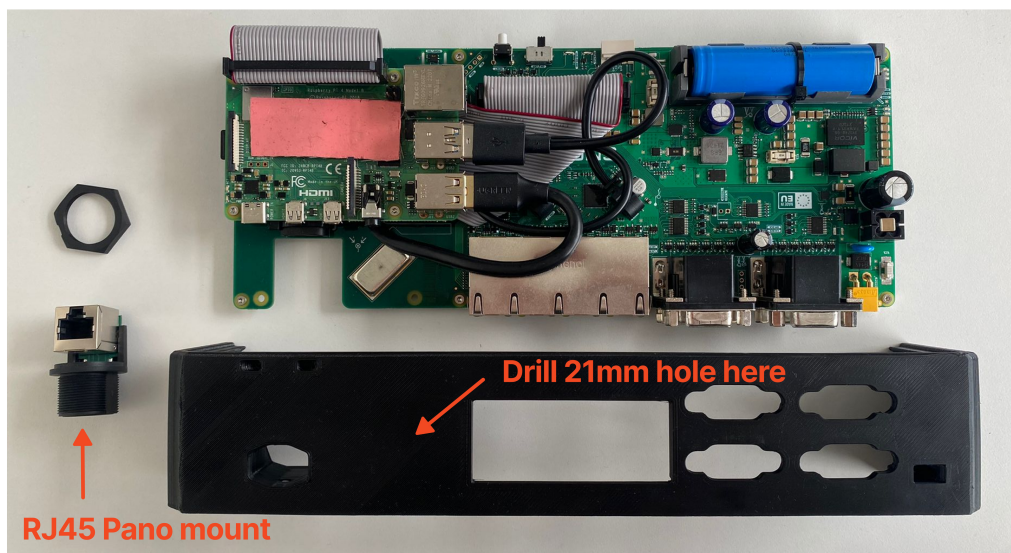


Figure 5.7: Disassembled MM for modification showing the location where the hole will be drilled and the RJ45 pano mount to be assembled on the hole

The second modification was Drilling the HM for passing the USB 3.0 cables. To do so, the following steps were followed:

- Disassemble the HM
- Find the best location for passing the cable and drilling the hole
- Drill a 20mm hole in the selected location using a step drill

When the cameras arrived at the office it was noticed that the HW design was a bit different from expected, since the USB 3.0 connector was placed in a different orientation. This mismatch forced a new iteration on the HM extruded case. This time the holes were drilled on the back side of the module as shown in Figure 5.8. After drilling the hole, some caps were 3D printed to close it. The cable goes through the cap and connects to the Camera Shield. Then the cap is placed on the hole using hot glue. As this is just a prototype for proving a concept, these processes are accepted, otherwise, a cable gland should be used. These modifications required the following steps:

- Mark up the exact position of the cameras on the HM
- Drill a 20mm hole in the selected location using a step drill
- Design the cap in Solidworks
- Export as a step document and 3D print it
- Assemble the parts

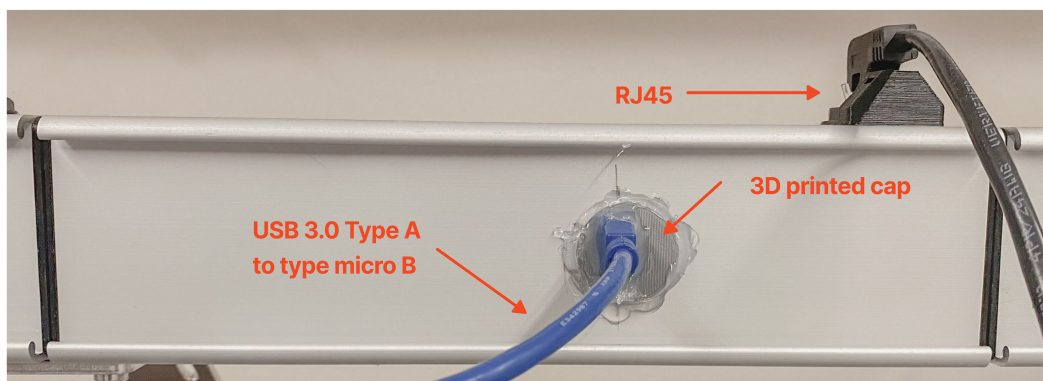


Figure 5.8: HM with USB 3.0 cameras

The last hardware modification performed was flipping the PCBAs of 4 HM 180° and removing the female DB9 connector from 2 HM - one regular and one flipped. In order to close the original RJ45 pano mount holes, a cap was designed in Solidworks and 3D printed. Figure 5.9 show the modified modules. To perform these modifications the following steps were performed:

- Drill a 21mm hole in the top right part of the HM using a step drill for placing the RJ45 pano mount
- Desoldering the DB9 connectors⁵
- Replacing 2 LEDs^{6 7}
- Design the cap in Solidworks
- Export as a step document and 3D print it
- Assemble the parts

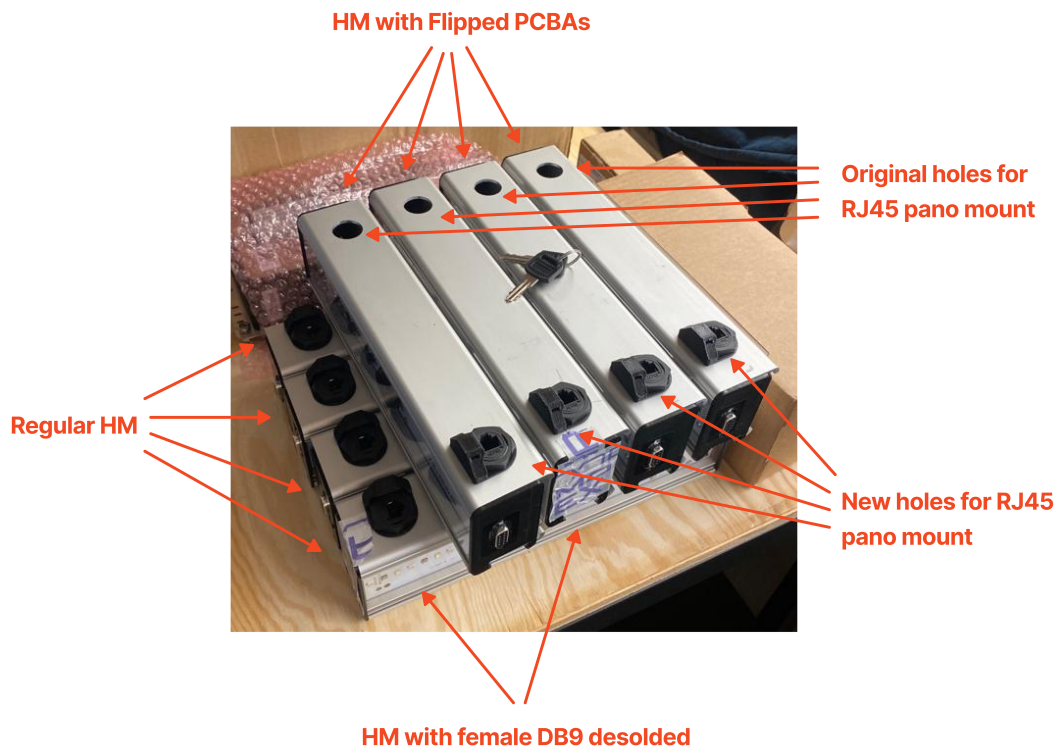


Figure 5.9: Modified HM - 4 HM with flipped PCBAs, 2 non-flipped HM, 2 HM without female DB9s after desoldering

5.5.2 Software modification

The first modification performed was altering the network settings on the Finis and Master Modules. The justification for that is that the MM will now communicate with the AI Booster via an

⁵This task was performed by a technician from the electronics lab

⁶due to their proximity to the desoldering region, they were damaged

⁷This task was performed by a technician from the electronics lab

Ethernet cable. Besides that, to increase the system performance, the setup of a dedicated network was done. To successfully alter these configurations, the following tasks were performed:

- Setting up a new network for the project ⁸
- Fetch the MM IP by accessing the list of devices on the network
- Accessing the MM via Secure Shell (SSH) and changing the network interfaces as shown in Figure 5.10
- Accessing the Finis via Secure Shell (SSH) and changing the WPA supplicant config as shown in Figure 5.10

```
nano etc/network/interfaces

# Change from Static IP to Dynamic Host Configuration Protocol (DHCP)
# Comment out the wireless network definitions
# Allow hotplug Ethernet for enabling the Master-Slave configuration if necessary by adding the following:

allow-hotplug eth1
iface eth1 inet dhcp
```

(a)

```
nano etc/wpa_supplicant/wpa_supplicant.conf

# Change network name to the new dedicated Wi-Fi
# Change the Wi-Fi password

# Ctrl + x -----yes | to exit and save modifications

Sudo systemctl restart networking
```

(b)

Figure 5.10: Modifications on Network Settings (a) Modifications performed on the MM (b) Modifications performed on the Finis Module

The next modification was integrating the config files from the new USB 3.0 cameras to Vision SW and altering some minor hard-coded configurations on the Sensing Service. ⁹.

⁸This task was performed by a technician from the IT team

⁹This task was performed by a developer from the Embedded team

Chapter 6

Workflow Documentation and Discussion

As of now, the main Analysis performed, Potential Solutions raised, and Modifications proposed were presented. This chapter will then document the Workflow and Discuss the decisions taken for addressing the problems and implementing the solutions.

6.1 Workflow Documentation

Since the initial stages of the project, it was clear that the Stenter Machine throughput would be the most challenging specification to meet. After analyzing Smartex technology, it was also clear that the USB 2.0 connectors were the main bottleneck regarding the hardware, as mentioned in 5.1.2. Although it was an already-mapped constraint, the HM-MM communication was stress checked using a legacy script from the HW team¹. This script allows one to see which would be the maximum amount of pictures the system could take by itself. In summary, this script ignores all the services and parts of the Sensing Service code that are not essential for taking pictures and sending them to the MM. Consequently, all the results acquired using this script will always outperform the full system operation. Hence the results will be used as a benchmark only. The obtained results could be faced as the maximum velocity at which a system could run if it were 100% efficient and all the other services were performed instantly. Therefore, the maximum machine throughput these systems would be able to inspect would be as follows:

According to the results, neither an 8-HM nor a 4-HM system would be able to cope with a machine throughput of $20 \text{ m/min} = 33.3 \text{ cm/s}$, which is typically the maximum throughput value for the operation of this type of machine within the Portuguese market^{2 3}

Some empirical tests were also performed on a regular 8-HM system. The system was assembled and placed at a PES⁴. As the system was static, which will also be the case at the Dyehouses,

¹This task was performed by an Engineer from the HW team

²Even though in the European market this value can reach $30 \text{ m/min} = 50 \text{ cm/s}$

³Values of 100 m/min were observed in a company in northern Portugal

⁴Tester used for product development at Smartex

the IMU will not be useful for defining when to send the next frame request. A workaround for this problem is manually setting a fake RPM value on the Sensing Service, guaranteeing the specification SR-03 is met. To do so, the MM was accessed via SSH, and the command seen in Figure 6.1 was given.

```
python3 /smartex/repos/tags/0.38.41/VisionSoftware/sensing_service.py --installation_id 577 -tm -rpm 35
```

Figure 6.1: Command given for setting a fake RPM value for the IMU in installation 577

This strategy allowed testing different RPMs and Rapport combinations⁵. These parameters would then be altered and the system would be left running for around 30 min. During this period, the system was monitored using Zabbix. The main parameter tracked on Zabbix was the Fabric Not Inspected (FNI). This parameter returns the percentage of fabric not inspected whenever the system fails on responding to a frame request.

Parallel to the monitorization via Zabbix, the Sensing Service was also monitored in real-time by checking the Sensing Service logs. To do so, an SSH connection was established with the MM in three different terminals. The commands shown in Figure 6.2 were used for monitoring it. These commands allowed evaluating of all the Sensing Service logs, as well as filtering some more relevant ones, which made the process easier.

Some iterations were performed with both RPMs and Rapport until the moment a warning log stated an FNI value, which means the textile was no longer inspected in its entirety.

After these preliminary assessments on the current Smartex technology, some HW modifications were performed⁶ to implement USB 3.0 cameras and continue with the tests. The proposal was to alter the cameras and repeat these tests.

As soon as the new cameras arrived at the Smartex office, another unforeseen obstacle arose: *the micro USB 3.0 connectors were placed in a different position than expected*. This forced another iteration regarding HW modification. After re-drilling the HM as mentioned in section 5.5.1, a couple of tasks were performed to guarantee that the cameras were in good condition and that the config. files sent to us were indeed compatible with the new cameras. This evaluation was carried out as follows:

1. Load the new cameras' config. file on a tester SW offered by the supplier
2. Assess whether or not the SW can identify the cameras
3. Assess whether or not the images taken by the cameras are good
4. Fetch the serial number of each camera

⁵The only two variable parameters out of the three used for defining the exact moment of sending a new frame request.

⁶Go to section 5.3.1 for a better understanding of the strategy. The HW modifications referred to in that section can be seen in more detail in section 5.5.1

```
tail -F /var/log/smartex/577.SensingService.log
```

(a)

```
tail -F /var/log/smartex/577.SensingService.log | grep CRITICAL
```

(b)

```
tail -F /var/log/smartex/577.SensingService.log | grep WARNING
```

(c)

Figure 6.2: (a) Command given on the first terminal to monitor all the Sensing Service logs (b) Command given on the second terminal to monitor only the critical logs (b) Command given on the third terminal to monitor only the warning logs

These tasks were performed successfully, leading to the next iteration step which consisted of integrating the config. files to the Sensing Service so the Vision SW can effectively communicate with the cameras' FW during the service⁷. After a couple of iterations, another problem emerged: *the new FW also required streaming mode instead of trigger mode only*. As the streaming mode would require a redesign of the Sensing Software, this strategy was put on hold.

After re-evaluating the scenario, a new leading strategy was defined - using a set of SMX 2.1 cameras in an 8-HM installation with 2MM operating as master-slave⁸. While this strategy reduces the data flow in the USB 2.0 connector by half, it is not sufficient to ensure a full inspection of the fabric. However, implementing this strategy would significantly improve the system's performance for now, as well as allow the evaluation of other relevant parameters in a real environment after its installation.

New HW modifications were performed⁹ and a set of SMX 2.1 cameras were used to update the prototype that would be soon installed in the Stenter Machine. After replacing the cameras, the *Ship Safe* routine was performed to guarantee the HW was working properly. In short, this routine is a Python script that performs a series of tests on the system before its installation. It stress-checks the hardware components, such as cameras and cables, which reduces further interventions for replacing low-performance components.

⁷This task required the expertise of technical staff from the embedded team

⁸Go to section 5.3.2 for a better understanding of the strategy.

⁹The required modifications were also referred to in section 5.3.2. The required HW modifications cited in that section can be seen in more detail in section 5.5.1.

6.2 Prototype Implementation

As soon as the mechanical design¹⁰ was finished, it was sent to production. In the meanwhile, the Bill of Materials (BoM) for this prototype was created.

The installation was scheduled for the day after the Clamps were supposed to arrive at the Smartex office. The installation took 6 hours and a complementary 3-hour intervention for minor adjustments was required.

As the installation began, a minor problem was observed: *some of the clamp fixation holes required to be widened*. The problem was solved on the spot with a straight grinder.

The power supply cables for powering the Master Modules needed to be extended. This task was performed by connecting multiple cables using appropriate connectors. This modification resulted in 2 extended cables - one with double the size and another with triple the size. To do so, the cable tips were stripped and then the ferrules were clipped to the exposed wires with a clipping plier.

Just like the machine assessment in the early stage of the project, the final installation was also very challenging for the very same reason. The machine never stopped. The final installation can be seen in Figure 6.3

After the installation one unexpected issue arose: *the Vision SW branch used in this installation was not compatible with the SMX2.1 cameras*. This problem led to white pictures, as seen in Figure 6.4. This problem was tackled by deploying a compatible branch version¹¹. After this modification, although the pictures were visible, another issue arose: *due to the different master-slave configuration, the system was not using the most efficient modules to calibrate the exposure*, as seen in Figure 6.5. As the Master-Slave feature was developed for a different type of CKMs, the cameras used for auto-calibrating the exposure were not optimal for this prototype. A new feature that allows one to select which are the desired cameras to be used during the auto-exposure calibration is being developed¹² to tackle this issue.

6.3 Open issues and Further work

As outlined in the dissertation chapters, following a meticulous industry characterization, a thorough evaluation of the existing Smartex system was conducted. Furthermore, a prototype was implemented at a selected partner company. Throughout the course of this research, several notable issues surfaced and must be addressed in the following months, including:

- The necessity of changing the current data transfer technology used between HM and MM to guarantee a larger bandwidth¹³.

¹⁰referred to in the section 5.4

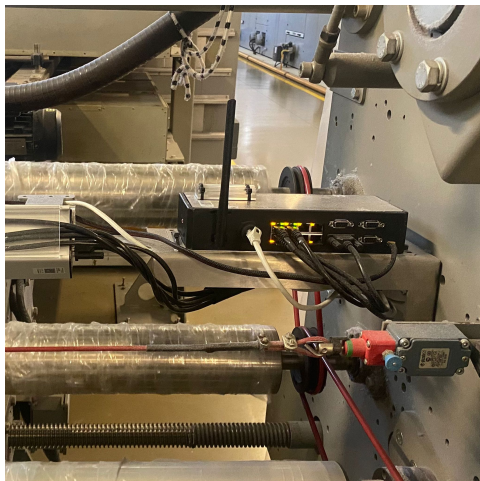
¹¹This task was performed by the Embedded SW team

¹²This task was inserted into the product backlog and performed by the Embedded SW team in the following sprint

¹³Which might include a redesign of some HW pieces' architecture



(a)



(b)



(c)

Figure 6.3: Final installation (a) System mounted on the Stenter Machine, (b) Master Module on top of the right side clamp, (c) Tablet and server cabinet

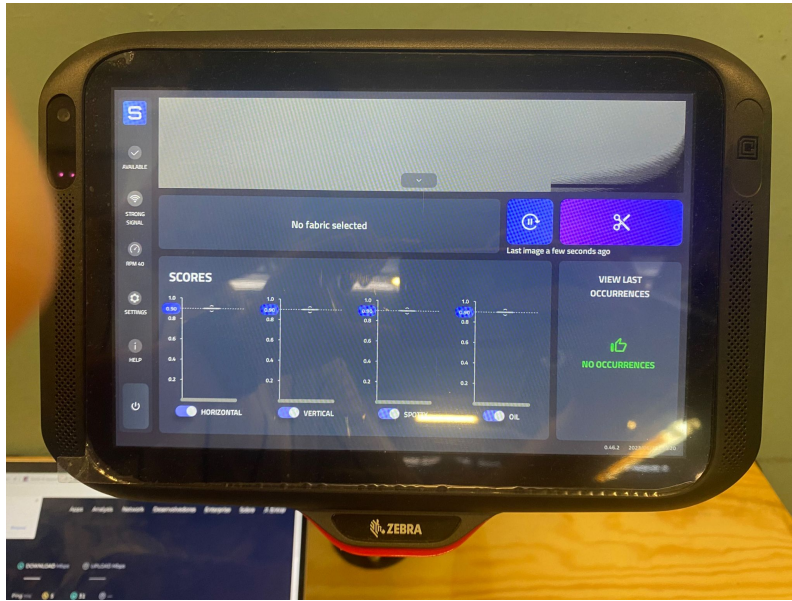


Figure 6.4: Tablet showing white pictures due to Camera Version and Vision SW incompatibility

- The necessity of training new Machine Learning models with defect pictures from Dye-houses defects
- The necessity of making the Vision SW IMU-independent.
- The necessity of assessing if there is room for optimizing the Vision SW, in special the Sensing Service. If not, assess the possibility of redesigning it, focusing on making the frame request routine faster.
- Integrating new camera protocols if needed

The above-mentioned issues are planned to be addressed until Q4 2023 in collaboration with the Hardware, R&D, Embedded SW, and QA teams. In the meanwhile, 2 more prototypes using different strategies will be deployed for further real-environment analysis. This strategy will allow both solving the main open issues already mapped and continuing the investigations on constraints and requirements for this new product.

The next steps towards the development of this work will be carried out in 3 main stages: (i) fine-tuning of the initial prototype, (ii) data collection for ML models to be trained, and (iii) implementing new cameras and integrating their FW into the embedded SW.

In the first stage, the main tasks consist of a continuous evaluation of any further issues that might arise in the following weeks, including potential camera fog-up, potential EMI, and potential mechanical adjustments.

The second stage consists of incremental modifications to the system in order to increase the velocity at which it can operate, as well as label and cluster data for training new ML models. To achieve this goal, other strategies of section 5.3 will be adopted.

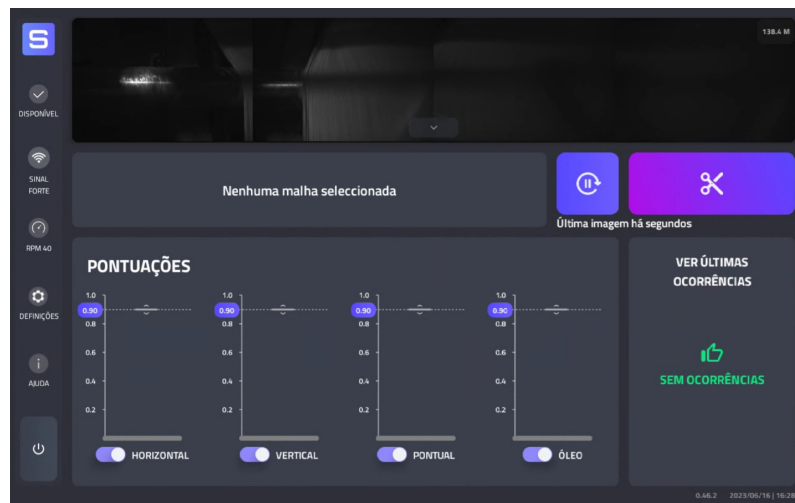


Figure 6.5: Tablet showing pictures with wrong exposure

The third stage, in turn, consists of integrating the new Smartex cameras into the prototype and making any modifications that might be necessary for it to work properly, both from a Hardware and Software standpoint.

This strategy will allow Smartex to implement a Proof-of-Concept prototype by late Q1 2024, placing this soon-to-be new product in the Technology Readiness Level (TRL) 3. This PoC prototype will allow finishing a first draft of what will become the Product Requirement Document (PRD)¹⁴ for this new product. After that, the testing strategy for the technology can be scaled, allowing the observation of further constraints.

In summary, this dissertation paved the way for a long, arduous, challenging, but also exhilarating endeavor that will last for years: put an end to the inefficient quality-control mechanism in Dyehouses, as well as allow good-quality data collection on textile processing.

¹⁴See template in Appendix [A](#)

Chapter 7

Conclusion

This dissertation aimed to address three main tasks, namely: (i) Perform an in-depth analysis of a new sector from the Textile Supply Chain and map out the problems not yet assessed by Smartex.ai, (ii) Select a suitable data-collection technology to tackle the problems discovered during the research stage and perform a system-based analysis for implementing it, (iii) Propose feasible solutions, perform tests, map out open issues, and plan the next steps of development of the soon-to-be new Smartex product.

The in-depth industry analysis showed how complex and singular the Textile Industry is, which can be seen as a giant opportunity for entrepreneurs who want to create disruptive technology and tackle the problems faced by the sector. The assessment performed was without a clue one of the most important contributions of this dissertation, allowing Smartex to plan the development process for their new product, as well as other new technologies they might want to launch.

Evaluating the potential technologies to address the problems identified in the initial research was exhilarating. This project step was indispensable for understanding how important it is to be customer-obsessed. The main lesson learned at this stage is that products should not be built solely for the sake of being cool, but rather they should be built because they provide value to the customers.

Analyzing the existing Smartex system and suggesting modifications to make it suitable for a new application was unquestionably the most challenging part of the work. Their technology is highly complex, which makes even small modifications difficult because they can have significant implications on other parts of the system. Despite the demanding nature of this project stage, the potential solutions presented are promising and indicate progress toward the development of a new product in the near future.

The existing prototype proved to be extremely valuable for validating assumptions and identifying new issues that need to be addressed. Although a fully functional prototype was not deployed as expected, the work accomplished in the past 12 weeks will serve as the basis for developing a new product in the upcoming year. However, in the following months, additional comprehensive analyses will be conducted to delve into specific hardware and software requirements, along with system specifications.

In summary, the work presented in this dissertation provided a valuable chance to apply concepts learned in both the Bachelor's and Master's Degrees in Mechanical Engineering. The practical experience gained at Smartex and in the Textile Industry was also essential in developing this work, highlighting the benefits of combining academic and industry knowledge for personal, professional, and academic growth.

Appendices

Appendix A

PRD Template

PRD Template

Problem statement

Example questions to answer:

What customer problems are we solving and when do they experience this issue?

Why is solving this problem urgent? Why is it important to our business right now?

Please provide examples that supports your above statements: both the customer problem and why is it important for our business. List the identified opportunities, from the user/customer perspective, that we are addressing with this product.

User personas

Example questions to answer:

Who is going to use this product?

Why is this product important for this particular persona?

Please give an example of how this persona is affected by the problem this product/feature is trying to solve.

Moodboard

Example questions to answer:

What other solutions are out there in the market (competition or similar) that may serve as an inspiration for what we want to

achieve with the product/feature?

Is there any tool related to this product to which the user is the user already used to and from which we look into?

Aren't we reinventing the wheel?

Please provide mockups and illustrations of such tools/products.

Features and requirements

Example questions to answer:

What are we building? How does it work? How do we know that it works?

What is the general shape of this solution? Do you have any mocks and prototypes?

Have we considered how we're building this to be fast, performant, scalable and/or relatively low-cost on our services?

How are we going to test these features in a high-level plan?

What dependencies does this product/feature has with other systems in our product? Please outline them.

Please detail the constraints of the features and how they should behave.



Success Metrics

Example questions to answer:

What are the metrics we should follow in order to track the progress of this feature?

Also, what metrics are we going to follow to assess the success of

the feature building and engineering phase (QA?)

Make sure that the metrics are outlined per service/dependency type.

What are the thresholds that will consider the success of these metrics?

What data needs to be collected to assess these metrics?

How are we going to collect this data?

Where is this data going to be logged? How are we going to build the metrics on top of the data logged?

How is this data/metrics going to be tracked/updated over time?

Please detail the constraints of the features and how they should behave.



Launch plan

Example questions to answer:

To what customers are we launching this too? What is the gradual plan that ensures we launch this with success?

Are we doing PR? What should be the messaging architecture?

When will it be ready?

What are we measuring? When will it be ready?

If it's a straightforward release, let us know as well.

? Open issues

Example questions to answer:

What parts of this product/feature are still yet to be discussed and

resolved?

May it be engineering related or customer related, leave those items here for further review.

References

- [1] Leonora Fuxman, Iris Mohr, Ali B. Mahmoud, and Nicholas Grigoriou. The new 3ps of sustainability marketing: The case of fashion. *Sustainable Production and Consumption*, 31:384–396, 2022. ISSN 2352-5509. doi: <https://doi.org/10.1016/j.spc.2022.03.004>. URL <https://www.sciencedirect.com/science/article/pii/S2352550922000586>.
- [2] Kimitaka Nishitani, Thi Bich Hue Nguyen, Trong Quy Trinh, Qi Wu, and Katsuhiko Kokubu. Are corporate environmental activities to meet sustainable development goals (sdgs) simply greenwashing? an empirical study of environmental management control systems in vietnamese companies from the stakeholder management perspective. *Journal of Environmental Management*, 296:113364, 2021. ISSN 0301-4797. doi: <https://doi.org/10.1016/j.jenvman.2021.113364>. URL <https://www.sciencedirect.com/science/article/pii/S0301479721014262>.
- [3] World Economic Forum and Boston Consulting Group. Net-zero challenge: The supply chain opportunity, 2021.
- [4] European Topic Centre on Waste and Materials in a Green Economy. Textiles and the environment in a circular economy. Technical report, European Environment Agency, 2022. URL https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/textiles-and-the-environment-in-a-circular-economy/@download/file/ETC-WMGE_report_final%20for%20website_rev20221118.pdf.
- [5] SOSV. Smartex is creating the textile factory of the future. SOSV website, 2023. URL <https://sosv.com/smartex-is-creating-the-textile-factory-of-the-future/>.
- [6] Julia Adamkiewicz, Ewa Kochańska, Iwona Adamkiewicz, and Rafał M. Łukasik. Greenwashing and sustainable fashion industry. *Current Opinion in Green and Sustainable Chemistry*, 38:100710, 2022. ISSN 2452-2236. doi: <https://doi.org/10.1016/j.cogsc.2022.100710>. URL <https://www.sciencedirect.com/science/article/pii/S2452223622001225>.
- [7] Hiroko Tabuchi. How fashion giants recast plastic as good for the planet, Jun 2022. URL <https://www.nytimes.com/2022/06/12/climate/vegan-leather-synthetics-fashion-industry.html>.
- [8] Gilberto Francisco Martha de Souza, Adherbal Caminada Netto, Arthur Henrique de Andrade Melani, Miguel Angelo de Carvalho Michalski, and Renan Favarão da Silva. Chapter 3 - engineering systems fundamentals. In Gilberto Francisco Martha de Souza, Adherbal

- Caminada Netto, Arthur Henrique de Andrade Melani, Miguel Angelo de Carvalho Michalski, and Renan Favarão da Silva, editors, *Reliability Analysis and Asset Management of Engineering Systems*, Advances in Reliability Science, pages 55–90. Elsevier, 2022. ISBN 978-0-12-823521-8. doi: <https://doi.org/10.1016/B978-0-12-823521-8.00012-8>. URL <https://www.sciencedirect.com/science/article/pii/B9780128235218000128>.
- [9] H. H. Rosenbrock and A. G. J. MacFarlane. State-space and multivariable theory. *IEEE Transactions on Systems, Man, and Cybernetics*, SMC-2(2):295–296, 1972. doi: 10.1109/TSMC.1972.4309115.
- [10] Alexander Kossiakoff, Samuel J. Seymour, David A. Flanigan, and Steven M. Biemer. *Systems Engineering: Principles and Practice*. John Wiley & Sons, Inc., Hoboken, NJ, 3rd edition edition, 2020. ISBN 9781119516668. Complete list of the titles in this series appears at the end of this volume.
- [11] German Institute for Standardisation. DIN 19226:1968-05. Superseded date: 02-01-1994. Published date: 01-12-2013, May 1968. CONTROL ENGINEERING - DEFINITIONS AND TERMS.
- [12] Mark W. Maier and Eberhardt Rechtin. *The Art of Systems Architecting*. Publisher Name, 2nd edition, 2000. ISBN 0-8493-0440-7. Library of Congress Cataloging-in-Publication Data.
- [13] BKCASE Editorial Board. *The Guide to the Systems Engineering Body of Knowledge (SEBOK)*. The Trustees of the Stevens Institute of Technology, Hoboken, NJ, v. 1.3 edition, 2014. URL <http://www.sebokwiki.org>. Accessed DATE.
- [14] Frederick P. Brooks Jr. *The Mythical Man-Month: Essays on Software Engineering*. Addison-Wesley Professional, Boston, MA, anniversary edition edition, 1975. ISBN 978-0201835953.
- [15] Winston W. Royce. Managing the development of large software systems. *Proceedings of IEEE WESCON*, 26:1–9, August 1970. doi: 10.1109/WESCON.1970.1232008.
- [16] Barry Boehm. A spiral model of software development and enhancement. *ACM SIGSOFT Software Engineering Notes*, 11(4):14–24, 1986.
- [17] Barry Boehm and et al. Using the winwin spiral model: A case study. *IEEE Computer*, 31(7):33–44, 1998.
- [18] Alan M. Davis. Operational prototyping: A new development approach. *IEEE Software*, 9(5):70–78, 1992.
- [19] Peter R.N. Childs. 1 - design. In Peter R.N. Childs, editor, *Mechanical Design Engineering Handbook (Second Edition)*, pages 1–47. Butterworth-Heinemann, second edition edition, 2019. ISBN 978-0-08-102367-9. doi: <https://doi.org/10.1016/B978-0-08-102367-9.00001-9>. URL <https://www.sciencedirect.com/science/article/pii/B9780081023679000019>.
- [20] Ian Sommerville. *Software Engineering*. Pearson, 10th edition, 2015. ISBN 0133943038.
- [21] Peter Sommerlad. *Software Engineering 2: Specification of Systems and Languages*. Springer, 3rd edition, 2013. ISBN 978-3642386743.

- [22] Hans Mulder. The chaos report, 01 1994.
- [23] Kent Beck, Mike Beedle, Arie van Bennekum, Alistair Cockburn, Ward Cunningham, Martin Fowler, James Grenning, Jim Highsmith, Andrew Hunt, Ron Jeffries, Jon Kern, Brian Marick, Robert C. Martin, Steve Mellor, Ken Schwaber, Jeff Sutherland, and Dave Thomas. Manifesto for agile software development, 2001. URL <http://agilemanifesto.org/>.
- [24] Rashina Hoda, Norsaremah Salleh, John Grundy, and Hui Tee. Systematic literature reviews in agile software development: A tertiary study. *Information and Software Technology*, 85, 01 2017. doi: 10.1016/j.infsof.2017.01.007.
- [25] Raoul Vallon, Bernardo José da Silva Estácio, Rafael Prikladnicki, and Thomas Grechenig. Systematic literature review on agile practices in global software development. *Information and Software Technology*, 96:161–180, 2018. ISSN 0950-5849. doi: <https://doi.org/10.1016/j.infsof.2017.12.004>. URL <https://www.sciencedirect.com/science/article/pii/S0950584917302975>.
- [26] PM Partners. The agile journey: A scrum overview, 2021. URL <https://www.pm-partners.com.au/the-agile-journey-a-scrum-overview/>.
- [27] McKinsey & Company. State of fashion. <https://www.mckinsey.com/industries/retail/our-insights/state-of-fashion>, 2022. Accessed: March 29, 2023.
- [28] Anthony Ulwick. *Jobs to be Done: Theory to Practice*. Strategyn LLC, 2016.
- [29] Jana van den Bergen and Georgia Parker. Textile processing guide: Pre-treatment, colouration and finishing, Apr 2023. URL <https://reports.fashionforgood.com/report/textile-processing-guide-pre-treatment-colouration-and-finishing/>.
- [30] Rose Sinclair, editor. *Textiles and Fashion: Materials, Design and Technology*. Woodhead Publishing, 1st edition, September 30 2014. ISBN 9781845699314. URL <https://www.elsevier.com/books/textiles-and-fashion/sinclair/978-1-84569-931-4>.
- [31] Asim Kumar Roy Choudhury. 1 - introduction to finishing. In Asim Kumar Roy Choudhury, editor, *Principles of Textile Finishing*, Woodhead Publishing Series in Textiles, pages 1–19. Woodhead Publishing, 2017. ISBN 978-0-08-100646-7. doi: <https://doi.org/10.1016/B978-0-08-100646-7.00001-1>. URL <https://www.sciencedirect.com/science/article/pii/B9780081006467000011>.