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Algorithms and Technologies for Inspection Places

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Abstract

In such competitive and global world where we live, the technology plays an important role on approaching people and enhancing their life conditions. Nevertheless, all the development faced along the time has the major responsibility of the most extraordinary creature: the Human. He is, in fact, the most important player for the significant changes and enhancements in our life conditions, making available to people the necessary tools to reach those goals.

The use of technology under the industrial context shall mainly focus on the working conditions improvement and, whenever possible, improving the manufacturing process performance. However, in order to have broader and robust approach to any process improvement, the focus shall be addressed to the Human. Human Resources are the most differentiated elements of any organization, once they are the natural engine to execute the change within the organization.

The inspection processes, as part of the manufacturing process, point to the quality assurance of the product, in order to grant the customer satisfaction. Although inspection processes are not added-value processes, they are crucial to guarantee the organization's image and perception from the customers point of view. A long-lived relation between the organization and the customers is also based on the credit build-up between them and the high quality standards provided by the organization.

The trend of the replacement of the Human by automatic systems verified over time has been essential to reach significant manufacturing process improvements, especially in what concerns the process costs and the guarantee of an uniform inspection process. In the beginning, this approach has been followed in repetitive tasks, where the human contribution was mainly by means of physical interactions, i.e. where the human intelligence did not play a significant role. This kind of approach has been also followed in other inspection processes, in particular on those where the human contribution is crucial to assure the product quality. Some of the disappointing results obtained are caused by the difficulty of gathering the intrinsic knowledge as a result of the cognitive processes used, with special emphasis on the extraordinary ability Humans have to quickly adapt to sudden changes in the manufacturing process with impact on the final product quality.

Although the significant number of scientific contributions in this research area, the replacement of Humans by automatic systems did not always obtain the expected results. Part of this failure might be addressed to the absence of people performing the inspection in the development process of the new solution. The operators who perform the inspection are the ones carrying the intangible knowledge that allows the quality assurance of the inspection process with high quality standards.

Facing the challenge of improving the process performance of an inspection process, to-

tally done by Humans, one seeks for a structured approach to the problem focusing the development of the potential solution on the operator, using the technology as a way to help him, allowing the continuous introduction of process improvements along the time. One of the biggest challenges one might face is the operator's awareness as well as to keep away the fear about the technology becoming a threat for their job positions. Those aspects forced to develop intense and continuous work with them to gather their difficulties, methods, and knowledge with the aim of developing a solution that incorporates their contributions and that could improve their working conditions.

The careful approach to the problem is also extended to the technology assessment and selection process that better fit in the inspection context, assuring a smooth adoption and diffusion process by the users, granting the desired compatibility between Humans and Technology. This compatibility shall also be inherent to the interface design adopted in the new inspection solution, leading to the enhancement of the inspection process performance by means of cost reduction granted by faster and more effective inspection.

The interaction between the technology and the human shall be seen as a way for technology serving the human needs, i.e. enhancing their life conditions. The transition from a purely manual process to a system that combines humans and technology, that evolves along the time, and adapts to different contexts, implies a different sight to the inspection process. The significant change expected in the inspection process requires a model which highlights the influence of the diverse variables that contribute to the inspection process performance, allowing the identification of the improvement elements and reinforcing the learning process.

The paradigm and mentality changes within an organization are extremely complex and critical. The very promising results obtained along the entire project create the idea that those changes are possible, even for those who were not so optimistic in the beginning of this path due to the complexity of the problem in hands in combination with the very demanding goals and unsuccessful results of previous attempts. The confidence demonstrated by the various entities involved in the project, the decision of the company to proceed with the industrialization of the solution proposed, and the extremely positive feedback from the operators, disseminate the idea that one followed the right approach to the problem. Being part of the changing process, contributing at the same time for the notion that human contribution is fundamental in any technical development, makes me proud and conscious that the scientific, industrial and personal objectives were reached.

Resumo

Num mundo globalizado e altamente competitivo como aquele em que vivemos, a tecnologia tem um papel fundamental na aproximação dos povos e na melhoria das condições de vida das pessoas. No entanto, todo o desenvolvimento que se tem verificado ao longo dos tempos tem a responsabilidade maior do ser mais extraordinário que se conhece: o Ser Humano. É ele o verdadeiro responsável pelas profundas alterações e melhorias nas nossas condições de vida, colocando ao dispor das pessoas os meios e as ferramentas necessárias à obtenção desses grandes objetivos.

A utilização da tecnologia em contexto industrial deve visar, no seu essencial, a melhoria das condições de trabalho e, sempre que possível, melhorar o desempenho dos processos de manufatura. Contudo, o foco de uma abordagem mais abrangente e robusta para a melhoria de qualquer processo, deve ser o Homem. O grande fator diferenciador de qualquer organização é o capital humano, os seus Recursos Humanos. São eles os verdadeiros motores da mudança que uma organização poderá ambicionar alcançar.

Os processos de inspeção, sendo parte integrante do processo de manufatura, pretendem garantir a excelência do produto, de forma a garantir a plena satisfação dos clientes a quem se dirige. Não sendo processos de valor acrescentado, os processos de inspeção são fundamentais para a garantia da imagem e perceção dos clientes face à organização com quem estabelecem uma relação. O valor da confiança entre organização e cliente é extremamente importante para consolidar uma relação que se pretende duradoura e com elevados padrões de qualidade.

A tendência verificada ao longo do tempo de substituição do Homem por sistemas de automação foi fundamental para a obtenção de melhorias significativas nos processos de fabrico ao nível do seu custo e da capacidade de ter um padrão de inspeção uniforme ao longo do tempo. Esta abordagem foi inicialmente focada em processos altamente repetitivos e mecanizados, onde a contribuição humana se centrava, essencialmente, nos aspetos físicos, ou seja, em processos em que a contribuição da inteligência humana era pouco significativa. Este tipo de abordagem generalizou-se para outros processos de inspeção, nomeadamente naqueles em que o contributo humano se revela essencial para a garantia da qualidade do produto. Os resultados nem sempre foram um sucesso pela dificuldade de adquirir o conhecimento intrínseco resultante dos processos cognitivos adoptados, em particular pela extraordinária capacidade humana de se adaptar rapidamente a variações circunstanciais no processo de manufatura.

Apesar dos imensos contributos científicos existentes nesta área de investigação, a substituição do Homem por sistemas autónomos nem sempre tem verificado bons resultados. Parte desse insucesso pode ser atribuído à ausência da contribuição das pessoas que integravam o processo de inspeção no desenvolvimento de novos processos. São essas

pessoas as portadoras do conhecimento intangível que possibilita a garantia de elevados padrões de qualidade do processo de inspeção.

Colocado perante um desafio de melhorar o desempenho de um determinado processo de inspeção, totalmente manual, é fundamental estruturar esse problema de uma forma coerente e prática centrando o desenvolvimento de uma possível solução no operador, utilizando a tecnologia como meio para o ajudar, possibilitando a introdução de melhorias nesse processo ao longo do tempo. A exigente tarefa de captar o interesse dos operadores, assim como afastar o receio da tecnologia se tornar uma ameaça aos seus postos de trabalho, obrigou a um intenso e persistente trabalho junto daqueles que realizam a inspeção, no sentido de absorver melhor as dificuldades, os métodos e o conhecimento existente, e desenvolver uma solução que incorporasse os seus contributos e melhorasse as suas condições de trabalho.

O cuidado a ter com a abordagem ao problema é igualmente extensível ao processo de seleção e escolha da(s) tecnologia(s) que melhor se adapta(m) ao contexto da inspeção, garantindo um suave processo de adoção e difusão pelos seus utilizadores, assegurando compatibilidade entre o Homem e a Tecnologia. Essa compatibilidade pode e deve também ser garantida através de um correto desenho das interfaces existentes, ambicionando, ao mesmo tempo, uma melhoria do desempenho do processo de inspeção, em particular com o objetivo de reduzir os seus custos através de uma inspeção mais rápida e mais eficaz.

A interação entre a tecnologia e o ser humano deve ser vista como um meio para a tecnologia servir os propósitos humanos, ou seja, melhorar as suas condições de vida de uma forma direta ou indireta. A passagem de um sistema puramente manual para um sistema que combina a tecnologia com o ser humano, e que evolui ao longo do tempo, adaptando-se às diferentes realidades, obriga a uma visão diferente do processo de inspeção. Esta alteração deve ser modelada de forma a ser perceptível a influência das diversas variáveis no desempenho do processo de inspeção, permitindo ao mesmo tempo a identificação dos fatores de melhoria e reforçando o processo de aprendizagem.

A mudança de paradigma e, também, de mentalidades dentro de uma organização afigura-se complexa e de difícil alcance. Os resultados extremamente positivos verificados ao longo de todo o projeto permitiram fazer acreditar que era possível, mesmo aqueles que se mostravam mais cépticos no seu início, devido à exigência dos objetivos, da complexidade do problema e do historial de experiências mal sucedidas. A confiança demonstrada pelas diversas entidades envolvidas neste projeto e a decisão de prosseguir a industrialização da solução, assim como os comentários extremamente positivos por parte dos operadores, transmitem a confiança necessária para acreditar que o caminho seguido foi o correto. Fazer parte dessa mudança, tendo ao mesmo tempo contribuído para passar a mensagem de que a inclusão do Homem no desenvolvimento de qualquer solução tecnológica é fundamental, deixam a sensação de orgulho e de ter atingido os objetivos científicos, industriais e pessoais.

Résumé

Dans un monde globalisé et hautement concurrentiel comme celui que nous vivons, la technologie a un rôle vital à rassembler les gens et l'amélioration des conditions de vie des populations. Cependant, tout le développement qui a été vu à travers les âges a la plus grande responsabilité d'être plus extraordinaire que nous connaissons: l'Être Humain. Il est vraiment responsable des profonds changements et des améliorations dans nos conditions de vie, en mettant à la disposition des personnes ayant les moyens et les outils nécessaires pour atteindre ces grands objectifs.

L'utilisation de la technologie dans un contexte industriel devrait viser, en substance, l'amélioration des conditions de travail et, si possible, améliorer la performance des processus de fabrication. Toutefois, la mise au point d'une approche plus globale et robuste à l'amélioration de tout processus, devrait être l'homme. Le grand facteur de différenciation pour toute organisation est son capital humain, ses Ressources Humaines. Ils sont les véritables moteurs du changement qu'une organisation peut aspirer à atteindre.

Le processus d'inspection, qui fait partie intégrante du processus de fabrication, cherchent à assurer l'excellence du produit, afin d'assurer la satisfaction complète des clients à qu'il s'adresse. N'étant pas des processus à valeur ajoutée, les procédures d'inspection sont fondamentales pour assurer l'image et la perception des clients contre l'organisation avec qui ils établissent une relation. La valeur de la confiance entre l'organisation et le client est extrêmement important de construire une relation que si attente durable et basée sur des normes de qualité élevée.

L' évolution dans le temps de remplacement de l'homme par les systèmes d'automatisation était essentielle pour obtenir des améliorations significatives dans les processus de fabrication au niveau de son coût et la possibilité d'avoir un modèle uniforme d'inspection au fil du temps. Cette approche a été d'abord porté sur les processus hautement répétitives et mécanisées où la contribution de l'homme portait principalement sur les aspects physiques, c'est à dire dans les cas où la contribution de l'intelligence humaine était négligeable. Cette approche a été généralisée à d'autres processus d'inspection, en particulier ceux où la contribution de l'homme est essentiel pour assurer la qualité du produit. Les résultats ne sont pas toujours un succès en raison de la difficulté d'acquérir la connaissance intrinsèque résultant des processus cognitifs adoptées notamment par la capacité extraordinaire des humaines à s'adapter rapidement aux changements de situation dans le processus de fabrication.

Malgré les énormes contributions scientifiques existantes dans ce domaine de recherche, le remplacement de l'homme par des systèmes autonomes n'a pas toujours vu de bons résultats. Une partie de cette défaillance peut être attribuée à l'absence de la contribution des personnes qui ont fait partie de la procédure d'inspection dans le développement de

nouveaux procédés. Ces personnes sont les porteurs de connaissances intangibles qui permet d'assurer des normes élevées de qualité du processus d'inspection.

Face à un défi d'améliorer la performance d'un processus d'inspection particulier, entièrement manuel, c'est fondamental de structurer ce problème d'une forme cohérente et pratique pour développer une solution centrée à l'opérateur, en utilisant la technologie comme un moyen d'aider, rendant possible la l'amélioration du processus au fil du temps. La tâche exigeante de capter l'intérêt des opérateurs ainsi que conjurer la peur de la technologie deviennent une menace pour leurs emplois, forcé au travail intense et persistant avec ceux qui font l'inspection afin de mieux absorber les difficultés,les méthodes et les connaissances existantes, et développer une solution qui intégre leurs contributions et qui peut améliorer leurs conditions de travail.

Le soin de la solution au problème est également étendu à la sélection et évaluation des technologies qui répondent le mieux dans le contexte du processus d'inspection, d'assurer un bon déroulement du processus d'adoption et la diffusion par ses utilisateurs, et pour assurer la compatibilité entre l'Homme et la Technologie. Cette capacité doit également être assurée par une conception correcte des interfaces existantes, convoitant tout en améliorant la performance du processus d'inspection, en particulier dans le but de réduire leurs coûts grâce à des inspections plus rapides et plus efficace.

L'interaction entre la technologie et l'être humain doit être considéré comme un moyen de la technologie pour servir des fins humaines, à savoir, pour améliorer les conditions de vie d'une manière directe ou indirecte. La transition d'un système purement manuel à un système qui combine la technologie avec des êtres humains, qui évolue au fil du temps, et qui s'adapt à des situations différentes, nécessite un point de vue différent du processus d'inspection. Ce changement doit être conformée de manière à être sensible à l'influence de plusieurs variables sur les performances du processus d'inspection, tout en permettant l'identification des facteurs améliorant et en renforçant le processus d'apprentissage.

Le changement de paradigme et aussi des mentalités au sein d'une organisation, était complexe et difficile à atteindre. Les résultats très positifs observés tout au long du projet ont conduit à croire que c'était possible, même pour ceux qui étaient les plus sceptiques au début, en raison de l'exigence des objectifs, de la complexité du problème et une histoire de mauvaises expériences. La confiance témoignée par les différentes entités impliquées dans ce projet et la décision de poursuivre l'industrialisation de la solution, ainsi que les évaluations très positives des opérateurs, transmettre la confiance de croire que le chemin suivi était le bon. Faire partie de ce changement, tout en contribuant en même temps à transmettre le message que l'inclusion de l'Homme dans le développement de toute solution technologique est essentiel établi le sentiment de fierté et d'avoir atteint les objectifs scientifiques, industriels et personnels.

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"Any process is better than no process! A good process is better than a bad process.
Even a good process can be made better!"

Michael Hammer

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AHP Analytical Hierarchy Process.

AMT Advanced Manufacturing Technologies.

AVT Allied Vision Technologies.

BDE Basic Decision Equations.

CCD Charge-Coupled Device.

CI Consistency Index.

CMOS Channel Metal Oxide Semiconductor.

CPB Combined Panning Buttons.

CR Consistency Ratio.

CVT Commercial Vehicle Tires.

DB Database.

DEA Data Envelopment Analysis.

DEA-AR Data Envelopment Analysis - Assurance Region.

DMU Decision-Making Units.

DoE Design of Experiments.

DOT Department Of Transportation.

DPB Distributed Panning Buttons.

ENCC Enhanced Navigator with Continuous Control.

EVA-MIX EVAluation of MIXed criteria.

FOV Field Of View.

fps frames per second.

G&D Grab & Drag.

GigE Gigabit Ethernet.

GP Goal Programming.

HD High Definition.

HMI Human-Machine Interface.

IDS Imaging Development Systems.

IP Intellectual Property.

IPC Industrial PC (Personal Computer).

LED Light Emitting Diode.

MADM Multi-Attribute Decision-Making.

MAUT Multiple Attribute Utility Theory.

MAVT Multiple Attribute Value Theory.

MCDM Multi-Criteria Decision-Making.

MU Uniformity Machine.

NC Non-Conformity.

NCs non-conformities.

NDA Non-Disclosure Agreement.

NPV Net Present Value.

OCR Optical Character Recognition.

OE Original Equipment.

OEM Original Equipment Manufacturer.

PCA Patent Co-citation Approach.

PVT Passenger & Light Trucks.

QFD Quality Function Deployment.

RI Random Index.

ROI Region Of Interest.

SDK Software Developer’s Kit.

SMART Simple Multiple-Attribute Rating Technique.

TCP/IP Transmission Control Protocol / Internet Protocol.

TCT Time Compression Technologies.

TOPSIS Technique for Order Preference by Similarity to Ideal Solution.

USB Universal Serial Bus.

UTA Utility Theory Additive.

VI Visual Inspector.

VIs Visual Inspectors.

Chapter 1

Introduction

In such competitive business world, any company is seeking for competitive advantages that allow them to be sustainable along the time. This competitiveness might be achieved by four distinct ways: overall cost leadership, overall differentiation, focus-segment cost leadership, or focus-segment differentiation [37]. In addition to the competitive advantage every company is following, organizations are always concerned about the customers perception with respect to the quality of products or services they provide. Quality is something inherent to any product or service from the customer's perspective [38].
Along the time, companies have been investing a lot of time and resources in enhancing the quality of the processes, products and services. Although the quality assurance does not add value to the final product or service, it is something that must be part of it. Different strategies have been followed: some of them with a focus on the product (product quality) and some others with focus on the process (process quality). There are also cases that combine the two approaches in order to get a superior quality. Sousa and Voss [39] mention five alternative approaches:

- transcendent: looking for excellence
- product-based: amount of desirable attribute
- user-based: fitness for use
- manufacturing-based: conformance to specification
- value-based: satisfaction relative to price

Nevertheless, one of the main concerns about quality assurance is related to cost [40]. The goal is to have a quality assurance process as much effective as possible and with the lowest possible cost.

With this motto in mind, Continental Mabor and MIT-Portugal Program came up with the AutoClass project. **AutoClass** stands for Automatic Classification and Quality Control for Car Tires. It is an industrial based project agreed between Continental Mabor Indústrias de Pneus, a Portuguese affiliated company of the multinational Continental AG Corporation, and MIT-Portugal Program, by the Engineering Design and Advanced Manufacturing focus area. The project intends to develop an automatic quality control system for the car tires final inspection process with the aim of reducing the actual process costs by 50%. The project has the target to develop an industrial prototype to be installed at the plant that can demonstrate the possibility to achieve the project goals.

Many different technologies were studied and tested along the project. A structured approach to the selection and assessment of the different technologies is essential to identify the most suitable options for the inspection solution. Since the current process is mainly a human-based process, workers but also all people involved in the process (managers, engineers, maintenance, quality, human resources, etc.) must be involved in the project development and definition. Their experience and knowledge are used as an input for the project development. In addition, an automatic system does not mean a simple non-human system. Process flexibility is inherent to human-based processes. A human-machine system is a more sophisticated system, but also a more flexible, reliable and effective solution. Technology should support workers to improve their job conditions. People should train the system to improve and to acquire new information. This also reveals another important outcome that should be expected in this project: an iterative system that constantly evolves with time. New tire types are always coming (different sizes, tread width, specifications, etc.) and the system must be able to adapt to new realities in order to keep the system flexibility and robustness through the time. The system shall create the necessary conditions to monitor and to allow acting online in the manufacturing process.

1.1 Motivation

The actual quality control process of inspection is performed by very knowledgeable, very specialized and well-trained operators. The decision of the tire classification (OK or NOK) is completely based on the human capability of analyzing correctly the tire quality taking into account all the requirements specified by the customers. The task performed by the operators is a multi-source process once they combine the information from different senses (like vision, touch, smell, etc.) in order to make a decision about the quality of the tire they are inspecting. In addition, the use of cognitive skills (memory, ability to associate a specific tire to a specific kind of imperfection, perception, awareness, etc.)

to enhance their capability of classifying a tire addresses the difficulty to translate these aspects into a system with a certain level of automation. Acquiring and transferring all these skills, knowledge and capabilities of humans into an automatic system means a significant degree of complexity and leads to an immense technical challenge.

This existing gap between the actual human-based quality inspection process and a full automatic system might be easily observed by the fact that until now, no one (company, research institute or organization) has been able to develop such a system, although several attempts and significant investments have been done to accomplish that.

Big challenges create high motivations. The problem one faces in this project represents a big challenge and has very high risks but also a great opportunity to create something innovative with significant impact in the industrial environment, and that can be generalized to other realities rather than the tire manufacturing process.

The project also contains several fields of expertise of research, from the technology selection and assessment to the design and definition of interfaces with operators.

1.2 Company description

Continental AG, internally often called Conti for short, is a worldwide leading German manufacturer of tires, brake systems, vehicle stability control systems, engine injection systems, tachographs and other parts for the automotive and transport industries. The company is based in Hanover, Lower Saxony, Germany. It is the world's 4^{th} largest tire manufacturer after Bridgestone, Michelin and Goodyear [41], according to the revenue data from 2009. At the Original Equipment Manufacturer (OEM) supplier's level, Continental AG is the European leader and takes the 4^{th} place in the worldwide market [42]. Continental AG had sales volume of almost 32 billion euros in 2012 which represented a sales increase of about 7.3% with respect to 2011. The company employs almost 170 000 workers in all facilities [43].

It was founded in 1871 as a rubber manufacturer, Continental-Caoutchouc und Gutta-Percha Compagnie. After acquiring Siemens VDO, it has become one of the top 5 automotive suppliers in the world [1].

Continental AG is organized in two main groups: the rubber group and the automotive group. The rubber group roughly represents 40% of the sales and comprises the following divisions:

- Passenger & Light Trucks (PVT)
- Commercial Vehicle Tires (CVT)

- ContiTech

The following divisions constitute the automotive group (60% of sales):

- Chassis & Safety
- Powertrain
- Interior

Continental AG is located in 13 different countries worldwide, consisting of 23 production plants, with facilities located worldwide (Figure 1.1).

One of Continental's main areas of expertise and technical leadership is Fuel Consumption Reduction, achieved through more efficient fuel injection systems, reduced rolling resistance tires and hybrid propulsion systems.

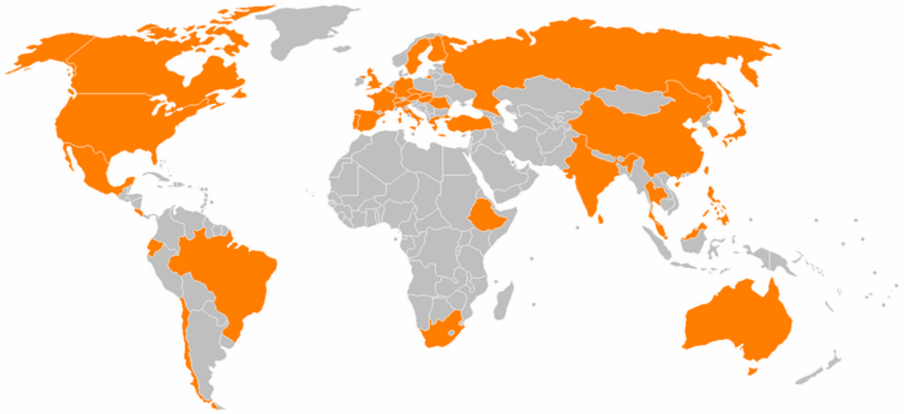


Figure 1.1: Continental AG global locations (*source: Wikipedia* [1])

Continental sells tires for automobiles, motorcycles, and bicycles worldwide under the Continental brand. It also produces and commercializes other brands on a regional level, such as General, Euzkadi, or Barum. Continental's customers include all major automobile, truck and bus producers, such as Volkswagen, Daimler AG, Ford, Volvo, Iveco, Schmitz, Koegel, Freightliner Trucks, BMW, General Motors, Toyota, Honda, Renault and Porsche [44].

In 2001, Continental acquired a controlling interest in Temic, Daimler Chrysler's automotive electronics business, which is now part of Continental Automotive Systems. The company also purchased German automotive rubber and plastics company Phoenix AG in 2004 and the automotive electronics unit of Motorola in 2006. In 2007, Continental acquired Siemens VDO from Siemens AG. In August 2008 Continental agreed to be taken over by the family-owned auto parts manufacturer Schaeffler Group and a consortium of banks in a deal valuing the company at €12 billion. Schaeffler has however pledged to restrict its stake in the company to less than 50% for at least four years. Dr. Karl-Thomas Neumann has succeeded Manfred Wennemer as chief executive officer of Continental on September 1^{st}, 2008 [45].

Continental Mabor Indústria de Pneus, S.A. is a Continental AG affiliate. The Portuguese plant produces PVT tires for the Original Equipment (OE) and replacement markets. Besides the Continental brand, it is also responsible for the production of brands such as Mabor, Semperit, Gislaved, etc.

Continental AG set up together with the Portuguese company Mabor in 1989/90 a joint venture for the production of tires in Lousado. In 1993, the company sees a complete takeover of the tire activities and of a factory producing textile cord [46]. Currently, Lousado plant is responsible for a daily production of about 50 000 tires. It employs more than 1600 workers from diversified areas (engineering, production, human resources, accounting, etc.) and the company had, in 2010, a turnover of €487.94 million.

1.3 Tire Manufacturing Process Overview

The tire manufacturing process comprises six main process steps: mixing, preparation cold, preparation hot, tire building, curing and final finishing. The final finishing process is the place in the manufacturing process where tire quality visual inspection takes place. It also includes the uniformity tests process before the tires are sent to the warehouse where the paletization process occurs. A simplified block diagram of the tire manufacturing process is presented in Figure 1.2 where the process dependencies are also shown.

The tire manufacturing process at the Portuguese plant follows exactly the same approach above mentioned. Besides the manufacturing process, there is a full supply chain

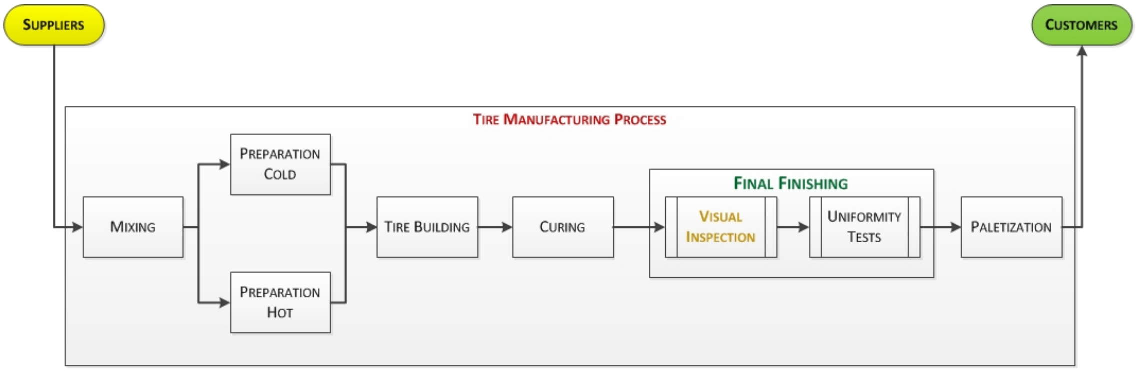


Figure 1.2: General tire manufacturing process from the raw materials supplier until the final customer

including the material and machinery suppliers as well as the end costumers OEM and aftermarket customers (replacement market). Under such a complex manufacturing process and supply chain, a production control system is implemented in the plant.

1.3.1 Process Data Overview

Tire industry uses specific terminology for the tire structures and for the information that is printed in the tire surfaces. Figure 1.3 shows a tire profile with the representation and meaning of the different tire parts. It is important to refer that some terms have more than one word to identify the tire surface. For instance, shoulder is also known (and it will be used as that along this document) by buttress. Inner liner will be used along this document with the term *interior*.

Another important aspect to be taken into account is the tire labeling. It is a mandatory information that is printed in the tire sidewall to provide the necessary data to the end-user. In particular, the tire dimensions (Figure 1.4) and the Department Of Transportation (DOT) information which gives the manufacturing origin of the tire as well as an identification code about the tire features.

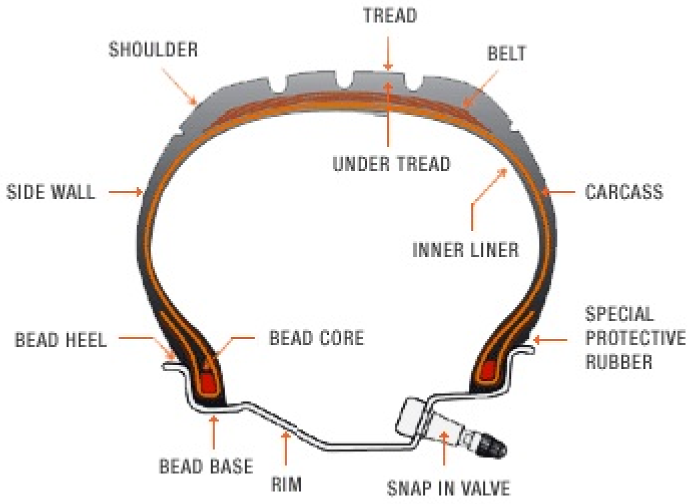


Figure 1.3: The structure of a tire and part names (*source: Hankook* [2])

The AutoClass project is focused on the quality inspection of tires at the end of the manufacturing process. The type of non-conformities (NCs) can vary significantly according to the tire surface location, type of imperfection (visual or structural imperfection), or process-related issues. The percentage of tires with NCs depends on the production mix and process performance but, in general, it represents 10% of the total production. 1% - 2% of the total production are going to scrap due to very critical NCs that cannot be

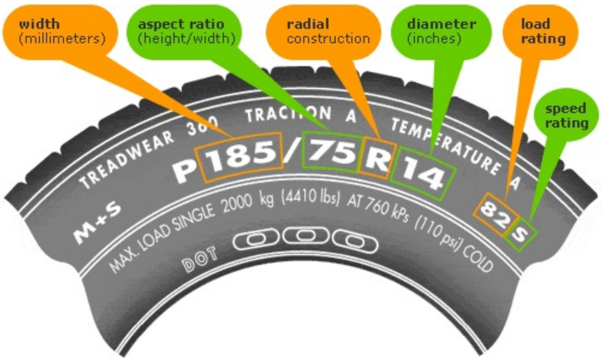


Figure 1.4: Meaning of the different tire dimensions placed in the tire sidewall (*source: Engine Basics* [3])

recovered.

In total, 76 different NC codes can be identified in the final finishing process with frequencies of occurrence that vary significantly according to the production mix but with a distribution similar to the one presented in Figure 1.5. NC codes are organized by groups of NCs with a generic format *xz*, where *x* represents the tire surface (see Table 1.1), and *z* is a sequential number that identifies a specific imperfection within a certain group of NCs [47].

Generally, a tire will be classified as NOK when an imperfection is detected and the tire is classified as OK when it does not contain any imperfection that can affect the tire performance or is “visible”.

Table 1.1: Groups of NCs according to the area

Area code (x)	**Area**
0	General
1	Tread
2	Buttress
3	Sidewall
4	Bead
5	Interior
6	Mechanical breakdown
9	Other

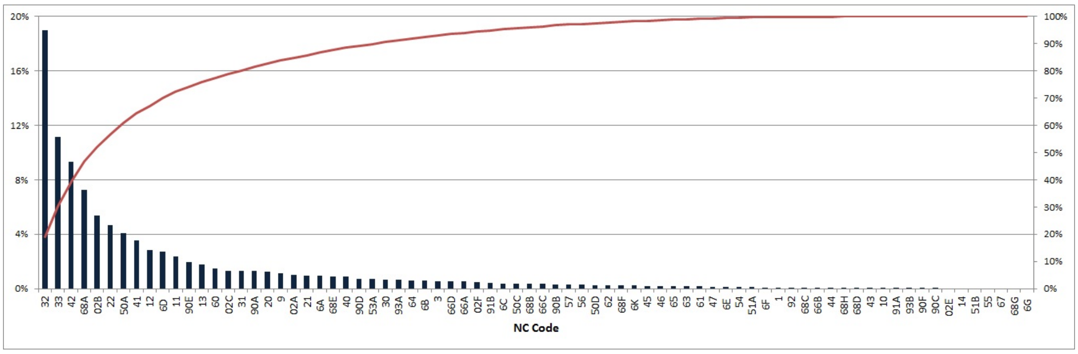


Figure 1.5: Pareto of the NC occurrence

1.3.2 Final Finishing Process Description

The final finishing process is the ultimate process before the tire is sent to the customers. It is responsible for the quality assurance of the tires previously produced (visual inspection) and for the tire performance analysis (uniformity tests). Although the inspection process does not add value to the product, it is of the most importance since it reflects the company's image to the customer.

Whenever a tire arrives to the final finishing process, a set of VIs perform the tire quality inspection and take a decision about the quality grade. When the tire is assessed as OK, the VI puts the tire on the conveyor to be transported to the uniformity tests process.. However, when the operator identifies a potential flaw in the tire, he suspends the state of the tire in the production control system and he sends the tire to the grading station (Figure 1.6).

The grading station is the place where the graders assign the NC code to the tire whenever

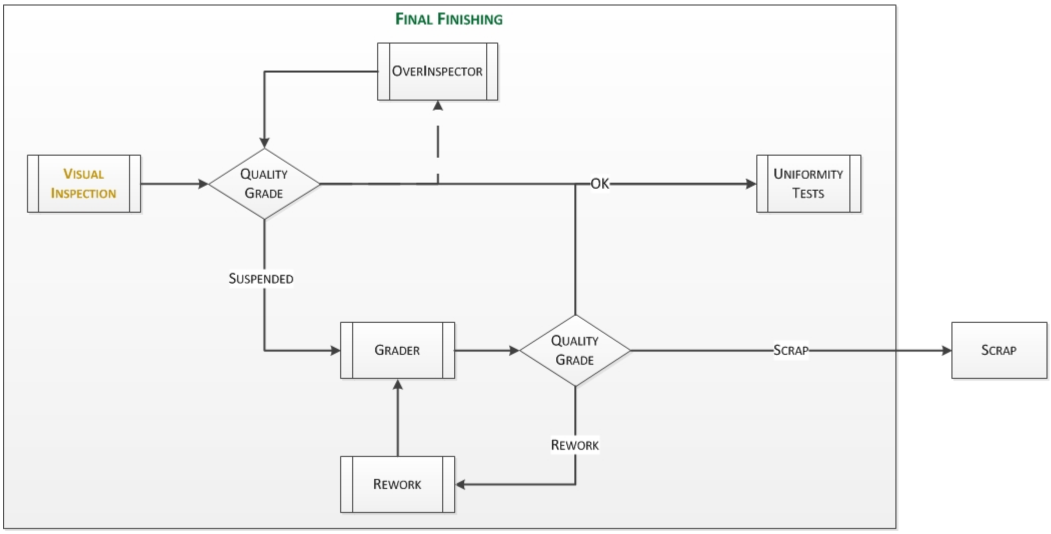
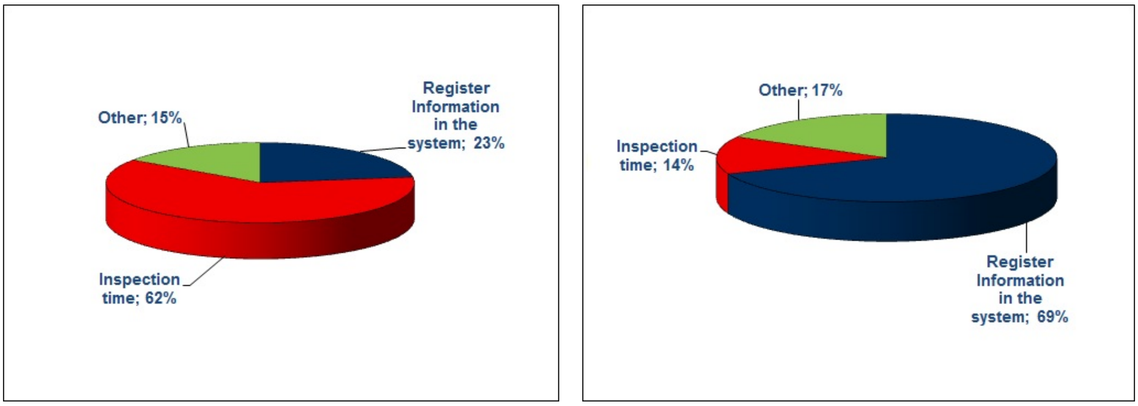


Figure 1.6: Detailed view over the final finishing process flow

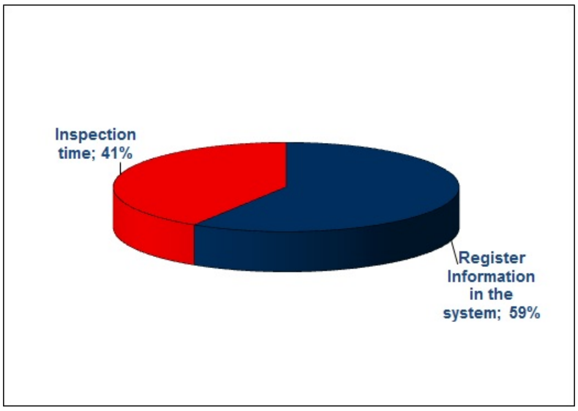
the tire is NOK. They are also the only ones that can scrap a tire, i.e. tires with imperfections that might compromise the tire performance. When the tire has an imperfection that can be recovered, the grader sends the tire to the rework process. After a tire is reworked, the grader performs an additional inspection to check the quality grade of the tire (Figure 1.6).

The grader roles include the tire inspection and the registration of the tire information in the system (barcode, tire mold number, and NC code). The task distribution with respect to the process time depends on the tire quality grade and the decisions that are taken by the grader (Figure 1.7). In Figure 1.7, *Other* refers to the tire handling (clean-up the marks drawn by the VI, some tire trimming, etc.).

One can notice the weight of the tire information registration in the system. The introduction of the data is done manually and the system does not have a quick response. The immediate impact is the low level of data inserted in the system (Figure 1.8). Not all tires with imperfections which are not going to scrap have the correspondent NC code inserted in the system. This has a very negative impact on the process tracking but the system



(a) Tire OK (b) Tire to rework



(c) Tire to scrap

Figure 1.7: Grader's task timings acccording to tire quality grade decision

restrictions will also interfere in the grader's performance.

There is another process step called OverInspector. The overinspector is a qualified person from the Quality department that randomly selects the tires classified as OK by the VI in order to perform the quality evaluation of each VI. Roughly 10 tires are daily selected from each VI and the results of the overinspector process reflects in the bonus policy of the VIs.

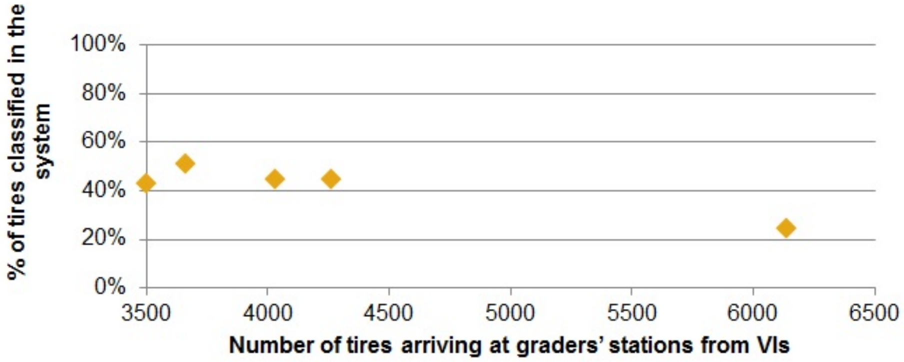


Figure 1.8: Information insertion into the system according to production volume

Tire uniformity process is done in an automatic way. The Uniformity Machine (MU) realizes the uniformity tests using a specific recipe for each article and based on the results, the machine paints the quality marks on the tire sidewall. These quality marks are very important to the end costumers, since they use these data to select the most suitable tires for car assembly.

1.3.2.1 Visual Inspection Task Description

Tire visual inspection is a 100% human-based process done by very experienced and well-trained operators. The visual inspection process comprises three main tasks: tire quality inspection which is the main and the most important task, tire trimming (flash and air vents removal) and tire identification. To be able to realize all these tasks, the operators have also to handle the tire. All tasks take an average cycle time of 30 seconds for a machine cycle of 12 seconds. The full visual inspection flow is shown in Figure 1.9.

Regarding the tire quality inspection, operators make use of the different senses such as vision, smell, and tact to analyze and take a decision concerning the quality conformance of the tire, taking into account the quality standards in place over Continental AG. The tire conformance includes visual aspects (e.g. blemishes) as well as tire performance and safety aspects (e.g. blisters).

The tire identification task done by the operators considers the information taken by the barcode read-out. There is a barcode scanner at each station that outputs the green tire code. With the green tire code, one or more possible cured tires (depending on the type of market: OE or replacement market) are listed on the screen. Then, the operator selects the correspondent article to the tire in front which is assigned to the barcode. From this point on, by reading the barcode, one can access to the article information. This information is crucial for the conveyor system to decide which path each tire shall follow.

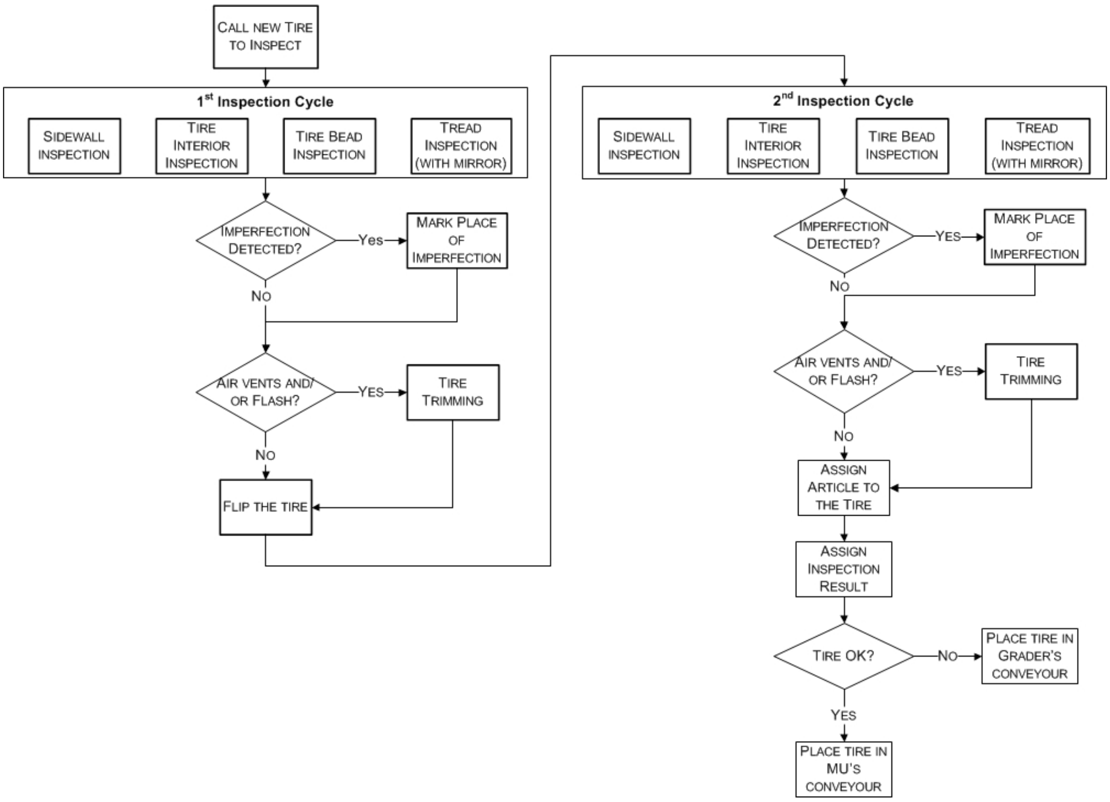


Figure 1.9: Visual Inspection process flow

The inspection station does not allow an uniform inspection of all tire surfaces. For that reason, VIs make use of a mirror to inspect the tread surface.

Although the tire trimming task is represented as an independent task, sometimes VIs perform this task in parallel with the visual inspection. The exact determination of the time associated to each task is then complex. Nevertheless, an idea of the task time distribution is provided in Figure 1.10 where one can observe that more than 50% of the time is spent in the trimming, and only 1/3 of the time is dedicated to the tire inspection. *Other* refers to the tasks of tire identification and tire handling.

The task time distribution is also dependent on the individual that performs the inspection and it also varies along the time with external factors. In a specific shift, the inspection

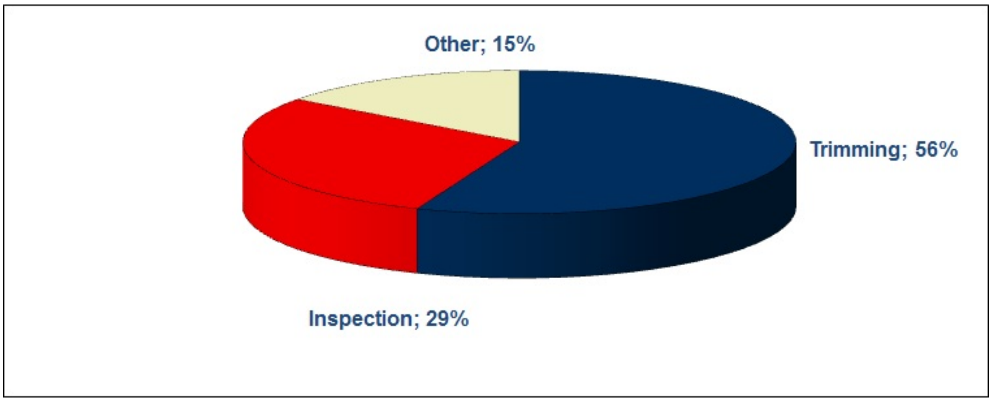


Figure 1.10: Time distribution over the different tasks performed by the VI

time variability among the different VIs can vary significantly as it is shown in Figure 1.11.

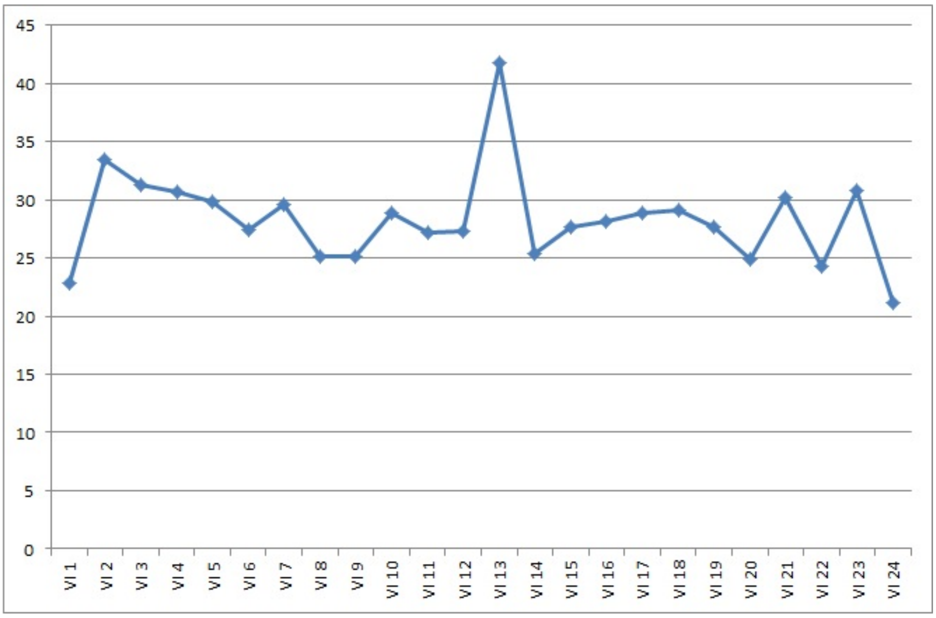


Figure 1.11: Inspection time variability among the different VIs of a shift

1.4 Problem Statement

The current inspection process is a full human-based process. At the Portuguese plant, this process is handled in 24 workplaces by very specialized, experienced, and well-trained workers in 8-hour shifts, 24 hours a day, 7 days a week, within 5 teams. The daily production in the Portuguese plant is about 50 000 tires, and the inspection is performed in 100% of the tires.

A safety product like a car tire requires a reliable and trustable process as the one in place. Flexibility is needed because of the product mix, but due to cost effectiveness the company would like to introduce an automatic system in the final inspection process, keeping the actual levels of quality. The types of flaws are diversified, either by the location (internal or external side) or by the type of imperfection: excess of material, lack of material, foreign material, some kind of deformation, etc.

The final inspection process includes a visual but also manual handling of the tire which means a significant degree of complexity. The use of different sources of information requires specialized and very knowledgeable actors to guarantee a high level of performance and quality assurance.

The problem described here seems to be a purely technical issue. However, a complex and critical system such as the final inspection process requires a more broadly approach considering also economical aspects of the different possible solutions and also the social impact of the developed system. One shall be able to identify the critical aspects of the as-is process and compare with the developed solution. Aspects like the average number of tires inspected per shift or how many kilograms an operator carries per day and its implications in his health shall be taken into account. Additionally, if one looks to the tire quality control as a decision-making process, humans play the central role in the system development and implementation. Technology shall be seen as a support tool for the operators task in order to enhance the overall process performance.

In fact, although the problem, in the initial phase, was seen as a technical challenge, the research done allowed to change the approach to the problem without compromising the ultimate goal: enhance the quality inspection system in the tire manufacturing environment by means of cost reduction. Technology is seen as a complementary tool to the humans.

1.4.1 Need of Process Automation

From the observations done in the final finishing process as well as the data analysis performed, one could identify some areas of improvement in the visual inspection process. The main outcome about the aspects to be reconsidered in the future solution for the visual inspection process are:

- Detection is a subjective process once one observe different decisions among VIs (Table 1.2)
- Occurrence of process deviations

- The current workstation does not allow an uniform observation of all the tire surfaces (Figure 1.13)
- Most of the time in the visual inspection is dedicated to the tire trimming and tire handling (Figure 1.10)
- The performance of the VIs varies significantly along the time regarding quality (Figure 1.15) and productivity (Figure 1.14)

The subjectivity associated to the tire quality assessment might be observed in the results obtained from the repeatability study frequently performed by the quality department to understand how "calibrated" VIs are. The study is composed by a set of tires with different grades that will be assessed by three operators at three different attempts. The results of the quality assessment are then gathered and compared with the expected result. Table 1.2 shows the results obtained for the different attempts for one tire NOK (NC: blemish at bead). The results clearly show that the three VIs have different decisions along the attempts. *VI 2* always assess the tire as OK when in fact the tire is NOK. The only time the three operators are coincident in the decision (attempt 3), they all fail the quality assessment.

The results gathered from the repeatability study show that the decisions among the operators are quite different. One of the reasons for that result might be in the definition of what is an imperfection and what is not. Figure 1.12 gives an example of two different tires with the same kind of flaw: blemish in tread. Although one could imagine that both tires shall be classified as NOK, in fact they are not. The reason for that classification is the customer requirements that are different from customer of the tire of Figure 1.12a and from customer of the tire of Figure 1.12b. The level of acceptance from the different customers introduce some ambiguity in the decisions operators have to perform.

Table 1.2: Repeatability study results for a group of VIs

	VI's Assessment		
Attempt	*VI 1*	*VI 2*	*VI 3*
1	OK	OK	NOK
2	NOK	OK	NOK
3	OK	OK	OK

Another aspect that requires improvement is the one related to the process deviations. Although the company defines a clear procedure for the visual inspection process [48], in

(a) Tire OK (b) Tire NOK

Figure 1.12: Tires with the same kind of imperfection assessed in different ways

fact one could observe deviations from the original procedure. In order to speed-up the inspection process, some operators do not follow entirely the full procedure. They also develop particular ways of inspecting the tires which they consider more effective and efficient. However, this can lead to process mistakes and wrong decisions. Additionally, the VI has to assign a decision to the tire and then drive the tire to the correspondent conveyor. In fact, one observed some situations in which the tire decision and the conveyor in which the tire was placed did not match, i.e. there is no correspondence between detection and decision. In the worst case scenario, an operator can detect an imperfection in a tire, mark it, but then assigns the tire as OK and sends it to the uniformity tests. If the imperfection is purely visual, this might lead to a tire that is sent to the customer with an imperfection that is tagged.

The feedback collected from the interactions with the operators highlight their difficulty to inspect some tire surfaces. In fact, the current workstation does not allow an uniform observation of the tire, mainly the tread area. The results from the overinspector process also show that imperfections in the tread area represents 25% of the cases (Figure 1.13). The results also demonstrate that the bead area which is hidden by the operator's hand is a critical area. Some of the imperfections in the bead surface are not detectable by haptics but rather by vision. The 28% of cases observed in the sidewall surface can be explained by the fact that the tire surface where imperfections are most common is the sidewall, i.e. that the probability to occur an imperfection in this tire surface is high which can lead to a higher probability of non-detection.

The time dedicated to the tire inspection is not so significant which is somehow contradictory to the inspection process aim. Indeed, only 29% of the time (Figure 1.10) is spent to perform the most important task of the inspection process. The introduction of

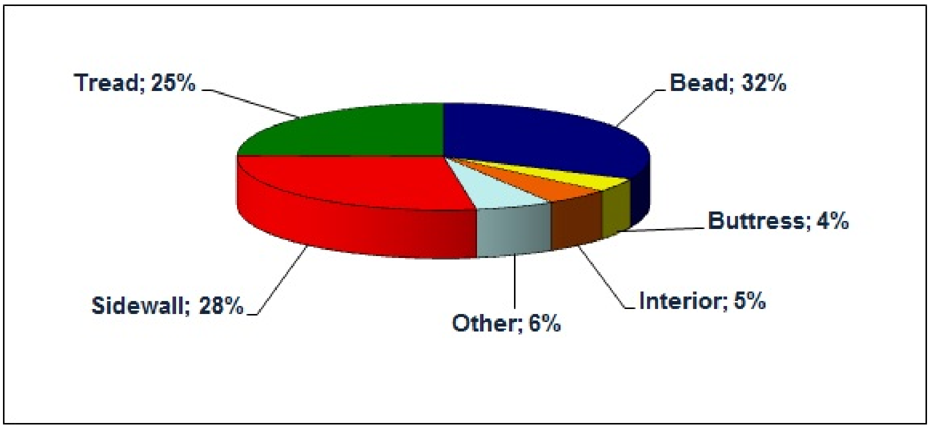


Figure 1.13: Imperfections caught at the overinspector station by tire surface

automation in the process shall focus in this particular aspect: identify the tasks that do not represent a significant added-value to the inspection process, although they are necessary, and that do not represent significant needs of flexibility. Tire trimming, tire handling and tire identification are the three main tasks that are aligned with this line of thought. Tire trimming is out of the project scope, but the impact of this task in the overall cost performance of the process is significant and efforts shall be addressed to this process in the future. Tire handling will reduce dramatically the ergonomic issues currently observed, minimizing the physical efforts needed to inspect a tire. Tire identification shall promote a better product and process tracking and minimizing the identification mistakes currently occurring which represents 10% of the customer complaints in 2010 [49].
Finally, the variability observed in the VI's performance is significant as one might observe in Figure 1.14 and Figure 1.15. This is particularly critical once the inspection process is placed between two automatic systems: the curing process and the uniformity tests. The productivity measured by the number of tires inspected by a VI in a shift has impact in the buffer dimension. The variability observed cause significant disturbances in the process management. The peaks noticed in the shift breaks and shift changes are also very critical, and special attention shall be paid to this issue.

As mentioned before, the ratio of OK and NOK tires is about 9:1. Once the tires are randomly distributed through the operators, one shall expect similar levels of rejection among the VIs. However, the results show considerable differences among them (min: 5%; max: 15%) denoting different criteria, awareness and cautious when inspecting a tire (Figure 1.15). The introduction of automation shall also contribute to a more uniform assessment of the tire quality aiming to reduce the impact in the process performance (tires OK sent to the grading station) and to avoid customer complaints (tires NOK sent to customers).

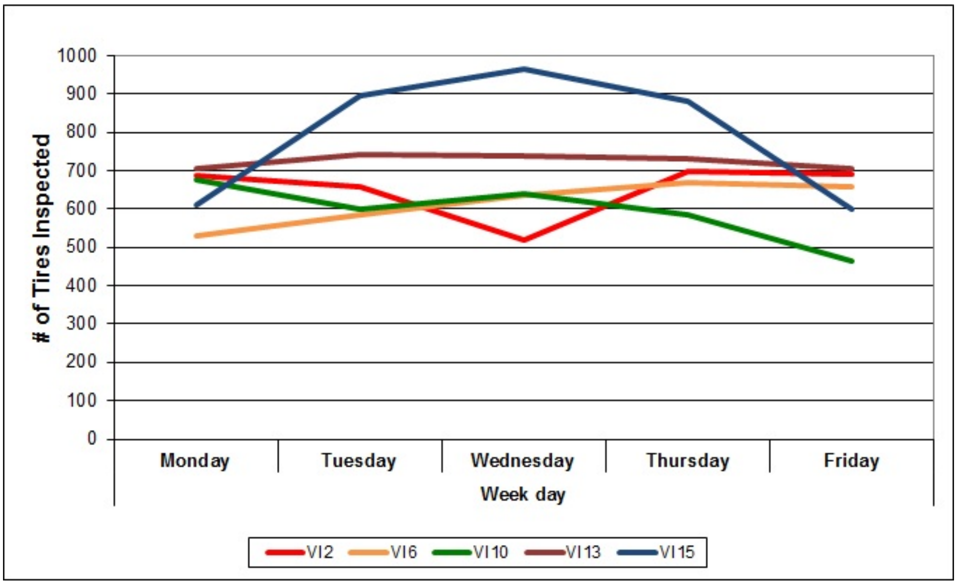


Figure 1.14: Number of inspected tires per shift along one week for some operators

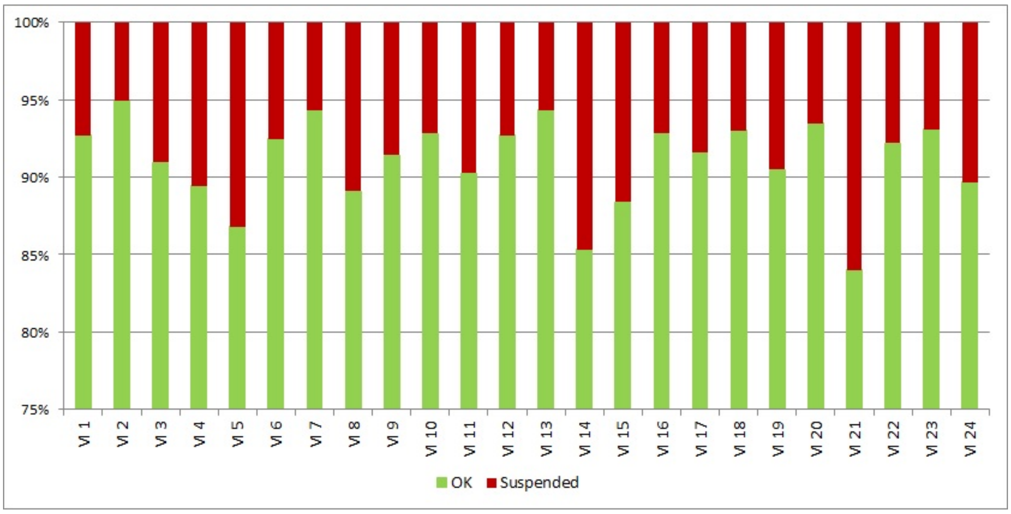


Figure 1.15: Rejection ratio for each VI observed in a particular shift

1.4.2 Need of Virtual Inspection

Some features of the actual inspection process require to be improved not only with the aim of reducing the process costs but also to improve the process performance and minimizing the negative impacts in the upstream processes. However, there are aspects of the current inspection process that shall be kept once they add value to the process. The deep knowledge of the VIs about the occurrence and detection of the NCs as well as their ability to quick react to sudden changes in the production are essential to maintain so the process keeps its performance adaptable to the circumstances and is inherently fed with the propriety of flexibility.

Additionally, the use of cognitive skills (memory, perception, awareness, etc.) that allow the relation between tires and imperfections is an added-value features that one wants to keep in the future process solution.

The aspects mentioned above require a different approach from the traditional way of replacing humans by machines on the system development, centering the approach on the individuals [50]. There are aspects where automation is not advised to be implemented, at least in an abrupt way, especially by the fact that subjectivity is inherent to the tire inspection decisions and since the object to be inspected is a natural-based product. For all these reasons, virtual inspection seems to be the right way to follow. It might be seen as a development platform that allows the introduction of small increments of automation in the system and at the same time empowers to gather the knowledge used by the operators to assess the quality grade of a tire.

By using virtual inspection, operators do not need to handle the tire and to trim it. This can have positive impacts in the time required to inspect the tire but also to improve the ergonomic conditions.

1.4.2.1 Ergonomic issues

The actual inspection process is very demanding in what concerns the physical aspects. Operators are constantly facing physical challenges due to the handling of the tires. Tires are becoming heavier and bigger which difficults even more the task of the VI.

By facing these challenges in a daily basis, operators can develop health problems with significant impact for the individuals but as well for the company. Besides that, even more restricted and challenging working laws are expected in the European Zone leading to new challenges for the industries in which human-based processes are in place.

The results of the ergonomic conditions faced by the operators in the tire inspection process as been analyzed (see Appendix D) in a parallel project - Ergos - requested by the company to assess the as-is process and implement the necessary changes. The use of virtual inspection will reduce significantly some of the ergonomic issues of the current inspection process. However, special attention shall be paid to the design of the workstation for the virtual inspection to not introduce new ergonomic issues.

Additionally, the virtual inspection workstation will require different awareness by the operators. From a task that currently combines a physical activity with a mental activity, the virtual inspection will introduce an almost 100% mental task. This aspect can be very challenging and might introduce new issues to the system performance. However, it can be overcome by the introduction of rotative tasks among the operators of each shift, combining more physical tasks with the virtual inspection.

1.4.2.2 Time issues

The introduction of the virtual inspection in the proposed solution for the new tire inspection process might improve the inspection time. However, to reach that important goal, one has to understand the contribution of the different variables involved in the inspection time on the new environment. The interface design plays an important role on the inspection time results as one could observe by the results presented in Chapter 5.

Moreover, the environment changing will require some time for the users to adapt and familiarize with the new system. An adequate level of training shall be provided to reduce the expected adaptation time.

On top of that, the system must provide high quality images in order to minimize the doubts virtual inspection can introduce by the fact the operators cannot touch the tire.

All these aspects can contribute positively for the inspection time improvement, but it is important to identify the contribution of each for the results.

1.4.2.3 Risks of changing environment

The introduction of such a significant change in the tire inspection process can lead to some risks that shall be considered and efforts shall be done in order to overcome them. The risks are associated to the technology adoption by the operators whom might be looking to the process changes as a threat to their task. Technology might be seen as something to replace their work instead of a support tool to allow them to take better decisions.

The involvement of the operators along the development of the solution is crucial to keep them aware of the path that is followed and to make them feel part of the solution to be developed. In the end, the VI will be the final user of the system, thus the system must be adapted and aligned with operator's expectations.

Another important aspect to take into account to overcome the risk of adopting new technologies is the role of the operator's training. It is of the most importance to provide intensive training to the operators for the new system in order to reduce the risks of poor adaptation to the new technical challenges.

Virtual inspection is a purely visual observation in contrast with the actual process in which operators make use of other senses (smell and touch) to perform the tire quality assessment. The use of the senses besides the vision can be an obstacle for the effectiveness of the virtual inspection. However, this issue can be minimized with the correct use of the technology to enhance certain aspects of the image where some features of the physical object can be perceived by the haptics.

1.4.2.4 Additional advantages

Besides the advantages and issues presented above, the adoption of virtual inspection in combination with an automatic data acquisition can provide the system with the following additional advantages:

- The system can record and store the tire images for many different purposes: customer's complaints analysis, quick identification of possible problematic tires that were already inspected, etc.
- Detect and react more quickly to problems in the manufacturing process (e.g. vulcanization)
- Creation of personalized training sessions for the operators based on the images recorded

By adopting this approach to the product inspection, the company is able to store the images of the tires in the exact way they leave the plant. The product assessment and analysis is enhanced by this approach too.

However, one of the most promising features of the virtual inspection is the capability of capturing the knowledge of the operators when taking decisions over the tire quality grading, guaranteeing with this approach continuous and iterative improvements along the time.

1.5 Research Methodology

The problem stated for this research and development project comprises a significant degree of complexity and risk. In order to accomplish all the objectives defined for the project a research methodology composed by six main steps is presented in Figure 1.16.

The baseline for the research methodology is the literature review. It provides the foundations for the project guidelines. Since the approach followed for the system development is focused on the operators, an ethnography study is conducted in order to identify the main features of the inspection process and to create a common knowledge essential for the project development.

The generation and test of hypothesis are fundamental steps in a scientific research. They give the ideas for the possible aspects that influence the inspection process as well as the

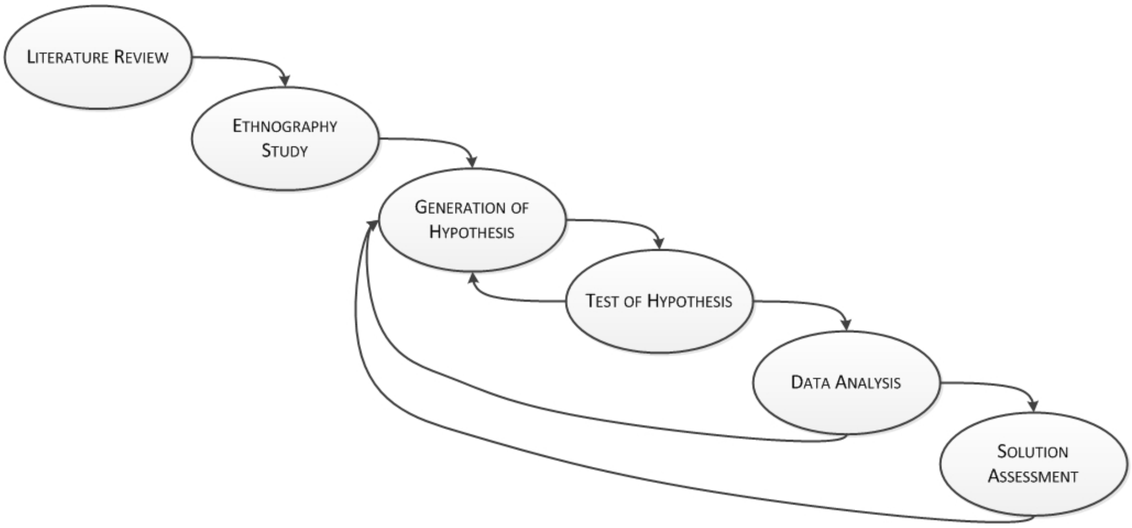


Figure 1.16: Research methodology followed in the project development

extent of technology implementation.

At the end of this phase, and based on the information collect until this point, a system is developed in order to accomplish the defined requirements. A set of data from different sources will be gathered and analyzed with the aim of making a quantitative and qualitative evaluation of the developed system.

Finally, in the ultimate stage of the research, a detailed assessment of the developed solution is done with the purpose of providing the end-user a broad perspective of the system with all its implications.

The ethnography study is a key piece of work with respect to the research project. Two methods for manufacturing improvement: learning by doing (in-process learning) on the shop floor and learning by development and experimentation away from the shop floor (off-line learning) [51]. Once the main focus of the problem solution is the operator and its behavior concerning the decision-making process of tire classification, it is essential to characterize in a very detailed way the environment and the operator, and to identify the set of criteria that is used to make the decision. Besides, it is also of the most importance to observe the external and personal factors that might contribute for a better or a worst decision. In summary, the main goal for realizing this ethnography study is to observe the operators behavior in the context of the tire inspection process.

Another important objective inherent to the realization of the ethnography study is to make a field work research, i.e. perform a hands-on experience in the tire quality inspection process. It is essential to experience the difficulties faced by the operators to classify a tire as OK or NOK, to feel the pressure associated to make the right decision within the specified time, to understand the language used by the operators to characterize their task, to have a perception of the work conditions, and to get the confidence from the operators in the work one will perform. It is important that the operators will not feel uncomfortable with external presences, not seeing them as a threat, so they can share their knowledge and experience to describe how they are able to classify and take a decision about a tire.

In addition to the personal experience of inspecting tires, one observes the daily work performed by the operators in order to get an idea about the way operators act under different conditions and make a comparison among the operators about the procedures adopted by them to inspect tires. Observing without interfering in the operator's work is the main challenge at this stage.

The last point mentioned is crucial for the next method used to complement the ethnography study: carry out semi-structured interviews with the operators. The aim of this task is to match the initial observations with operators perspectives of the inspection task. The use of semi-structured interviews seems to be the most suitable option. The idea is to perform those interviews in the place and environment where operators feel more comfortable, in the exact context in which they experience their professional lives. With the interviews, one assumes the possibility to understand the way each operator carries out his task, the difficulties experienced by each of them, and get an idea about improvements they think useful for enhancing the process they carry out.

Finally, to close the loop and conclude the ethnography study, one collects data from available sources in the company (databases, documents, etc.) and make formal interviews with engineers, managers and people from human resources. In the end of this ethnography study, one intends to identify all the selection criteria necessary to make a decision about the classification of a tire.

From the results gathered in the ethnography study, one might raise up some hypothesis to be tested like the influence of some aspects in the new system performance, or the possibility of some decision criteria to not be translated into explicit knowledge. The Design of Experiments (DoE) is essential to clearly define the objectives and the measurements to be taken and to identify the groups that will be selected to run the experiments. The correct definition of the experiments will allow the system validation as well as a comprehensive comparison with the actual inspection process.

The interaction with the operators will be constant along the system development once preliminary solutions will be presented and tested with them. Their feedback is essential to decide the next steps and to identify areas of improvement.

1.6 Structure of the document

The present document is organized in seven chapters, starting by the *Introduction* where the general presentation of the AutoClass project is provided as well as an overview of the tire manufacturing process and a more detailed description of the tire inspection process where this project is focused on. The problem statement and some particular aspects of analysis are also introduced to enhance some of the issues that will be analyzed and described along the document. The research methodology used along the research and development project is also shared.

Chapter 2 presents the state-of-the-art of the subjects researched along the project with special emphasis to the handling solutions, technology assessment and selection methodologies, human-machine interfaces, and decision models for semi-automatic systems.

In Chapter 3, one is giving the first overview of the proposed solution for the new tire inspection process. It reveals the overall solution and provides a description of the different sub-systems. It presents the architecture suggested for the new solution as well as the validation process followed.

The technology solutions analysis, in Chapter 4, is a very detailed description of the methodology used for the selection, integration, and deployment of the technologies adopted for the proposed solution. The case study used to illustrate the application of the mentioned methodology refers to the tire image acquisition station, one of the systems implemented in the final solution.

In the next chapter (Chapter 5), all the topics related to the human-machine interfaces are described. It includes the description of the methodology followed for the development and test of the different interfaces, the presentation of the diverse interface designs, as well as all the results obtained in the different phases of the development process. At the end of the chapter, a comparison between the performance of the actual and the proposed solution is presented as well as the final remarks about some future developments that shall be done.

Chapter 6 provides the general decision model for the tire inspection solution, with special focus on the automatic tire inspection system and the virtual tire inspection process.

Finally, in Chapter 7, the conclusions are presented as well as the scientific contributions and suggestions for future work that can be developed based on the results obtained along the project.

Chapter 2

State-of-the-art

The foundations for a reliable research work are based on an extensive literature review. Four main topics are covered in the literature review: handling solutions, technology assessment and selection, human-machine interfaces, and decision models for semi-automatic systems.

Handling solutions are important to analyze once the object handling is fundamental to acquire the information necessary to classify the object under inspection. The search is mainly focused on handling solutions used in the tire manufacturing industry due to the specificity of the inspection process in analysis.

The technology assessment and selection proved to be of the most importance for the project development. Several technologies are under consideration and comprehensive and structured methodology must be in place and shall be done in such a way that one might generalize for other applications.

Human-machine interfaces are an essential piece of the approach followed for the problem solving by understanding the main features of this kind of tools as well as the fields of application and its implications. It is also important to analyze the characterization and behavior of the humans, and take individuals as the central actors of the development process.

Finally, a system that combines automation and human-based processes requires a sort of decision model to take the most suitable decisions about the desirable level of automation and the influence of humans in the overall system performance. In another words, a tool for the decision-makers to implement the system version that is aligned with the organization objectives.

2.1 Handling Solutions

Handling is an important feature of the system to be developed. The object of inspection shall be handled in such a way that facilitates the information gathering from the object, avoiding missing parts and duplication of the information. In addition, it shall guarantee system efficiency with respect to the process performance.

Handling is a very broad topic, although the handling solutions analysis one is seeking for are mainly the ones related to the object of inspection: the tire. Tires have specific geometry and characteristics that make them unique when analyzing handling solutions for inspection places. For that reason, the literature review will focus on handling solutions used in the tire manufacturing industry in its diverse manufacturing processes as well as commercial solutions available in the market.

Tire manufacturing industry is a very conservative business where information is not always available for the public since the information is very critical due to safety and competitive advantages' issues. The review done for the research project gathers the information in the handling solutions available in the company that belongs to the partnership where this project is involved. Additionally, one also considers some of the commercial solutions available in the market from tire manufacturing suppliers one has the possibility to get in contact with in the Tire Technology Expo 2011 held in Cologne. Moreover, one also search for patents related to handling solutions related to tire manufacturing industry. Each of the handling solutions will now be presented and described.

2.1.1 Handling solutions available in the company

ContiSeal Laser Marker

The ContiSeal Laser Marker solution (Figure 2.1) is used to imprint the additional feature of the tires that contain a special sealant product. Whenever the tire arrives to this station, the system positions and centers the tire in the conveying system by using four cylinders that adjust according to the tire dimensions.

The handling system that carries the laser system has the possibility to move on the three directions (X, Y, and Z) in order to guarantee the correct positioning with respect to the tire. Then, the laser system scans the tire which is fixed for the desired laser mark position. The tire scan movement depends on the tire dimensions and it is done based on the recipe provided to the system.

Bead Lubricant Applicant

The bead lubricant applicant solution (Figure 2.2) is used right before the MU system.

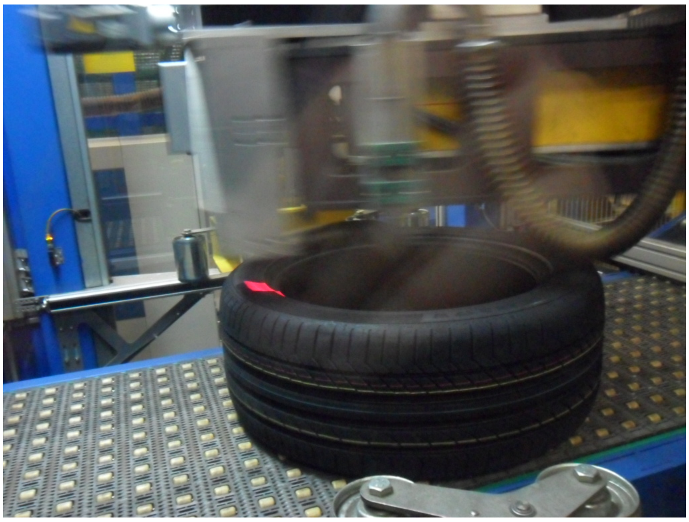


Figure 2.1: ContiSeal Laser Marker handling solutions

The system is composed by two articulated and independent arms, each of them with two actuators that are in charge of the correct tire positioning and centering.

Whenever the tire positioning and centering process is concluded, an actuator placed in the tire center will apply the lubricant to the tire bead while the tire rotates. By the end of the entire process, the two articulated arms release the tire for the uniformity tests.

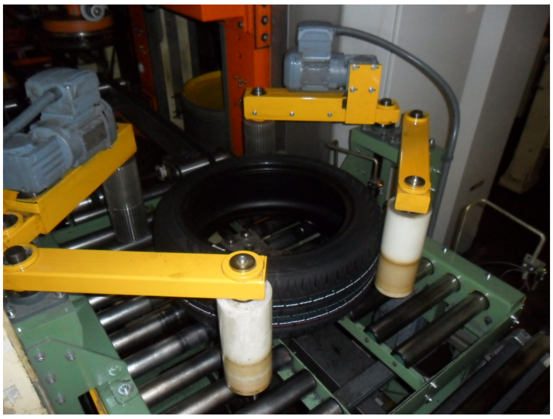


Figure 2.2: Bead Lubricant Applicant (Uniformity Machine) handling solution

Uniformity Machine

The MU system (Figure 2.3) is capable of performing the uniformity tests. The system is based on laser triangulation technology that gathers the tire data. The acquisition system is fixed and placed according to the tire dimensions.

The tire is placed in a rim and then it is inflated to a specific pressure. The tire and the rim can then rotate at a certain speed specified in the recipe. The laser technology scans the tire while it rotates.

The tire rotation is done at a constant speed and guaranteeing minimal vibrations.

Figure 2.3: Uniformity Machine Test Area handling solution

InspectoMat [52]

The InspectoMat (Figure 2.4) is the handling solution used in the final finishing process to help operators while they perform the visual inspection of the tires.

The tires drops from the conveyor placed just above the machine and the tire rotation is granted by two rolling axes positioned right below the tire. The distance between the two rolling axes guarantee the adaptation to the different tire dimensions.

In addition to the rolling axes, the InspectoMat has also an handler that is placed in the bead of one tire side with the aim of granting some rotation stability and at the same time to spread the bead in order to provide better inspection conditions.

The tire flip and tire placement in the outlet conveyor is done manually.

ContiSeal Sealant Applicant

The ContiSeal Sealant Applicant (Figure 2.5) is the system that applies the sealant to the tires. The system comprises an handling system to interface with the conveying system, the applicant system, and an interface with the outlet conveyor.

The interface with the inlet conveyor uses an elevator system that carries the tire from the conveying system where the tires are in the horizontal position. The elevator system places the tire in the vertical position and leaned to a metallic wall. The metallic wall contains a set of metallic spheres so that the tire can slide along the wall. Whenever the system is ready, the tire is pushed to the applicant system by a kicker that places the tire between two metallic walls, one of them fixed and the other one adjustable. Both contain metallic spheres to allow the tire rotation without significant friction.

Figure 2.4: InspectoMat handling solution

The wall adjustment is done in order to guarantee a stable tire rotation without damaging the tire. The applicant system has also a presser on top of the structure to press the tire with the necessary pressure to avoid vibrations. The tire rotation is granted by two rolling axes placed right below the tire.

The application system comprises a manipulator that introduces the applicant tool inside the tire and performs the applicant process while the tire rotates at a constant speed. By the end of the applicant process, the system releases the presser and the moveable wall allowing the tire removal by the kicker.

Figure 2.5: ContiSeal Sealant Application handling solution

Manual Bulge Measurement Machine

The manual bulge measurement machine is an handling solution where the tires are placed in the rim manually. The tire is then inflated at a specific pressure and rotates at a constant speed.

The tire is placed in the vertical or horizontal position depending on the machine version. The approach followed by this system is similar to the one used in the MU system.

ContiSeal Tire Washing Machine

The ContiSeal tire washing machine (Figure 2.6) is used prior to the sealant applicant process to clean-up the tire from undesirable particles. The system is composed by a set of grips placed in each sidewall to spread the bead. The grips are also responsible for the tire rotation, and the tire is placed in the vertical position, rotating at a constant speed.

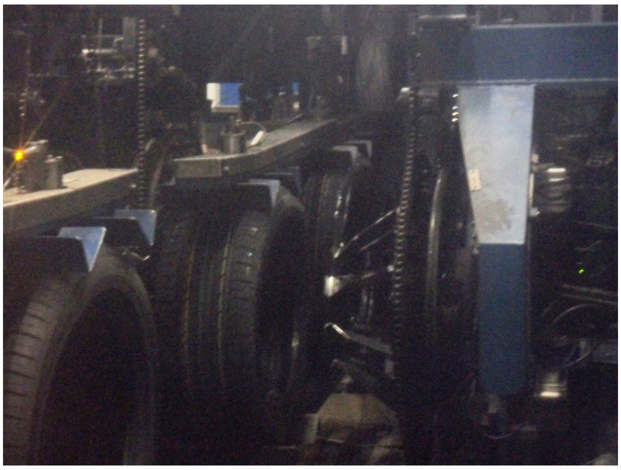


Figure 2.6: ContiSeal Tire Washing Machine

2.1.2 Handling solutions available in the market

DOT read-out application

The application developed by *Bytewise* (Figure 2.7) intends to perform an Optical Character Recognition (OCR) of the DOT data printed in the tire sidewall. For that reason, the tire is placed in the horizontal position, i.e. supported by the sidewall opposite to the one where the DOT data is printed.

A manipulator system carrying a laser scanner solution will scan the entire sidewall surface in order to gather all the relevant information to process the OCR. The manipulator system must adapt to the different tire dimensions, guaranteeing similar acquisition conditions for the different tires.

The supplier does not mention how the tire is handled in order to initiate the overall process. One assumes that the tire shall be positioned in such a way that assures that the geometric center of each tire is always placed in the same position with the aim of reducing the complexity and size of the manipulator system.

Figure 2.7: DOT read-out application handling solutions

Trimming Machine - Trimmer 3000 [4]

The solution provided by Matteuzzi SRL (Figure 2.8) comprises three main stations: the inlet conveyor, the trimming station, and the outlet conveyor. The inlet and outlet conveyors assure the interface with the conveying system. The trimming station is the one where one is more interested.

The tire is positioned and centered by four conical cylinders that also elevate the tire. The conical form of the cylinders guarantee the necessary flexibility to the different tire dimensions. The cylinders are also responsible for the tire rotation.

Although the system is designed to trim the tire, one might look to this handling solution as an handling system that is also able to perform inspection tasks by replacing the trimming tools by inspection technologies. The way the tire is centered and positioned as well as its rotation are the critical features one is seeking for.

The handling solution is able to process tires with tire external diameter sizes between 22 to 38 inches.

Modular Tire Inspection System for truck and bus tires [5]

The modular tire inspection system from YXLON offers a versatile method of testing the finished tire by applying X-ray technology in real time.

The four-point bead spread and vertical tire rotation (Figure 2.10) offered by this solution

Figure 2.8: Trimming Machine handling solution (*source: Matteuzzi* [4])

are key factors in acquiring distortion free, symmetrical 360° X-ray images. Whether large and rigid or small and flexible, both types of tires can be tested with excellent repeatability. Tire throughput is maximized via bead-to-bead inspection.

The inspection system is linked to the conveying system which is supposed to drive the tires in the horizontal position. An handling system is responsible for the tire positioning and centering as well as to flip the tire from the horizontal to the vertical position. The handling system grabs the tire and introduces it into the inspection system which must be isolated from the remaining systems due to radiation issues. At the end of the inspection process, the tire is again placed in the conveying system.

The handling solution for the inspection system is composed by four rolling axes that also spread the bead and allows a constant tire vertical rotation. The system allows the inspection of tires with rim sizes between 13 to 26 inches.

Figure 2.9: Y.MTIS Family TBR solution from YXLON (*source: YXLON* [5])

Figure 2.10: YXLON bead spread technology (*source: YXLON* [5])

X-ray Inspection System - VerTIX-PLUS [53]

The VerTiX-PLUS X-Ray inspection system (Figure 2.11) is a complete X-Ray system with an integrated manipulator. The transport and feeding unit assures the exact position of the tire. The tires are X-rayed in a vertical position limiting deformations.

It provides an integrated X-ray system for unique tire rim ranges from 13 to 30 inches. It incorporates a fully automatic process from the inlet conveyor to the outlet conveyor, without any operator intervention.

Whenever the tire is in the inlet conveyor, the conveyor flips and places the tire in the carriage device which is responsible to feed the inspection system. A similar process is done when the tire inspection is concluded. The outlet conveyor is in the horizontal position and then flips to the vertical one.

The handling in the inspection system is performed in a similar way as the solution provided by YXLON (Figure 2.10).

The system is designed to process tires with rim sizes between 13 to 30 inches.

Tire Surface Inspection [54]

For tire surface inspection, three laser profile sensors are used to detect bulges and depressions as well as radial and lateral run-out in tire production. They are mounted on a solid and accurate transport system. Laser sensors provide single/multi track measurement, in case of spot laser sensor or whole sidewall is scanned by sheet-of-light laser providing tire profile in every sample instance.

Figure 2.11: VerTiX-PLUS solution from MicroPoise

It uses a 4-axis positioning system for a robust transport mechanism and it adapts for different tire dimensions (Figure 2.12).

The solution has the same principle as the MU solution. It inflates the tire at a certain pressure and then rotates the tire in the horizontal position. The laser profile sensors are then able to acquire the data from the tire to perform the necessary tests. The tire rotates at a constant speed with very low level of vibrations.

Figure 2.12: Tire Surface Inspection solution from Micro-Epsilon

2.1.3 Handling solutions under patent protection

The patent search revealed a set of patents in the area of technologies and apparatus for tire handling and inspection (by means of image capturing or other sensing technology). The solutions are mostly based on single surface (e.g. sidewall) inspection and analysis, and making use of a single technology (e.g. 3D images), although different methods are claimed. Some patents are identical to MU solution.

Tire Bead Inspection [6]

The apparatus (Figure 2.13) is designed for receiving a tire for inspection and is mounted on a base. The tire is mounted so that its tread is in contact with a drum which may frictionally drive the tire rotation. Two conical rollers which can be mounted either to the base or with stationary axes 45° to the vertical close to the highest point of the tire are used to keep the tire in the vertical position.

The tire is mounted for inspection on the apparatus to be driven by the drum and held for rotation in a vertical plane by the side rollers and further supported in place by the steadying roller bearing against the tire from above.

After the tire is placed in the machine, the main arm is moved axially of the tire to insert the sensing roller within the periphery of the tire by actuating the cylinder and linkage assembly. The next movement of the arm brings the sensing arm down and at the same time performs a rotational movement. As the main arm rotates, the sensing roller being engaged in the bead of the tire resists this motion. The resultant motion brings the sensing roller inside of the tire bead.

Tire Inspection and Preparation Device [7]

It is a self contained unit (Figure 2.14) which can be transported and used at any location. The unit measures the tire circumference, run out, and wear of an automobile tire or for preparing the surface of the tire.

The tire inspection and preparation device includes a mount for supporting and rotating the tire during measuring or repairing tasks. The mount includes an elongated member attached to a base for elevating the tire above a support surface (e.g. the ground). It also comprises a rotatable member for enabling the tire to rotate with respect to the elongated member and the ground.

By positioning the tire within the rotatable member and enabling the tire to rotate as a unit with the rotatable member, the tire is securely supported by the mount and evenly balanced

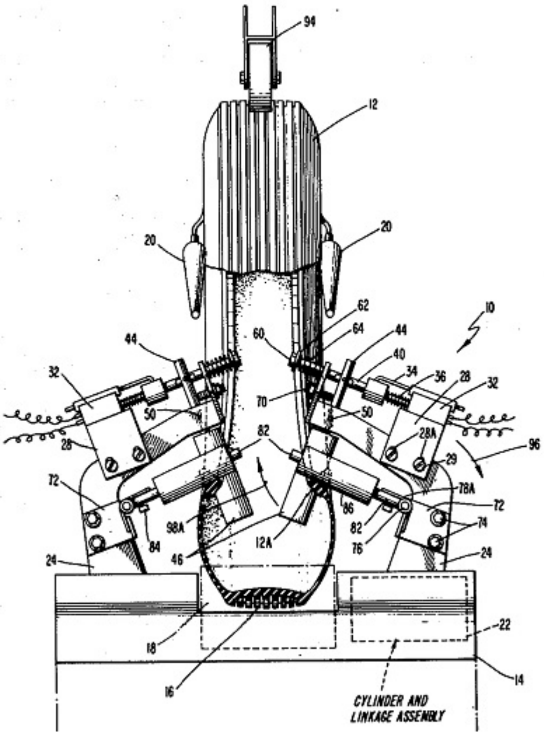


Figure 2.13: Tire bead inspection apparatus (*source:* [6])

for providing accurate measurements of the tire during inspection and preparation. The tire rotates about an axis extending longitudinally through the elongated member.

Method and Device for Inspecting Tire [8]

Device for inspecting tires while the tire is rotating in a rim (Figure 2.15). It corresponds to a sequence of processes similar to MU solution.

A tire inspecting method provided with a process in which, at a rim assembly station, one side rim is attached to one side bead portion of a tire to be inspected and the other side rim to the other side bead portion. Both side rims are connected to from a rim/tire assembly which are driven to a tire inspecting machine.

Tire Inspection System [9]

An automated tire inspection system based on X-ray technology (Figure 2.16) to inspect the integrity of portions of tires fed sequentially along the conveying system.

The inventors claim the ability of the solution to adjust quickly and automatically to the different tire dimensions. The system is able to process tires with rim size equal to 10 inches until external diameters of 56 inches.

The tires coming from the conveying system are accommodated in a centering table which retains the tire before it is tested in the inspection system. The tire is centered laterally by a

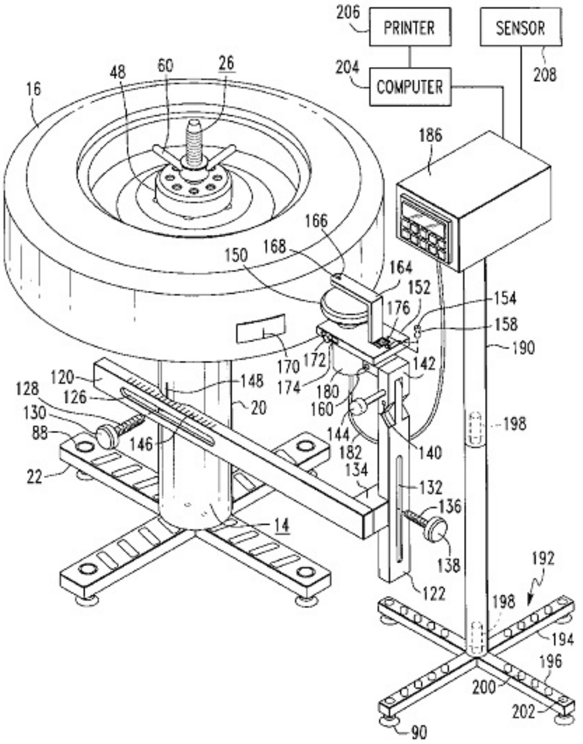


Figure 2.14: Self contained unit for tire inspection and preparation (*source:* [7])

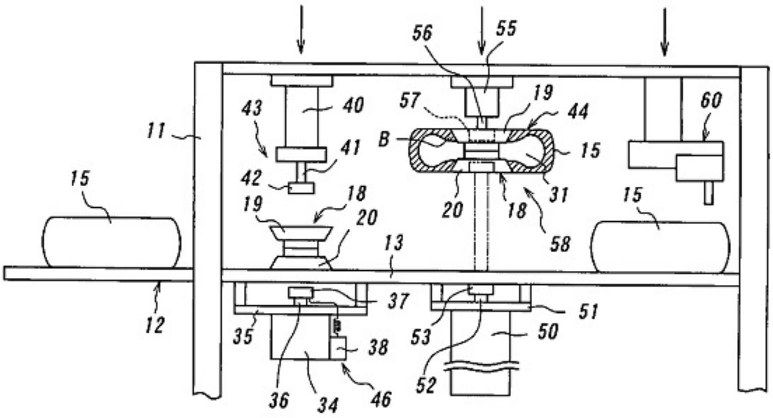


Figure 2.15: Apparatus for tire inspection (*source:* [8])

pair of arms which move inwardly to engage opposite sides of the tire tread. The centering arms also serve as sensors to measure the outer diameter of the tire. An additional width sensor bar measures the tire tread width.
As the tire to be inspected goes into the inspection station, the conveyor system on which it travels is elevated or lowered in order to position the tire with its center plane in a predetermined inspection place. The tire is enclosed and the X-ray tube rotates around the tire to gather the data for inspection.

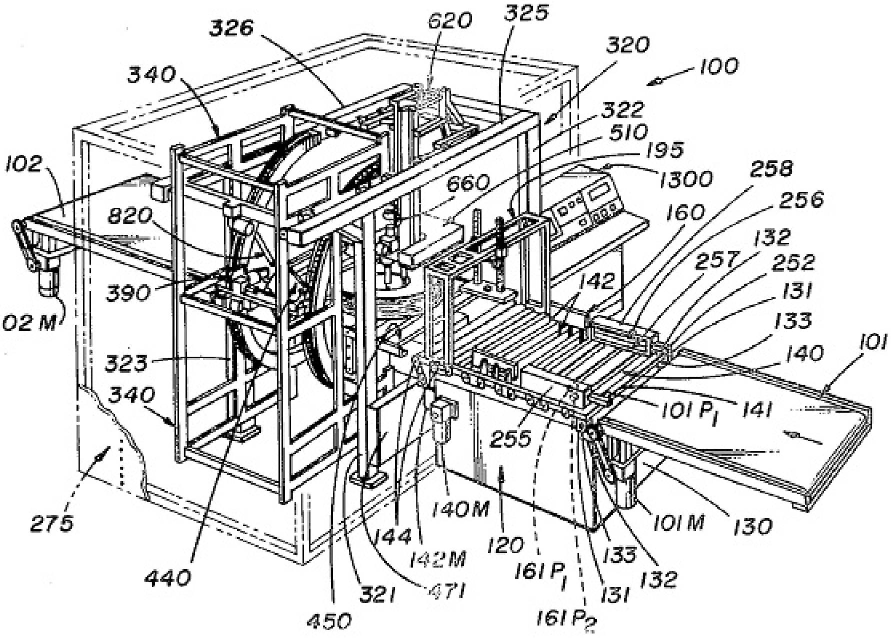


Figure 2.16: Tire inspection system based on X-ray technology (*source:* [9])

Inspection Apparatus for Tires [10]

The invention concerns an inspection apparatus for tires (Figure 2.17) having a positioning device for the tire to be inspected and a laser inspection device. The inspection apparatus has a measuring head which is located in the inner region of the tire. It has an inspection device which consists of a table and four laser measuring heads which are disposed on the table at an angular distance to one another of 90°. The inspection device is pivoted around its vertical central axis. The inspection device is adjustable in a vertical direction. The inspection apparatus for tires also comprises a positioning device structured and arranged for positioning a tire to be inspected.

Defect Marker Method and Apparatus for Use with Tire Inspection Machines [11]

The defect marker apparatus (Figure 2.18) comprises a slide assembly, together with

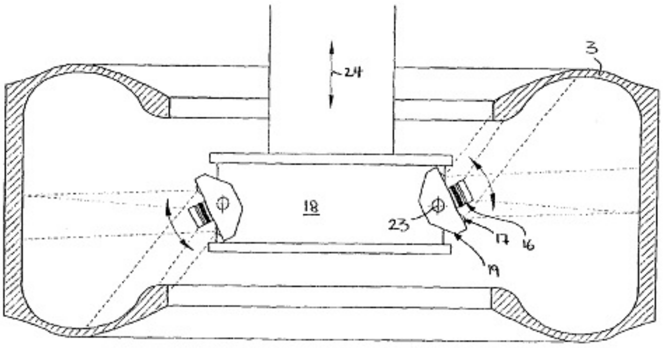


Figure 2.17: Inspection apparatus for tires (*source:* [10])

marker arm and marker head assemblies. The apparatus is mounted adjacent to the inspection machine imaging unit and the marker arm and marker head assemblies being adapted to be operatively interposed between the imaging unit and the tire being inspected.

A tire to be inspected is rotatably supported by a plurality of power driven spindles that are adapted to engage the inside diameter or bead area (number 14 in Figure 2.18). The imaging system is supported by a carriage moving on a pair of semi-circular parallel and vertically directed tracks so that it can be pivoted upwardly and downwardly with respect to tire and can inspect the tire from one bead radially around to the other bead. The imaging system is set to inspect one surface of the tire and then the tire moves for a full rotation so that the entire annular surface might be inspected.

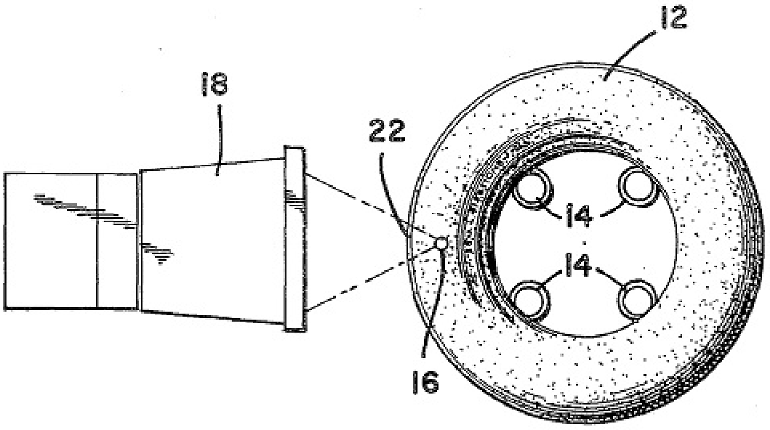


Figure 2.18: Defect marker apparatus (*source:* [11])

Method of Inspecting Tires for Defects [12]

The method consists of applying to an interior surface of a tire a coating material which accentuates defects. The coating material fluoresces or brightens when subjected to ultraviolet light. The method allows to detect defects both in the tire interior and exterior.

The tire is placed upon an expandable mandrel and a liquid material which accentuates defects when influenced by pre-determined electromagnetic wavelenghts and it is introduced into the interior of the tire (Figure 2.19). The expandable mandrel or hub is expanded and the interior of the tire is pressurized after which the hub and the tire are rotated. During this rotation the material is uniformly applied over the entire interior surface of the tire and due to the internal pressure, the liquid is forced to migrate through any defects toward and to the tire exterior.

As the tire continues to rotate relatively slowly, light of pre-determined electromagnetic wavelenghts is applied to the exterior surface of the coated tire whereby any coating material which has migrated through a defect in the tire to the exterior is enhanced and might be detected.

The apparatus for the tire inspection includes a hollow, cylindrical, tubular mandrel surrounded by and carrying a flat tubular expandable hub formed of rubber material. A flexible air pipe opens into the interior of the expandable hub, runs through a tubular shaft and is connected through a rotatable coupling to an exterior source of pressurized air. Another flexible tube passes completely through the expandable hub and has an outlet directed toward and opening into the interior of the tire when it is positioned loosely upon the expandable hub.

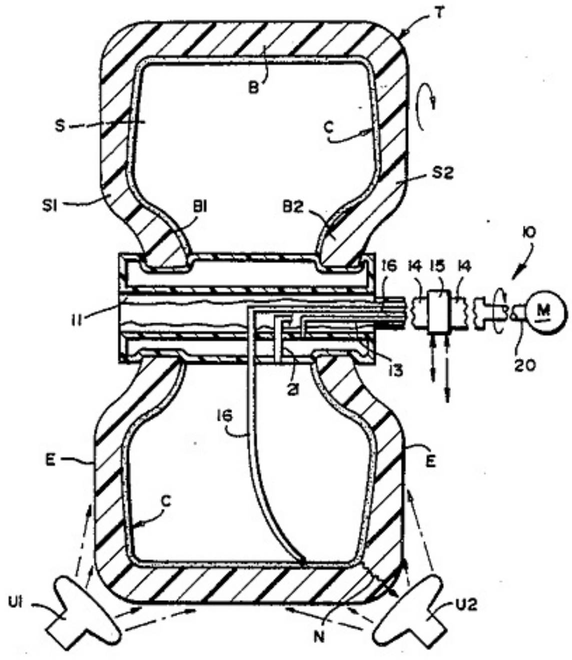


Figure 2.19: Apparatus used to apply the coating material inside the tire surface (*source:* [12])

Tire Spreading and Inspecting Machine [13]

The tire spreading and inspecting machine (Figure 2.20) comprises a frame for supporting a tire in an inspection position. Drive rollers are provided on the frame for rotating the tire and spread arms are arranged for engaging the beads of the tire and spreading them apart to allow inspection of the tire interior. An offset in the spreading arms prevents the rollers from jumping out of the tire while the tire is rotating. Sidewall support rollers are also provided on the frame for contacting the sidewalls of the rotating tire to prevent the tire from collapsing before enough spread is reached. Moreover, a tire lift attached to the frame includes a lock and roller for applying pressure to the tire to prevent it from coming off the rollers during rotational movement.

The tire support and rotation assembly includes a box-like frame, having rectangular front and back panels. The lift assembly of the apparatus comprises a pneumatic cylinder and a framework for lifting a tire from the floor to the inspection position with the tire tread placed in drive rollers. The lift assembly also includes a lock mechanism for applying pressure to the tire to prevent the tire from moving off the drive rollers during inspection and operation of the system.

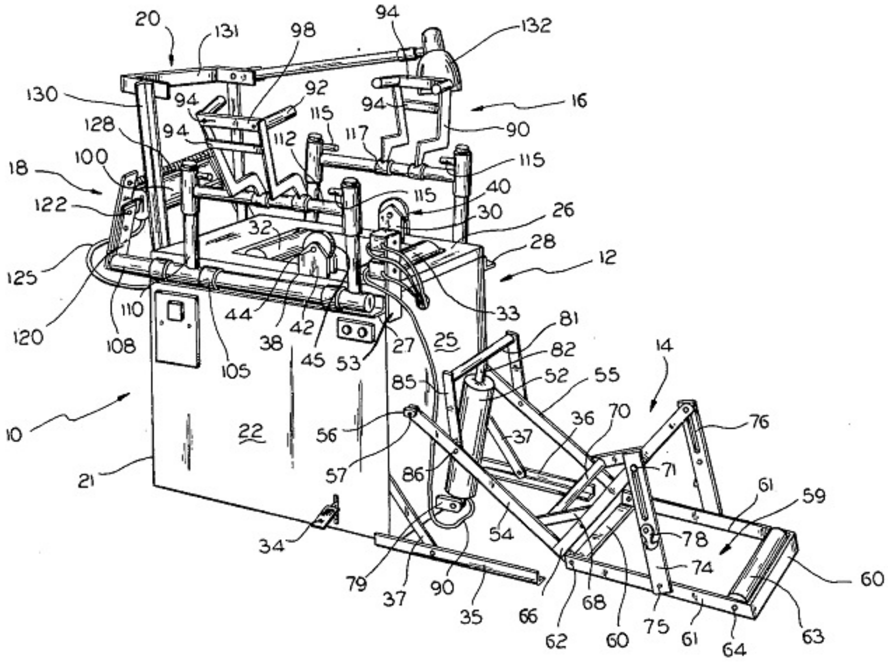


Figure 2.20: Tire spreading and inspecting machine (*source:* [13])

Adjustable Tire Spreader and Inspection Apparatus [14]

Tire handling structure that positions the tire and spread the beads in order to be inspected (Figure 2.21). The apparatus comprises a pallet for supporting the tire to be inspected.

The pallet has an aperture aligned with the tire geometrical center, and a pair of paws are vertically aligned and adapted to spread the beads in order to allow an optical inspection apparatus to inspect the tire.

Each pair of paws is positioned about the aperture of the pallet and capable of rotating from a closed position to an open position of the tire beads. The paws are spaced about the beads of the tire and they move simultaneously to spread the beads for tire inspection. The inspection apparatus have a set of laser scanner solutions. When the tire beads are spreaded by the paws, the ensemble move from outside to inside the inspection station and the inspection apparatus starts the operation. The laser light is reflected off the interior surface of the tire as the tire is being stressed and the light reflected is captured by the camera.

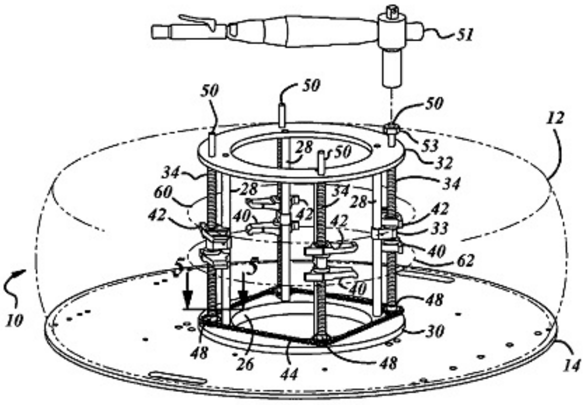


Figure 2.21: Tire spreader and inspection apparatus (*source:* [14])

Tire Shape Inspection Method and Tire Shape Inspection Device [15]

Tire shape inspection method for embossed marks defects on the sidewall surface of a tire. The method is based on the height distribution information captured by a line light source which is compared to a reference. The tire rotates and a set of image pickup elements are acquiring the information (Figure 2.22). A single line is taken at each time while the tire rotates. The image processing device compiles all the data received and builds-up a 2D image.

The working principle is identical to the one followed in the MU solution.

Ultrasonic Tire Testing Apparatus [16]

An ultrasonic, non-destructive inspection system for detecting separations in tires (Figure 2.23) employs a through transmission method at ultrasonic inspection in which the ultrasonic transmitter array and the ultrasonic receiver array are both mounted in air and in a non-contacting, non-critical relationship with the tire under inspection. The inspection is

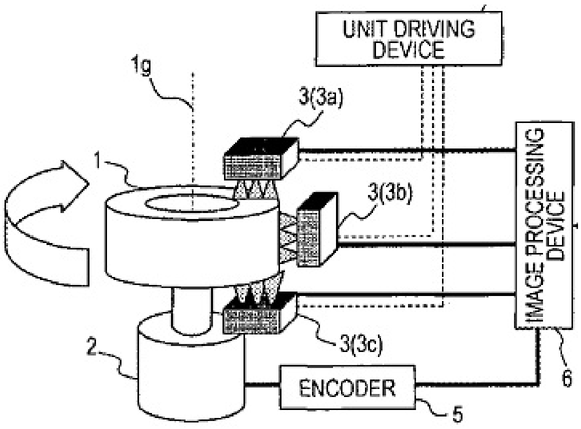


Figure 2.22: Tire shape inspection device (*source:* [15])

performed in one revolution of the tire.

The ultrasonic transmitters are pulsed and the receivers are sampled during pre-determined time intervals which are related to the transmitter-receiver-tire geometry.

The tire is rotated about its central axis while the complete area of the tire carcass is swept out. Both the trasmitting array and the receiving array are disposed in a non-contact relationship with respect to the tire interior.

The apparatus includes a rectangular box-like base containing motor driven drive rollers on which the tire carcass is placed during the inspection process. Spreader arms are used to spread the tire beads.

Tire Appearance Inspection Apparatus and Method [17]

The tire appearance inspection apparatus (Figure 2.24) includes a sectional shape acquiring device for gathering cross-sectional shapes of the tire in the radial direction along the circumference of the tire.

The tire appearance inspection apparatus is constituted of an image capturing apparatus, a sectional shape acquiring device for capturing the images of tire surface, and an image processing apparatus. The image capturing apparatus is composed by a rotating table on which the tire is placed, and camera sets which gather images of the respective regions of the tire interior.

The camera sets are positioned within the inner opening area of the tire such they are distant from each other by a specific angle.

Tire Inspection Apparatus [18]

A tire support structure with mechanisms for rotating and spreading a tire is mounted for rotation on top of a stationary pedestal (Figure 2.25). The tire support structure includes

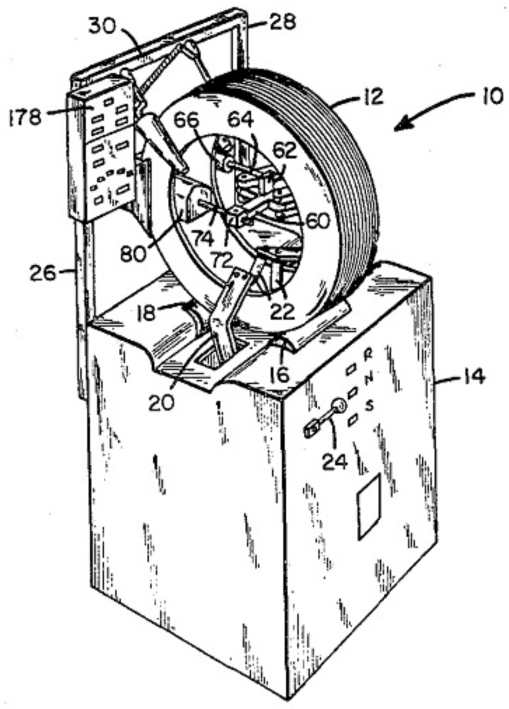


Figure 2.23: Tire testing apparatus (*source:* [16])

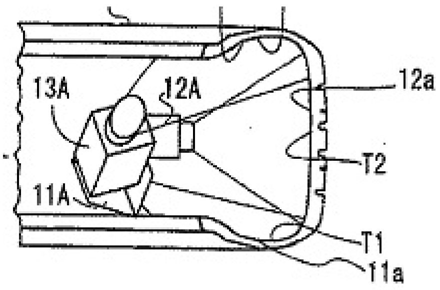


Figure 2.24: Tire appearance inspection apparatus (*source:* [17])

a pair of horizontally disposed rollers for rotating the tire, and a pair of spreader arms carrying rollers for engaging the tire beads.

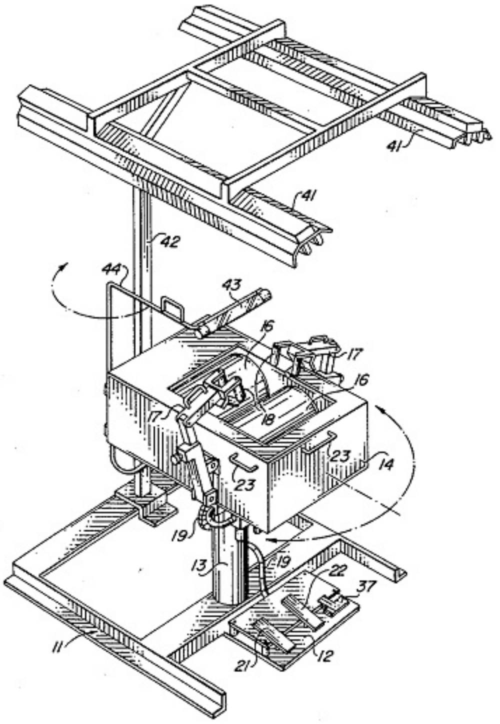


Figure 2.25: Apparatus with mechanisms for rotating and spreading a tire for inspection (*source:* [18])

Tire Inspection Device [19]

The tire inspection device (Figure 2.26) is provided with holders for holding the tire. The holders perform a similar role to a wheel for actual fitting on the tire. The holders are configured with a pair of circular disk portions that are disposed facing each other and parallel to each other. A rotational axis holder is attached at the center of one of the holders.

A camera is attached to the rotational axis holder through an arm. The camera is disposed so as to be able to gather the image of the tire interior. The rotational axis holder is configured with a bearing for enabling the holder and the arm to rotate relative to each other. The camera is then able to acquire the images around the entire circumference of the tire.

Tire Interior Inspecting Method and Tire Interior Inspecting System for Carrying Out the Same [20]

A tire interior inspecting method emits x-rays to irradiate a tire being continuously driven

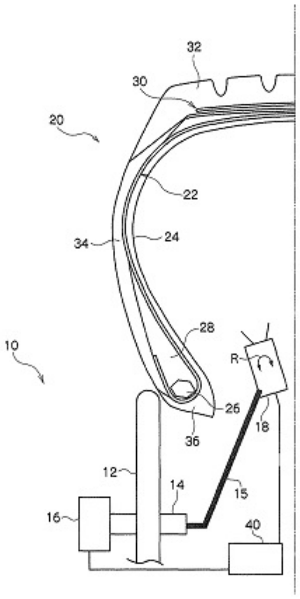


Figure 2.26: Tire inspection device (*source:* [19])

by the conveying system. All the tires passing the conveying system might be inspected for total interior inspection without stopping the conveyor (Figure 2.27).

An X-ray tube is disposed at a pre-determined position above the conveyor with the aim of irradiating X-rays downward. A linear X-ray sensor is disposed directly below the X-ray tube at a position corresponding to a space between two adjacent conveyor rollers to detect the X-rays irradiated. Therefore, a curtain of X-rays perpendicular to the direction the tires are moving is formed between the X-ray tube and the linear X-ray sensor.

2.2 Technology Assessment and Selection

Technology is one of the main drivers of the system to be developed. Technology shall be the trigger for the process improvement, together with the human contribution. Besides, technology is also seen as an important determinant of cross-country variation in income per capita [55] and is a key driver for innovation and sustainable business growth [56]. Chung *et al.* [57] highlights that new manufacturing technologies are needed to assist in compressing the production time to move products to the market more quickly and efficiently than competitors. Acquiring and implementing new technologies are perceived as high-risk investments and determinants of competition. In the end, a technology is feasible if it satisfies the following conditions [58]:

- Minimal environmental conditions
- Minimal performance requirements

- Budget ceiling

If a company selects a technology and ignores the difference between its own resource level and the selected technology's required input levels of resource, the selected technology cannot be carried out in reality [59].
Not a single technology, in most of the cases, is available for a specific application. The availability of more than one kind of manufacturing technology gives rise to the following questions [60]:

- What kind of manufacturing technology is appropriate for a given situation? What particular capabilities must it have and what weaknesses or constraint can it afford to have if trade-offs are required? How frequently should changes be made in the technology and what circumstances or events are likely to trigger them?

- What procedures should be adopted to help identify, select and pursue the best opportunities for changing the company's production technology? How should these changes be implemented and what organizational strengths are required to carry out the company's strategy for technical improvement?

Technology selection involves decision-makings that are critical to the profitability and growth of a company in the increasing competitive global scenario [61]. It is also considered one of the most challenging decision-making areas that the management of a technology-based company encounters [62]. Managers are faced with hard decisions concerning how best to allocate limited resources, in terms of the increasing cost, complexity

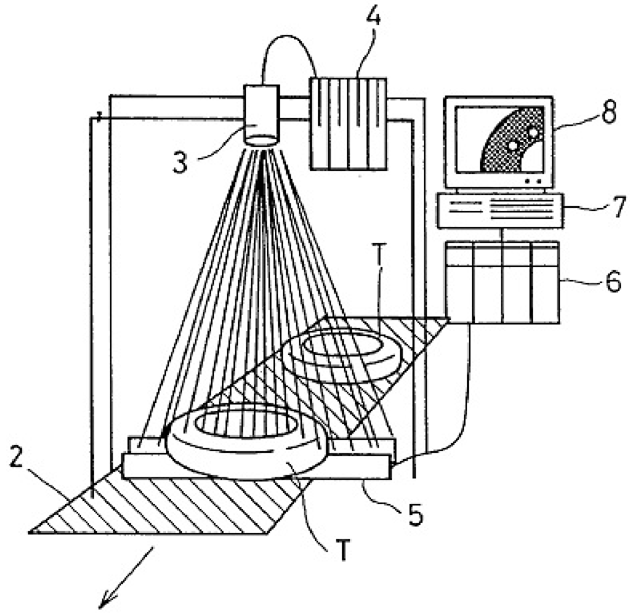


Figure 2.27: Tire interior inspecting system (*source:* [20])

and risk of technology investments, against a background of increasing global competition. A key objective of technology management is to ensure that technical resources are effectively linked to business requirements [56]. Managers are often faced with the dilemma of selecting a single most appropriate technology from a range of competing options. The rapid development of technologies, together with their increasing complexity and variety, has made the task of technology selection difficult [63]. In addition, decision-makers have difficulty processing multi-dimensional information, once they frequently experience difficulty in aggregating various pieces of information to produce a single response. To reduce cognitive strain, they resort to simplifying heuristics which may cause them to ignore or misuse relevant information [64]. Evaluation and selection of the most appropriate technology arises and suitable methods must be applied.

In the literature, there is a special focus on technology selection due to the complexity of their evaluation which includes strategic and operational characteristics [65]. The selection and evaluation of Advanced Manufacturing Technologies (AMT) is complex due to interplay of several factors, both external and internal. It is always necessary to involve different levels of management in the decision-making process as AMT cannot be evaluated merely on hard economic criteria [66]. Technology selection, like strategic decision-making, is a very complex problem because the decision involves uncertain environment, lengthy time horizon, inadequate information and subjective factors, which cannot be easily quantified [67]. Chan *et al.* [61] also calls the attention for the fact that usually the information available for decision making is vague and uncertain.

The definition about what is the technology selection process is diverse in the literature, although the use in many scientific fields and the conscious that the selection problem is a difficult multi-criteria decision-making problem remains unanimous [68] and one of the most challenging decision-making areas that a technology-based company encounters [59]. Some authors refer to the technology selection problem as the process to identify the best from a set of possible alternatives, i.e. distinct option for a purchase or project decision [69, 63]. Gregory [70] refers to the technology selection problem as involving the choice of technologies that should be supported and promoted within the organization. He also separates the identification and selection phases where the former is concerned with gathering alternatives and the latter is concerned with the action to decide on an alternative. Dussauge *et al.* [71] define the technology selection process as the identification and selection of new or additional technologies which the firm seeks to master. Stacey and Ashton [72] gives another perspective over the technology selection process. They consider it as a process of prioritizing technical investment alternatives, implying that the choice of technology should take into account the business and technical risks involved in fulfilling an organizational objective. Technology selection involves gathering information from various sources about the alternatives, and the evaluation of alternatives against each other or some set of criteria [73]. Technology selection requires several capabilities: the ability to identify a set of candidates to be considered, the ability to evaluate (either comparatively or in isolation) the candidates, and the ability to choose from amongst the candidates based upon the evaluations [74]. According to Hendrickson and McNeil [75], technology selection falls into three general classes of problems:

- Accept-reject problems require an assessment of whether an investment is worthwhile
- Selection of the best project from a set of mutually exclusive projects is required when there are several competing projects or options and only one of them can be built or purchased
- Capital budgeting problems are concerned with the selection of a set of projects when there is a budget constraint and many, not necessarily competing, options

In order to provide appropriate selection criteria for performing the technology selection, metrics have to be defined and allocated in terms of superiority, robustness, maturity, and flexibility [76]. In the selection of the most suitable technology, objective factors such as cost, profit, revenue, saving in time, time of completion, etc. are considered but subjective factors such as flexibility, learning, capacity increment, etc. are overlooked [67]. Some approaches to the technology selection decision have usually been narrowly focused on assessment of the financial viability of technology options, or conventional investment justification factors.

In many cases, the selection processes are based on generic decision support tools which are not fully adapted for technology selection [63]. Moreover, Farooq and O'Brien [77] introduces the risk calculation in the technology selection, splitting the decision-making environment into manufacturing and supply chain environment. According to the authors, the evaluation of a technology considering supply chain opportunities and threats provides a broader perspective to the technology evaluation process. The inclusion of supply chain dimension in technology selection process facilitates an organization to select a manufacturing technology not only according to its own requirements, but also according to the interest of its constituent supply chain [78]. The same authors [78] mentioned that the existing technology selection processes do not provide support for the inclusion of inter-organizational factors in the technology selection decision making environment.

For any multi-attribute problem, the selection of the "best" family of alternatives is inherently subjective and no single answer will fulfill all requirements. Kirby and Mavris [21] propose three approaches to account for the subjectivity of the problem:

- Scoring Models (Multi-Attribute Decision-Making (MADM) techniques)
- Technology Frontiers (performance, economic, and system effectiveness vs. investment costs) - Figure 2.28
- Resource Allocation (one-to-one technology comparison)

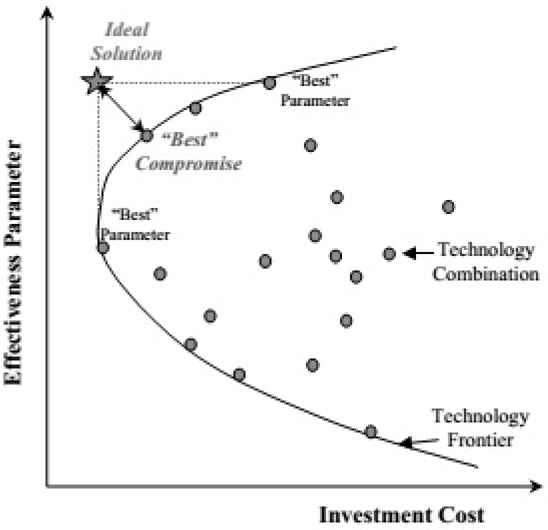


Figure 2.28: Example of technology frontiers (*source: Kirby and Mavris* [21])

An example of the use of scoring models is presented by Georgakellos [69]. He uses scoring model for screening and selecting candidates, suitable for simple cases such as equipment purchase projects. The model considers for each possible alternative its technical performance together with commercial aspects, and analyzes the results on a single "score". According to the author, the main advantage of the proposed technique is that it is easy to understand and use, while not very time and effort consuming.

In literature there are several traditional engineering economic analysis methods that are used for justifying new technology investments, for example Net Present Value (NPV), internal rate of return and methods including payback period. These techniques primarily include the tangible financial costs and benefits. However, investment in a new technology is often hard to justify by just using the measurable cost and benefit data alone and investing in a new technology often result in uncertain future benefits that are very hard to estimate using a conventional financial analysis [79]. Farzin *et al.* [80] also highlights that the conventional NPV method only takes into account cash flows and ignores the option value of waiting for more efficient future technologies, thus failing to account for this opportunity cost component when an investment decision is made.

Meredith and Suresh [81] classified the methods for AMT evaluation into three groups:

economic analysis techniques, analytical methods and strategic approaches. Limam *et al.* [82] distinguish three classes of multi-criteria methods: multi-criteria decision aid methods, elementary methods and optimization mathematical methods. The choice of one of the three classes methods depends either on the set of data, or on the way in which the decision-maker models preferences. The multi-criteria decision aid methods support the decision-maker refining his decision-making process to choose an action among a set of potential actions, or to classify a set of actions by examining the logic and the coherence of its preferences.

Different methods and techniques are used among the authors concerning the technology selection process. The choice for one or another method or technique depends on the sort of problem in hands and the kind of feature the author would like to take from the method. The methods can be used alone or in combination. Shen *et al.* [83] highlights the importance of integrating different methods in order to improve the technology selection process. Kengpol and O'Brien [74] stress the need to structure a decision support tool that can integrate models for:

- Quantifying the impact of the value of reducing development time (or Cost/Benefit Analysis)
- Measuring decision-making effectiveness
- Assessing common criteria used by decision-makers in evaluating Time Compression Technologies (TCT) and methods of relating criteria to alternatives

Limam *et al.* [82] identified several methods to deal with complete aggregation:

- Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)
- Multiple Attribute Value Theory (MAVT)
- Multiple Attribute Utility Theory (MAUT)
- Simple Multiple-Attribute Rating Technique (SMART)
- Utility Theory Additive (UTA)
- EVAluation of MIXed criteria (EVA-MIX)
- Analytical Hierarchy Process (AHP)

AHP is widely used to classify alternatives based on a range of criteria [82, 84, 36, 85]. The AHP is a method for complex multi-criteria problems for which quantitative and qualitative aspects could be taken into account [86]. The AHP has the strength of identifying criteria and obtaining their relationship and their weights [83]. The AHP method is the only one that allows the measure of the coherence of the decision-maker preferences and takes into account at the same time the independence and the inter-dependence of the considered criteria. Moreover, the AHP method allows to consider qualitative and quantitative criteria [82].

However, AHP has also some weaknesses. Farzipor Saen [65] mention subjectivity that is inherent to AHP and the impossibility to include inter-relationship within the criteria in the model. Another method commonly used in the literature is the Data Envelopment Analysis (DEA) [58, 87, 68]. DEA is a fractional mathematical programming technique which measures relative efficiency of decision making units in a homogeneous set [88]. DEA also have some limitations: possibility to select a sub-optimal solution and the use of simple efficiency score [87].

Another method used in the technology selection process derives from the product development process. The Quality Function Deployment (QFD) is a set of powerful product development tools and procedures originated in Japan to take the concepts of quality control from manufacturing and transfer them to the new product development process [89, 57]. Lowe *et al.* [89] developed a multi-attribute matrix analysis tool from the techniques of QFD and applied to the evaluation of potential products for an innovative process.

Rai *et al.* [90] suggest the application of a fuzzy Goal Programming (GP) concept to model the problem of machine-tool selection and operation allocation with explicit considerations given to objectives of minimizing the total cost of machining operation, material handling and setup. A genetic algorithm based approach is adopted to optimize the fuzzy GP. Chan *et al.* [91] also uses a fuzzy GP approach to model the machine tool selection and operation allocation problem of flexible manufacturing systems.

Karsak and Ahiska [92] propose a practical common weight Multi-Criteria Decision-Making (MCDM) methodology with an improved discriminating power for technology selection. The MCDM methodology enables the evaluation of the relative efficiency of Decision-Making Units (DMU) with respect to multiple outputs and a single exact input. Xiaofeng *et al.* [93] symbolize conventional technology selection approaches as Basic Decision Equations (BDE) and introduce a connectivity matrix and processing methods so as to arrive at simple and comprehensive views of the nature of engineering technology selection problem.

The use of more than one technique intends to enhance the most promising features of each method. Yu and Lee [59] propose a method to cluster technology alternatives according to their required input levels of resource. After that, in each cluster, the proposed method Data Envelopment Analysis - Assurance Region (DEA-AR) method to evaluate the efficiencies and AHP rating method to evaluate the priorities of the technology alternatives. Shen *et al.* [83] integrates fuzzy Delphi method, AHP, and Patent Co-citation Approach (PCA) in the technology selection process. The PCA identifies the major R&D fields of a specific technology from patent data. The fuzzy Delphi method is applied to identify critical economic or social criteria for technology selection. The combination of fuzzy Delphi method and AHP is employed to construct a technology selection structure. One of the main issues in the technology assessment and selection is the uncertainty or lack of information with respect to the technologies and factors influencing the choice. In order to overcome that issue, Chan *et al.* [61] use fuzzy numbers and linguistic variables to evaluate tangible and intangible factors. Jaganathan *et al.* [94] propose an integrated fuzzy AHP based approach to facilitate the selection and evaluation of new manufacturing technologies in the presence of intangible attributes and uncertainty. AHP is also used by Ragavan and Punniyamoorthy [67] to evaluate the intangible benefits of a technology.

The technology selection also comprises the technology evaluation. Technology assessment is an important area in technology management that has received increasing attention among researchers in both public and private domains [84]. Tran and Daim [84] also identify the approaches and methods used in the business environment for technology assessment:

- Cost benefit analysis methods
- Decision analysis
- Measures for technology
- Road mapping
- Scenarios and Delphi
- Surveying, information monitoring, new technology assessment
- Mathematical and other synthesis methods

Whenever new technologies are implemented in a certain context, one shall pay special attention to the technology adoption by the individuals who will use it. Understanding why a workforce adopts or rejects new technologies has proven to be one of the most challenging issues for organizations to exploit new technologies [95].

The factors influencing the technology adoption differs whether the context is the industrial environment or it is the more general context of a country. Comin and Hobijn [55] indicates that the most important determinants of the speed at which a country adopts technologies are the country's human capital endowment, type of government, degree of openness to trade, and adoption of predecessor technologies. Suri [96] adds that credit constraints explain the lack of technology adoption which it is valid both for a general context and for the industrial environment.

In one particular aspect many authors [97, 98, 55, 99] are aligned: user involvement is of the most importance. Besides, lack of an understanding, technical difficulties, lack of training, and insufficient support from top management and perceived complexity, are considered as the main causes of user resistance [97]. Abukhzam and Lee [95] stress the importance of the workforce perspective. If the workforce primarily considers the new technology will decrease working time and/or process complexity and its adoption will not affect their positions, then they will adopt it. Fichman and Kemerer [99] refer that users may reject some technologies because technologies are not compatible with the values, beliefs, and past experiences of their social system. Understanding specifically who the user is can have an important influence on a given technology's acceptability to that user. Only by understanding the underlying drivers of individual technology acceptance and usage decisions can organizations effectively deliver appropriate support mechanisms designed to help the user perform his or her job [98].

Factors such as innovation characteristics (e.g. perceived usefulness and ease of use, compatibility, reliability, security), organizational and managerial characteristics (e.g., leadership characteristics, fear of loss of autonomy, fear of security breach), and facilitating conditions (e.g. availability of top management support) have been found as the key influential factors affecting users' attitude towards adopting the proposed technical systems [95].

Morris and Venkatesh [98] studied the age differences influence in the technology adoption decisions. They conclude that younger workers' technology usage decisions were more strongly influenced by attitude toward using the technology. In contrast, older workers were more strongly influenced by subjective norm and perceived behavioral control, although the effect of subjective norm diminished over time.

Another important decision managers have to take is about the optimal timing of technology adoption in an organization, especially when technology choice is irreversible and the firm faces a stochastic innovation process with uncertainties about both the speed of the arrival and the degree of improvement of new technologies [80].

An intrinsic aspect of technology adoption is the technology diffusion. Technology diffusion results from a series of individual decisions to begin using the new technology, decisions which are often the result of a comparison of the uncertain benefits of the new invention with the uncertain costs of adopting it [100]. Technology diffusion can be seen as the cumulative or aggregate result of a series of individual calculations that weigh the incremental benefits of adopting a new technology against the costs of change, often in

an environment characterized by uncertainty and by limited information.
Comin and Hobijn [55] identify the seven main theories used in technology adoption and diffusion:

- Vintage capital theory
- Vintage human capital
- Innovator-imitator models
- General purpose technology with complementary inventions
- Factor endowments
- Trade
- Vested interests and political institutions

Abukhzam and Lee [95] list some of the technology adoption frameworks used to understand the key factors affecting user's attitude towards technology adoption and diffusion:

- Theory of reasoned action
- Technology adoption framework
- Theory of planned behavior
- Decomposed theory of planned behavior
- Innovation diffusion theory

The importance of all these factors and theories is essential for a successful implementation of a technical change. The workforce involvement in the overall development process is one of the key aspects that one will follow along the project.

2.3 Human-Machine Interfaces

The approach followed for the research and development project is focused on the contribution of the individuals that currently perform the inspection process. It also looks to the inspection task as a decision-making process. Looking to the inspection process as a decision-making process reinforces the importance of humans in the development process and in the final decision-making process solution too. The key issue, in the first stage, is to acquire and understand the implicit knowledge operators have in the current process and environment. The socio-technical approach to the problem seems to be suitable. However, this approach seems not to be always applied [101]: *"It is widely acknowledged that adopting a socio-technical approach to system development leads to systems that are more acceptable to end users and deliver better value to stakeholders. Despite this, such approaches are not widely practiced"*.

Socio-technical approaches can have very positive impacts in economical, social, and engineering development [102]. In addition, one has to deal with ethical issues arising from the tension between the technical world and the social world. It is necessary a richer perspective of rationality as regards the social impact of technology and automation based upon human skills [103].

In order to avoid the risks inherent to this approach, the characterization of the population (operators, in this case) is a key issue with respect to the decision-making process [104]. Another important aspect is to "take engineers to the workplace" [101]. This is decisive to create a common language and to have hands-on experience in the process one would like to improve. It is also essential to gain the operators trust on what an engineers are doing. Changes are always dramatic and understanding their difficulties and ideas is crucial. This is one of the main reasons to conduct an ethnography study. Ouellette and Wood [105] complement this idea referring that it is essential to understand the operators behavior in different situations and the impact in the daily decisions. Knowledge from biology, psychology and neuroscience incorporated in new approaches for systems that have sensory-motor capabilities and operate in complex environments shall also be considered for a successful solution [106]. Moreover, one shall have a transversal approach to processes in a plant, considering the different social and technical impacts and issues [107]. Attention has also to be paid to the system validation and reuse of knowledge [108].

Allais *et al.* [50] highlight the importance of operators know-how in the quality inspection of natural products. Tires can also be considered as natural products since most of the material used in tires is rubber, a natural product that creates additional complexity to the inspection process. Thus, it is imperative to incorporate this knowledge in the future decision-making process [109]. Irène Allais [110] describes a system that combines human and decision-support tool to determine the quality grading of products.

To incorporate the knowledge or even to transfer some of the implicit knowledge into explicit one, there are many approaches to reach it. The use of both quantitative and qualitative methods to build-up a model of human decisions [50], the use of collaborative learning schemes, specially when considering a large population [104], or even developing cooperation control algorithms [111]. Different sources of information for modeling the human knowledge are seen as a relevant approach [112]. Press *et al.* [102] highlight the importance of perception in the transfer of human knowledge to automatic systems.

In a decision-making process where humans will have a central role, the interaction between the operator and the system needs to be strong in order to establish an effective system performance. This approach is very common in the classical architecture of expert systems [113]. Another idea presented by Jordan [114] is the need of complementariness between humans and machines. This complementary approach shall be stressed and valued much more than a comparison approach between the two “systems”. Moreover, it is also important to create a functional model of the task with user-system partition to represent the roles of user and system, having in mind the idea of aiding as a cognitive support to complement human knowledge [115]. Meng and Lee [106] refer the need of incremental learning and adaptive abilities similar to those seen in humans in advanced autonomous artificial systems. The same idea is transmitted by Sester [116], suggesting the combination of semi-automatic and incremental knowledge system.

The solution to be developed will incorporate a close connection between humans and some sort of automation. In another words, the developed solution needs to have a Human-Machine Interface (HMI) and the corresponding design. The design of human-machine interfaces is viewed under a human-centered and integrated automation approach [117]. Clancey *et al.* [118] highlights the importance of designing of human-computer systems that respect how work actually gets done, and it is seen as one of the most critical issues in the business. The design quality of HMI is influenced by many factors, such as the percentile of human models, the position and structure of display or control equipments [119]. Karikawa *et al.* [120] refer that appropriate HMI design is a key issue for preventing significant hazards resulted from human errors. Humans must be the central point in the design development.

Johannsen [117] proposes a conceptual design of HMI based on a structured development process, from the scenario definition, goals specification, means specification, and task analysis, until the final evaluation of the system. Along this process, there are different forms of user participation in order to guarantee full satisfaction of users.

In order to evaluate the performance of a HMI two main approaches are currently used : empirical approaches and analytical approaches. Empirical approaches are user-focused approaches. Analytical approaches are based on the automated examination of interfaces using well-defined structures and rigorous analysis techniques [121]. Analytic evaluation techniques allow to predict user performance, time execution of tasks, how a design will perform and to explain the performance of an existing interface [122]. Cognitive models are used to forecast some aspects of utility and usability of HMI, and also simulating the interaction with these interfaces [123]. Chikhaoui and Pigot [123] also describe three cognitive models: the ACT-R architecture, the GOMS model, and the contextual assistant.

The cognitive architecture ACT-R is built to simulate and understand human cognition. ACT-R is an hybrid architecture that combines two sub-systems: symbolic system including semantic and procedural knowledge, and sub-symbolic system evaluating knowledge activations. GOMS model is a formalized method to predict task performance based on four basic elements: goals, operators, methods, and selection rules. The contextual assistant is a framework developed to assist persons with cognitive disabilities. The aim is to foster autonomy in the daily living tasks, and particularly during complex cooking tasks [124].

Whenever an evaluation of a HMI is required, it is of the most importance to estimate the human errors that might occur. Lee *et al.* [125] propose a method for quantifying human errors and an evaluation framework for quantifying the execution error probability using soft controls under a nuclear power plant environment.

An important aspect to be taken into account is the technology criteria: design production systems which are cognitively compatible with the mental models of the workers. A comprehensive checklist of criteria is presented by Fuchs-Frothnhofen *et al.* [126], in which workers shall be able to learn about and adapt easily to the system and its different uses, directly experience and manually influence the manufacturing process, maintain and repair the system, make use of the system's self-explanation features and documentation, make use of databases and decentralized information networks, simulate manufacturing processes before starting the "real" process, and develop communication and cooperation in groups and networks.

In the end, the HMI functions can be specified in the following global categories [117]: goal functionality, means functionality, task functionality, dialog functionality, presentation functionality, and human error-tolerance functionality.

The design of the interface is a critical aspect. Geometrical factors significantly affect operational efficiency in the visual interactions of a humancomputer interface. A research work concludes that small graphical items shall be avoided in computer interface design, although it should be noted that taking into account other studies there could exists an optimum of item size [127].

One well-known HMI is the cockpit design of an aircraft. The example of aviation human-machine interface design reveals a trend in this industry: newest aircrafts are designed to be able to return to a safe state by the use of control systems, which do not need human intervention. Several rationales may lead to the conclusion that "humans" should limit themselves to monitor the "machine". Thus, the dilemma whether one really needs operators might arise. However, social-technical approaches in recent human error analyzes are pointing out the so-called "organizational errors" and the importance of a HMI harmonization. Typically plant's operators are a "redundant" safety system with a much lower reliability when comparing with a machine: organizational factors and harmonization requirements suggest designing the HMI in a way that allows improvement of operator's reliability [128].

The HMI shall match human satisfaction in order to guarantee the effectiveness and efficiency of the system. The HMI must not only be physically safe, but also psychologically comfortable [129]. Matsunaga and Nakazawa [130] propose an adaptive HMI to match human satisfaction which is evaluated by the satisfaction measurement system with neural network based on measuring electroencephalogram. This adaptive HMI can comply to individual operators and varying context based on human satisfaction.

In HMI, it is necessary to use one of many available devices: light pens, digitizers, joysticks, arrow keys, track balls, touch screens or computer mouse [131]. Albert [132] performed a study and ranked the different devices according to two different categories: operational speed and accuracy. He ranked the devices in descending order of operational speed as: touch screen, light pen, digitizer tablet, track ball, force joystick, position joystick, and keyboard. In terms of accuracy, he also ranked in descending order like: track ball, digitizer tablet, force joystick, position joystick, and keyboard, with the light pen and the touch screen performing worst.

In the area of HMI development, the mouse is the most common input device [133, 134]. However, growth for desktop touch technology has increased by more than 25% in 2008 and 52% in 2009 [135]. If the mouse is replaced by other input devices, like touch screens, the user may have some difficulty in operating and suffer lower efficiency [134].

Many pointing devices are available for use with computers, but none are as natural to use as the touchscreen. Pointing at an item, or touching it, is one of the most natural ways to select it [133]. Since touch screens do not require explicit intermediate devices, there is no displacement between control (input) and feedback (output). The touch screen technology is characterized by intuitive input, the touch screen is learned and operated more easily by the user [136]. Such directness and intuitiveness makes the technology ideal for public kiosks, commercial and industrial systems, and more recently mobile devices such as smart phones, portable navigation systems, and portable game consoles [137]. Touch screen technology is popular due to its flexibility in design, speed and convenience [135]. Touch interfaces are easy to adjust the design parameters, such as key size, spacing between keys, and location on the screen [138].

The advantages of touch screens are that they make use of direct eye-hand coordination, they have a direct input- output relationship, all valid inputs are displayed and training is minimized [131]. Albinson and Zhai [139] add that touch screen has no need for such an extra device as the mouse, which needs a space-occupying carrier and operating environment, and compared with other mobile input devices, the touch screen is much more robust and durable.

Nevertheless, some disadvantages are also pointed out by Helander *et al.* [131], most of them related to ergonomic issues like arm fatigue. Irwin and Sesto [135] run an experiment build upon ergonomic and bio-mechanical knowledge to quantify touch characteristics (kinetic information) during touch screen use. There are also users that reported greater levels of subjective discomfort with touch screen use than with keyboard use [140]. The arm and finger often block the line of sight to the screen and target resolution is limited due to the size of operators' fingers [131]. Lee [141] proposes a technique to have shorter movement time with small targets and densely packed distracters to overcome the finger occlusion and imprecision. Experimental results under industrial environment and within the research group show that dirtiness and frequent use might cause some damage in the screen, limiting its use and adoption in critical applications.

Touch key sizes and locations, especially for small touch screens, are critical aspects in the HMI design [142]. Additionally, the different navigation techniques also play an important role for the HMI performance. Wu *et al.* [143] made a comparison between mouse and touch screen interfaces when used with four different navigation techniques: Combined Panning Buttons (CPB), Distributed Panning Buttons (DPB), Enhanced Navigator with Continuous Control (ENCC), and Grab & Drag (G&D). Mouse generally showed better performance than touch screen although users considered identical with respect to the ease of use and overall preference criteria. The ENCC, in this study, showed the best performance and the authors suggest to be applied to touch screens.

Kwon *et al.* [144] studied the effect of control-to-display gain on the usability of tap-n-drag navigation method for small touch screen interfaces as well as the effect of movement direction of the information space relative to the drag direction. They conclude that time and number of touches using tap-n-drag are smaller when using push viewport technique than when using push background technique.

The device used for the interface is of extreme importance as well as the techniques to make available for the users.

2.4 Decision models for semi-automatic systems

The design of flexible manufacturing systems is an essential but costly process [61]. Such a flexible system shall be efficient and cost effective in order to better answer to the daily challenges in the manufacturing process. The tire inspection process due to its specific characteristics requires a flexible but also reliable solution. Although the inspection process do not add value to the final product it is an essential step in the manufacturing process because of the process variability inherent to a natural product like a tire. Nevertheless, the operator who performs the inspection adds value to the task he/she executes once his/her tacit knowledge is essential for the process effectiveness. Most of the times, inspection processes might be seen as decision-making processes where the system (no matter is fully automated, fully human-based, or mixed) takes a decision about the quality grade of the product. At the end, the inspection process either accept or reject a product. The decision-making process should be structured in such a flexible and iterative manner that enables a range of structured to unstructured decisions to be considered, built and solved in an appropriate manner [145].

Pal and Ceglarek [146] propose an analytical model based on Rough Sets theory and identify decision rules which give statistically significant association between product historical data and product behavior. Rough Sets theory is a methodology related to the classification and analysis of imprecise, uncertain or incomplete information and knowledge [147]. According to Rissino and Lambert-Torres [148] Rough Sets theory is considered one of the first non-statistical approaches in data analysis. The use of manufacturing process data in the decision-making processes is widely applied in the literature. Pan and Tai [149] use process data of different characteristics in production to verify the reliability of the decision-maker model. Moreover, defect-related knowledge on a manufacturing process can be integrated in the decision making process at an operational and organizational level [150].

Gathering the data from the manufacturing process is then crucial and it might result in an improvement of the usability, usage, and usefulness of the decision support system. Semi-automatic knowledge acquisition from the production floor and generation of comprehensive reports for the quality department is suggested by Gebus and Leiviskä [150]. Chan *et al.* [61] go even further by integrating manufacturing system design, systems analysis, decision-making support and artificial intelligence techniques and methodologies into one system. Alvelos and Cabral [151] modeled a decision system through a logistic regression where the dependent variable is the decision itself and the independent variables are the decision-maker features that were considered relevant for the product evaluation. Semantic engineering is currently being adopted to support the knowledge-management processes needed by organizational users for decision-making and task-intensive knowledge activities [152]. Barzanti *et al.* [153] uses a knowledge based description of the product features and of user's profiles and integrates these data with two models for strategies and historical information evaluation. Barzanti *et al.* [153] propose a fuzzy knowledge based decision support system that provides a ranking of suitable strategies using fuzzy evaluations. In the end, one needs to merge several uncertain values representing qualitative and quantitative parameters to obtain an evaluation of an inspection strategy. In industry, tacit knowledge has been recognized as a critical resource in the development of sustainable competitive advantage and firm growth [154]. The knowledge might be associated to the humans (explicit and tacit) or to the process or product (process knowledge and concept knowledge). In order to gather the knowledge that better fullfils the requirements of the problem in hands, several knowledge extraction techniques are available, from the process or concept mapping, throughout the interviews or observations [155].

The decision-maker, commonly an operator in the inspection process, is a key actor in the overall process performance. Bezerra *et al.* [156] observed that decisions correspond to the acquisition, while the processing of information allows an individual to choose between various options, and consequently to act on the basis of this decision. The authors also proposed a mathematical model to characterize the decision-maker, considering the influences of the personalization of the individual together with the model of the instantaneous state when the decision occurs. Alvelos and Cabral [151] present a method for modeling and monitoring individual process of a decision-making process usually applied in scenarios of sensory analysis where binary decision (acception or rejection) is required. The need of a decision-maker model is also needed in other fields rather than inspection processes. Decision-making in judicial processes is very critical. Danelski [157] developed an empirical theory of judicial decision-making in which the concept of values is central. He also proposes a multi-dimensional conception of judicial values and explores the utility of cumulative scaling and factor analysis in verifying values in the decisional process. Extracting the knowledge from the decision-maker and representing it in a knowledge base using a proper conceptualization, however, cannot take place without first overcoming some obstacles: information bias (lack of willingness to share knowledge and availability of knowledge) and knowledge extraction [150].

Matsunaga and Nakazawa [130] propose an adaptive HMI, something that will be followed along the research project. In addition, plant conditions might change significantly along the years due to layout changes, new products, innovation in the manufacturing process, or information systems. In this sense, the solution to be developed shall be able to adapt to those changes which means that needs to have a kind of self-learning process, incorporating intelligence through the system. An effective decision support system is achieved efficiently when integrating knowledge into the decision making process [150]. Typical knowledge based systems, and derived types such as expert and fuzzy systems, are comprised of the following system elements: knowledge acquisition subsystem, knowledge base, case specific database, inference engine, explanation subsystem, and user interface [158].

Accordingly to Michalewicz *et al.* [159], real-world applications operate in dynamic environments, where it is often necessary to modify the current solution due to changes in the problem setting, such as machine breakdown or employee illness, or the environment, such as consumer trends or changes in weather patterns or economic indicators. Handling flexibility in an ever changing manufacturing environment is one of the key challenges for a successful industry [160]. Researchers have found one answer to these questions through the attempt to solve a basic design problem, called the stability-plasticity dilemma, faced by all intelligent systems capable of autonomously adapting, in real time, to unexpected changes in their world [161].

For this reason, it is important to research on adaptive algorithms that do not require restart every time a change is recorded. However, one has to take into account that standard evolutionary algorithms get stuck on a single peak, diversity preservation slows down the convergence, random immigrants introduce high diversity from the beginning, but offer limited benefits, memory without diversity preservation is counter productive, and non-adaptive memory suffers significantly if peaks move [159].

Carpenter and Grossberg [161] also mention that one of the central goals of computer science is to design intelligent machines capable of autonomous learning and skillful performance within complex environments that are not under strict external control. Many scientists have turned to a study of human capabilities as a source of new ideas for designing such machines. When a scientist undertakes such a study, he/she encounters a number of basic issues, of which everyone is aware through our own personal experiences.

Many authors [162, 163, 164] suggest the use of artificial neural networks to approach this self-learning need. Conventional methods cannot be used to uncertain plant which could not be expressed as an acceptable or useful model. On the other hand, fuzzy logic controllers (a type of artificial neural network) which do not require analytical or accurate model of the controlled process have demonstrated a number of successful applications. Perhaps the most important application field where fuzzy logic plays a significant role is the control of complex industrial processes. In general, these processes may be strongly nonlinear with considerable time delays, wide range time constant and asymmetric gain characteristics, operating under the influence of strong non-stationary noise or uncertainties, and conventionally controlled by a human operator due to its complexity [163]. However, the process of learning and tuning the linguistic rules to achieve the desired performance remains a difficult task. The learning task may include the identification of the main control parameters or the development and tuning of the fuzzy membership functions used in the control rules.

The artificial neural network is a representation that attempts to mimic the functionality of the brain, and its model and control system have the following characteristics: a strong robustness, fault tolerance, universality, parallel distributed processing, learning and adaptive abilities [163] Fuzzy logic has an essential role in defining an enhanced expected gift

evaluation, improving the target selection procedure and evaluating the strategies [153].
Li and Lee [165] suggest the use of a cluster-based self-organizing neuro-fuzzy system for control of unknown plants. The neuro-fuzzy system can learn its knowledge base from inputoutput training data. A plant model is not required for training, i.e. the plant is unknown to the self-organizing neuro-fuzzy system.
The motivation for developing a decision-model is to determine the most suitable level of automation. Determining a suitable level of automation can provide a manufacturing system with the flexibility needed to respond to the unpredictable events that occur in factory systems such as machine failures, lack of quality, lack of materials, lack of resources, etc. [160]. The level of automation employed in semi-automatic systems is crucial, both to system performance and cost [166]. Frohm [167] has establish seven different levels of automation for inspection systems, from totally manual to totally automatic. He also refers that the relationship between humans and technology can be viewed as a continuum from fully manual to fully automatic by approaching the sharing of tasks between the human and technology. Research has shown the importance of integrating humans and technology in manufacturing automation, thus supporting sustainable and robust manufacturing systems [168]. There is also the need for developing tools which support alignment of both strategy and operational levels for re-configuration of automation levels.

Chapter 3

Proposed Solution for Tire Inspection Process

The current tire inspection process has the inherent complexity associated to a human-based process. The presence of humans in the inspection process introduces some level of subjectivity to the inspection process. The nature of the product, essentially made of a natural product like the rubber also contributes to that complexity and subjectivity. A product made of a natural material implies a significant level of variability in the manufacturing process and makes the quality process control hard to do and to estimate. For that reason, final product inspection is required to guarantee the desirable level of product quality demanded by the customers. Humans are crucial in this process since they develop cognitive skills along the time which allows them to enhance their performance. However, human-based processes are influenced by the performance of each individual which is not constant among the different people and it is not also stable for each individual along the time. Human's performance is affected by several factors, some of them external to the individual and some others inherent to each personality.

The tire inspection process involves a significant level of complexity that advises a careful approach to the system development whenever a process improvement is desired. In one hand, one shall identify the tasks in which humans do not add special value to the overall process, those that are repetitive, boring, and error prone. On the other hand, due to the nature of the product to be inspected, flexibility, deep knowledge of the acceptable product variations, and rapid adaptability to process changes are required.

The proposed solution for the improvement of the current tire inspection process intends to combine these two realities. The idea behind the proposed solution in not to replace humans by automation but rather complementing and enhancing the capabilities of humans and providing automation as a tool to take better decisions. The know-how and experience of the VI in the current inspection process cannot be dismissed. By the contrary, it is of the most importance to keep them in the inspection process as well as collaborating with them in the solution development. Longenecker *et al.* [169] state that "productivity trough people is the name of the game". In that study, they also highlight the importance of having a work force motivated, educated, and committed, in compliment with technologies to achieve the success. Without a work force aligned with these principles, long-term success "will be a struggle".

The proposed solution for the new tire inspection process derives from the actual inspection process presented in 1.3.2 and it is shown in Figure 3.1. One splits the process flow into two main categories: the physical flow and the data flow. The physical flow corresponds to the transport and handling of the tire. The data flows corresponds to all data flow needed to link each sub-process and always integrated with the physical flow.

The tire trimming task, currently integrated in the tire inspection process, is now a separated process. Special attention shall be dedicated to this process in the future in order to minimize the impact of this process in the overall tire inspection process costs.

After the tire is correctly trimmed, the object goes to the tire image acquisition process. There, a set of vision technologies and handling solutions are used in order to obtain the tire image data necessary for the following steps. Each tire belongs to a specific article and it has a particular configuration, stored in the Database (DB) of the system that indicates the features for the tire image acquisition station to perform a correct and complete tire image acquisition. The parameters include the distance between the two walls, the pressure target for the presser, the rotation speed, and the relative position with respect to the tire sidewall height for the manipulator to place the equipment in the tire interior. The tire image acquisition station can be a single station or a set of stations depending on the technologies used and the process characteristics (space, timings, etc.) that optimizes its use. When the information of the tire is gathered, the tire is placed in the conveying system and the data acquired is stored in the DB.

The following sub-process is the so called Automatic Tire Identification. This is an automatic process that gets the data from the tire and runs a set of algorithms with the aim of correctly identify the tire. A correctly tire identification involved the identification of the color lines painted in the tire tread and the DOT characters recognition. The mold number and the tread segments number are also identified for process tracking. Whenever the tire is not correctly identified, the tire shall be sent to the grading station. The tire might not be identified due to tire imperfections or by the inability of the automatic system to do so. When the tire is correctly identified, the following steps are then possible to run. The automatic tire detection sub-process runs a set of algorithms to determine the areas where the actual tire image differs from the tire image reference. The tire image reference is an

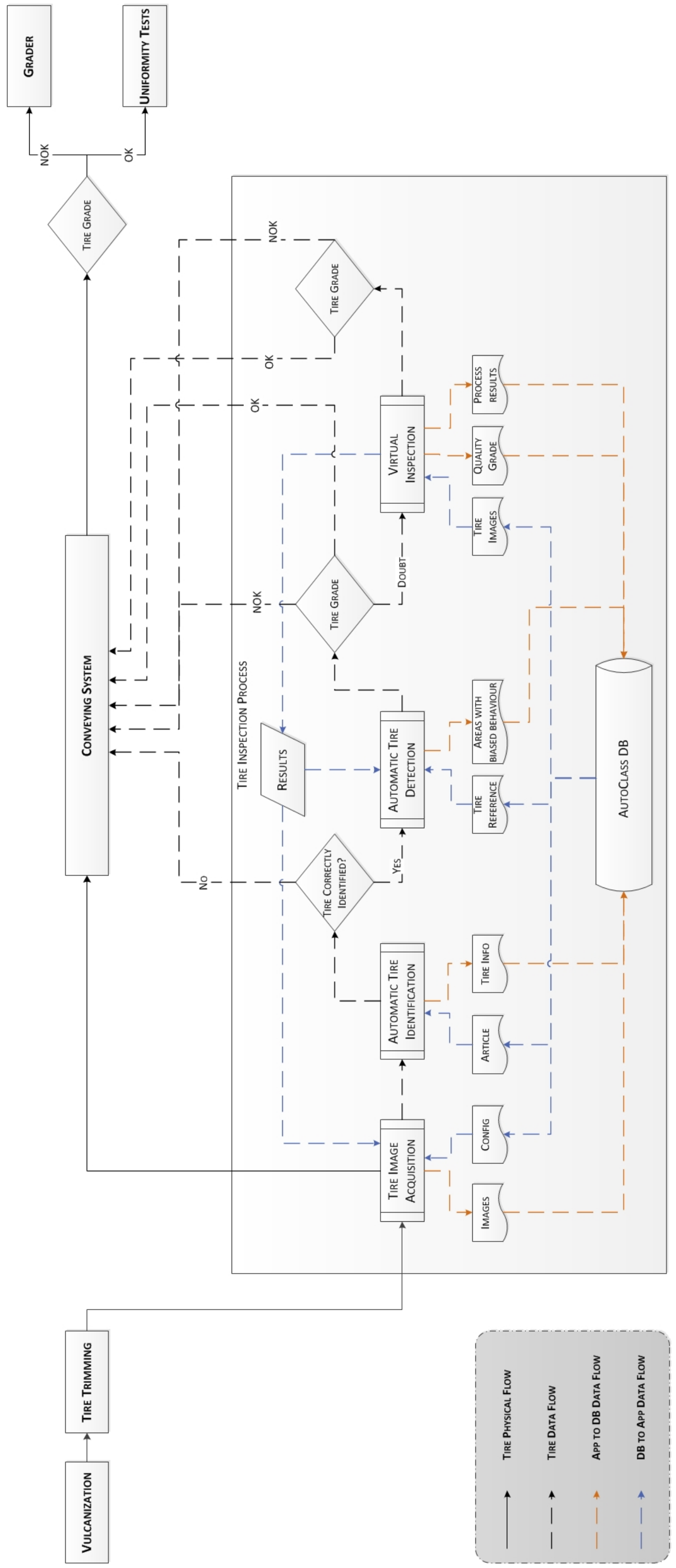


Figure 3.1: The new inspection process flow suggested for the Tire Inspection process

image or a set of images of OK tires from the same article acquired and validated by an experienced person. Any biased feature of the image identified by the system is stored in the DB. Depending on the level of confidence of the system in the areas identified, the tire can be classified in three categories: OK, NOK, or doubtful. For OK and NOK categories, the tire is driven to the uniformity tests process or grading station, respectively. When the system has no guarantee about the quality grade of the tire images, the data is sent to the virtual inspection sub-process.

In the virtual inspection, the operators are responsible of inspecting the tire images (or the image portions obtained from the automatic tire detection sub-process) and taking a decision over the quality grade. The different data resulting from this sub-process (quality grade, inspection time, areas of imperfections, etc.) are stored in the DB. Depending on the quality grade, the “physical” tire is driven to the correspondent process.

One of the main advantages of this approach is the capacity the system has to provide feedback to the different sub-processes. The results of the virtual inspection, provided by the operators can feed the automatic tire detection sub-process as well as the tire image acquisition system. One can look to this solution as a platform where continuous process improvements might be expected. In the first phase, the virtual inspection can serve as a validation tool for the tire image acquisition station and for the automatic tire detection sub-process. The operator’s capability of taking correct decisions over the tire images allow the developers to identify improvement areas for the tire image acquisition station (e.g. changing the lighting position in order to better enhance certain areas of the tire). Moreover, the areas identified by the automatic tire detection sub-process might be compared with the areas identified by the operators in the virtual inspection sub-process.

After the validation phase, the virtual inspection results can provide added-value information for the automatic tire detection system by means of image features that allows to identify the potential areas of imperfections. The time needed to improve the automatic tire detection can be extensive but the way the process is designed guarantees that continuous process improvement is possible without the need of process changes. An iterative process is established and small increments in the level of automatic decisions might be introduced with low risks once the system is able to validate those changes before one decides to put it online.

Along the chapter, one will present the proposed solution for the final inspection as well as some necessary validation processes used along the development process.

3.1 General System Architecture

The complexity associated to the new tire inspection process solution requires an adequated architecture to support all its features. The two sub-processes where this document is focusing are the tire image acquisition sub-process and the virtual inspection sub-process. The general architecture presented in Figure 3.2 answers to the requirements and needs identified for the new tire inspection process. It is a modular architecture where each feature of the tire image acquisition station runs in a specific application.

The two sub-processes are logically linked by a central DB (AutoClass DB) where all the information is gathered and introduced.

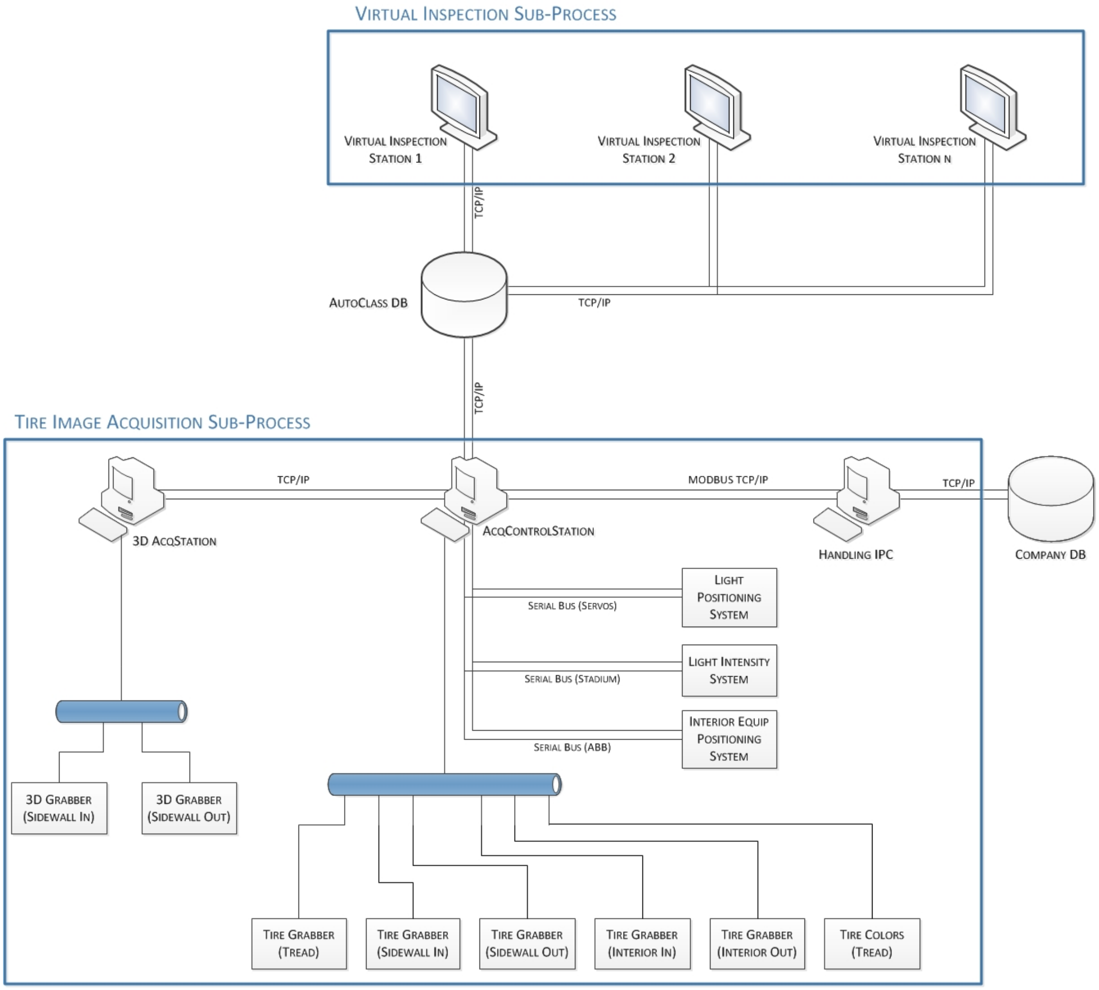


Figure 3.2: General system architecture for the tire inspection process

The virtual inspection sub-process has a quite simple architecture. It is composed by a set of workstations each of them equipped with a desktop with a touch screen solution where the users are able to take decisions over the tire images provided by the DB. Each tire image can be observed in one or more virtual inspection stations depending on the configuration used.

The tire image acquisition sub-process has a bit more complex architecture. The central point, where the main application is running and manages all the data flow in this process is the *AcqContolStation*. This station is connected via Transmission Control Protocol / Internet Protocol (TCP/IP) with the *3D AcqStation* and via Modbus TCP/IP with the *Handling Industrial PC (Personal Computer) (IPC)*. The *3D AcqStation* manages the acquisition of the 3D data gathering, i.e. the 3D Grabber applications. Each 3D Grabber application has a 3D laser scanner solution responsible for the 3D data acquisition of the tire sidewall inside and sidewall outside. These 3D laser scanner solutions are connected in a Gigabit Ethernet (GigE) bus. The *Handling IPC* is the tire handling control station which is in charge of the complete handling control (tire rotation speed, machine parts adjustments, etc.). There is also a connection to the company DB in order to generate process data reports. In future implementations of the process, this DB can provide additional data for the tire identification and tire configuration for the tire image acquisition station.

In the *AcqControlStation* all the 2D solutions are linked through a GigE bus, each of them running a Tire Grabber application concerning each tire surface (tread, sidewall inside, sidewall outside, interior inside, and interior outside). An additional application for the color lines identification (Tire Colors (Tread)) is also connected to the GigE bus. Additionally, in order to control the remaining systems (lighting intensity and positioning, and manipulator commands) three serial bus (Universal Serial Bus (USB) or serial port) connections are established for each application. Whenever the system is fully industrialized, the connection between the main application and each sub-system (lighting positioning and intensity, for instance) might be done by other communication link depending on the solution adopted for these systems. The main application that implements the overall flow chart is running in the *AcqControlStation*. The other applications send/receive data according to the commands from the master application.

3.1.1 Tire Image Acquisition System

The tire image acquisition system is an essential part of the new tire inspection process. This system is in charge of the tire image acquisition for the remaining sub-processes. The quality and consistency of the image acquisitions along the time are of the most importance.

The system is composed by a handling solution (Figure 3.3) that is responsible for the tire handling and the guarantee of good and constant conditions for the image acquisition. The machine adjustments are dependent on the specific tire and each article has its own recipe stored in the AutoClass DB.

For the image acquisition, 2D vision solutions are used to acquire the information from all tire surfaces. Additionally, 3D laser scanner solutions are adopted to complement the information gathered for the tire sidewall (inside and outside) and bead areas. Cameras are triggered by an external signal controlled by hardware, guaranteeing that all cameras start the acquisition at the same time. The lighting intensity and positioning target are also controlled by hardware in order to grant the proper light conditions for the tire image acquisition. Each article has a recipe with all the parameters needed for the lighting configuration.

Figure 3.3: Image acquisition station: overview of the structure used in the prototype

A manipulator is used to place the equipment (2D cameras and lighting) inside the tire for the acquisition in the interior (Figure 3.4). The placement depends on the tire dimensions which are sent by the *AcqContolStation* application.

An overview of the flow chart developed for the *AcqControlStation* application is shown in Figure 3.5. It considers some process steps only used during the development phase,

Figure 3.4: Image acquisition station: detail of the use of manipulator to place the equipment in the interior of the tire

like the possibility to re-acquire tire images in certain circumstances. For each new acquisition cycle, the user has to read-out the barcode placed in each tire sidewall (inside). This value is used in the AutoClass DB has the primary key for each tire acquired. The barcode value is an unique value that can identify each article. In the tire image acquisition station, if the barcode already exists in the DB this means that the tire has been already acquired before. However, one might need to re-acquire the images (replacing the previous images stored in the DB) in order to enhance the image quality or correct lighting positioning.

The next step consists in introducing the mold number and the DOT information. This is introduced in the first phase of acquisition with the aim of validating the tire identification system with these data.

Whenever the tire contains an imperfection, the user shall identify the NC code. The NC code is classified by the grader and this information is only used in this phase to have a reference information for further validation of the virtual inspection and the automatic tire detection systems.

After all this information is inserted, the system is able to perform the correspondent setup of the machine and lighting as well as the image acquisition. At the end of this process, the application shows the images acquired for a preliminary assessment. Along the development phase, if the images are with no sufficient quality, one needs to re-acquire images of the tire. If the images have good quality and all the imperfections (whenever the tire is NOK) are visible, the user has to tag the NC in the correspondent image and indicate the respective NC code.

The setup and acquisition process step requires a set of commands which are organized in a flow chart like the one presented in Figure 3.6. When the structure is free to receive a new tire, the user introduces it and the system checks whether the configuration for that specific article exists or not. The result depends on the previous acquisition of the same article.

When the configuration already exists, the system automatically load the values and adjusts the machine parameters and then the lighting parameters (intensity and positioning). Whenever the article is firstly acquired in the tire image acquisition station, the system does not know in advance which configuration is the most suitable for the tire. In this situation, the system entries in the *Config* mode where the user is able to perform the necessary adjustments to the machine (flow chart in Figure 3.7a) and to the lighting (flow chart in Figure 3.9a) in order to get an adequate tire image from the different surfaces. With regard to have some feedback about the image quality, the system provides the user with the image histogram and the correspondent average, median, max and min values for the image Region Of Interest (ROI) (see Figure 3.8). One shall define the configuration as much as possible considering similar values among the different tire grabber applica-

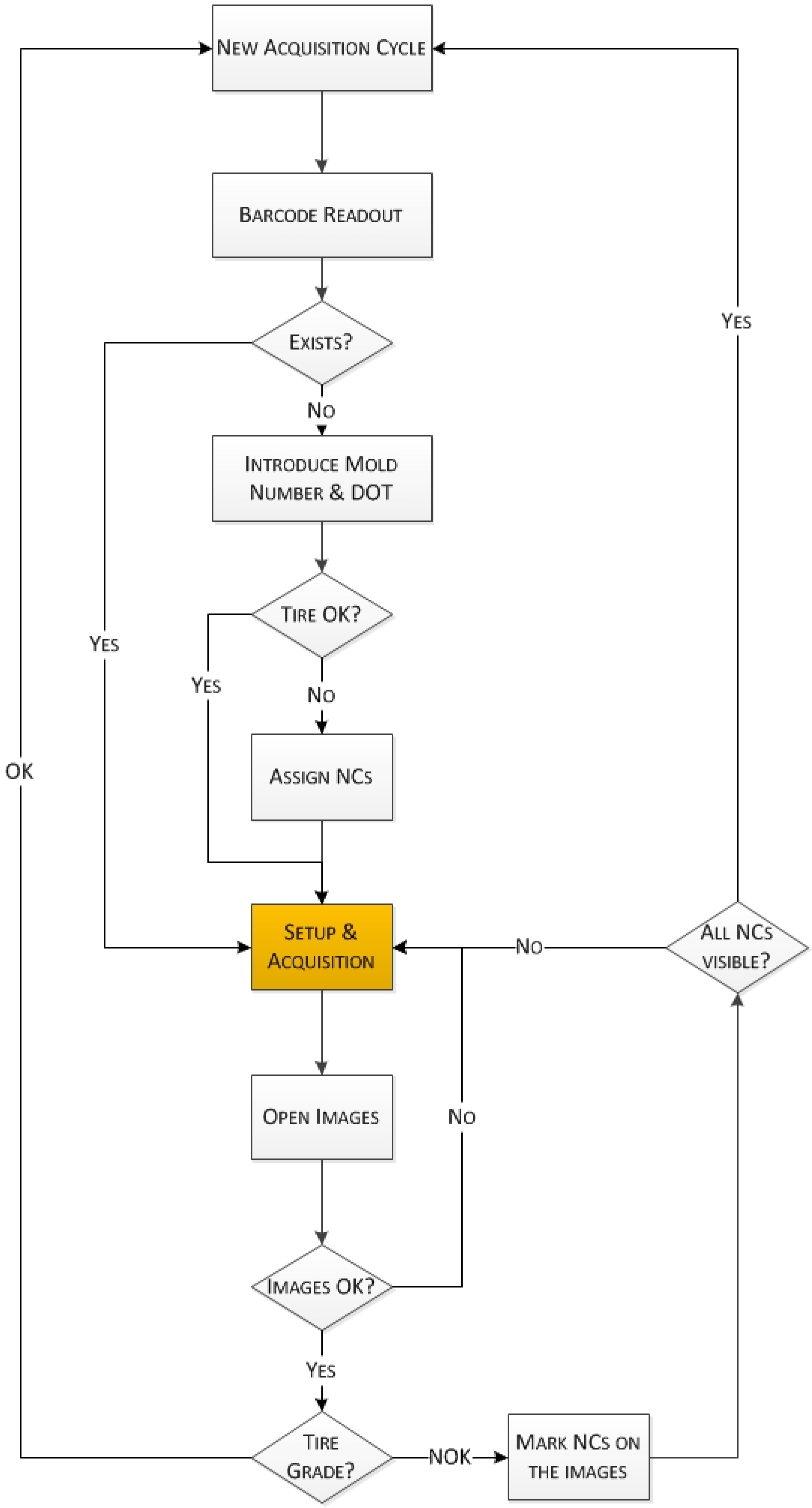


Figure 3.5: Flowchart of the acquisition control station application for the tire image acquisition station during the development phase

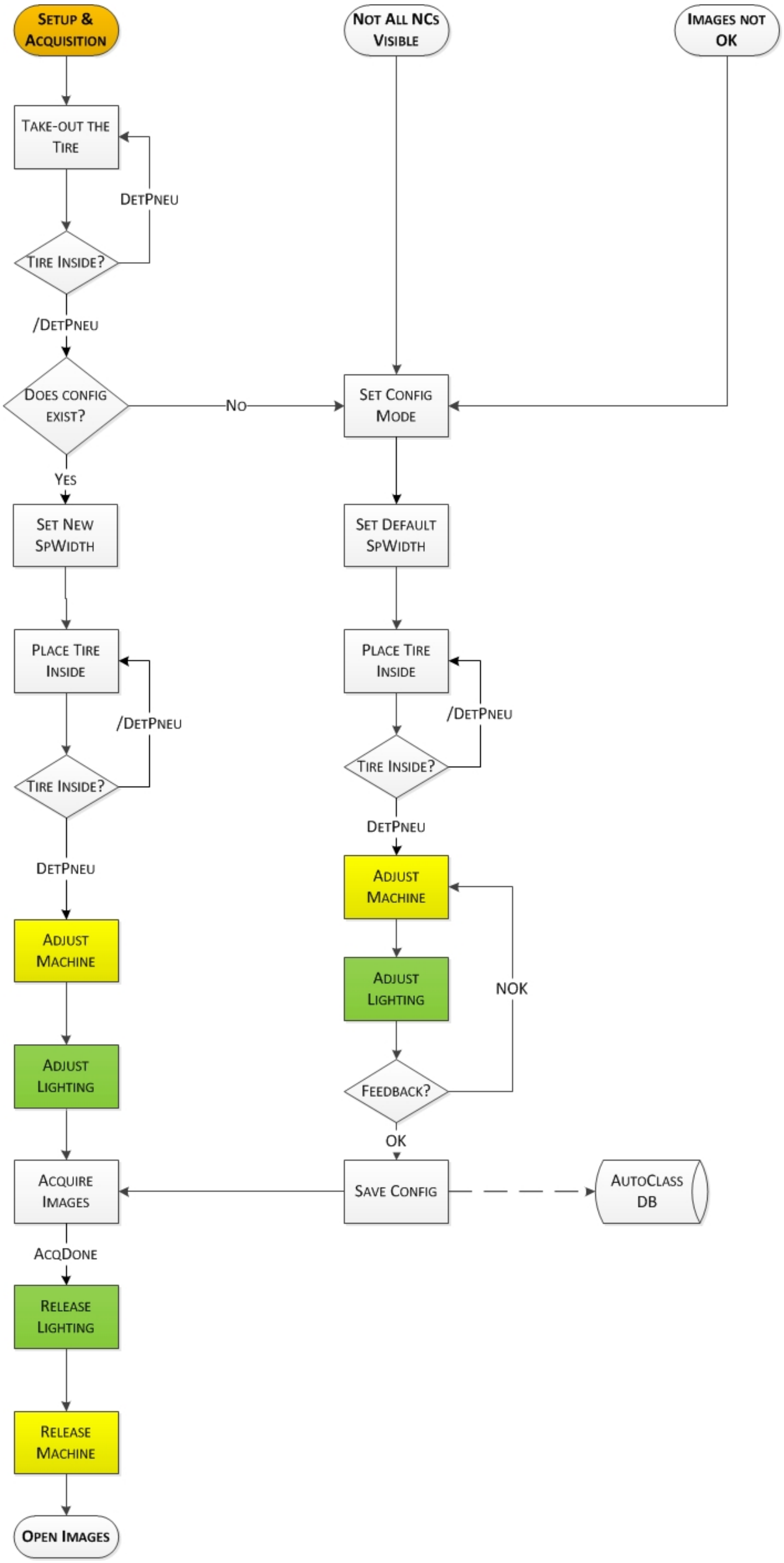


Figure 3.6: Setup & Acquisition flow chart

tions as well as avoiding under or over exposed areas. At the time the user considers that conditions are appropriated, one saves the configuration into the DB and the acquisition start command is sent to all applications.

The number of frames to be acquired by each tire grabber application depends on the tire dimensions. All tire grabber applications acquire the same number of frames, once all cameras work at the same frame rate and they are configured to acquire with the same image resolution. Whenever the acquisition is done, the tire grabber applications sent a signal to the *AcqControlStation* application. At the time, the *AcqControlStation* application sends an order for the release of the lighting system (Figure 3.9b) and for the machine release (Figure 3.7b).

For the industrial implementation of the solution, one suggests to follow the flow chart presented in Figure 3.10.

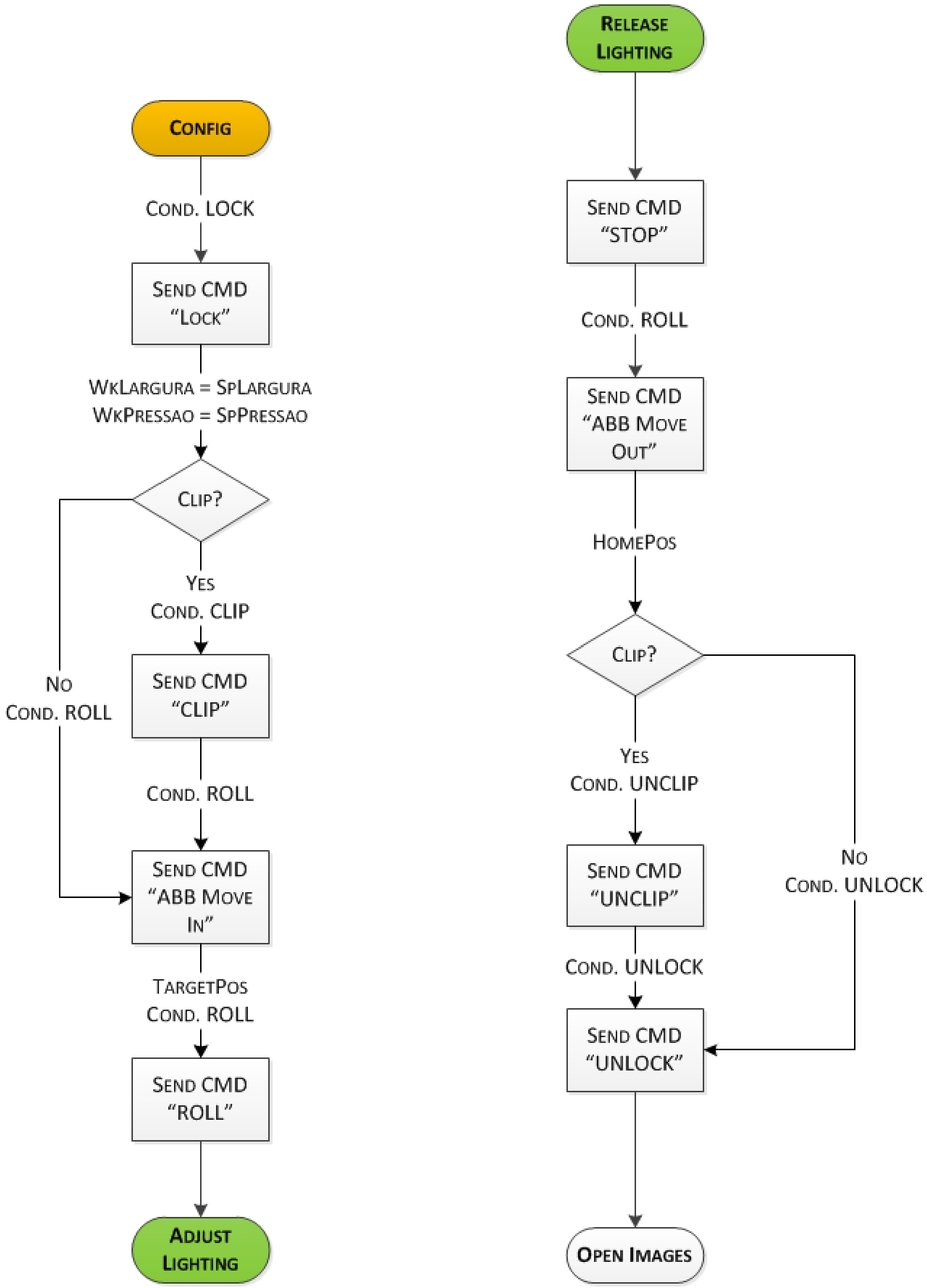
3.1.2 Tire Virtual Inspection

The idea of the tire virtual inspection implementation might be seen in two different development steps. In the first one, the virtual inspection shall be seen as a computer assisted manual inspection. In the second step, the tire virtual inspection intends to be an enhanced manual inspection.

In the first step, one intends to use high-resolution images and 3D representations of tires as basis for the operator's assessment, providing them better conditions to visualize imperfections. Better conditions granted by better ergonomic conditions and for showing images with all the details revealed in high-resolution. In the first step, one wants also to make use of the exhaustive knowledge of VI as the starting point of the system development, enrolling the operators in the development process.

In the second step of development, the virtual inspection shall be seen as a decision-support system that allows operators to perform the inspection in a faster and more effective way. Based on historical data from previous inspections and the output from the tire automatic detection system the tire virtual inspection tool can actively select specific areas of interest, in particular highligthing the imperfections. Along this step, one intends to value the collaborative work between the operators and the system.

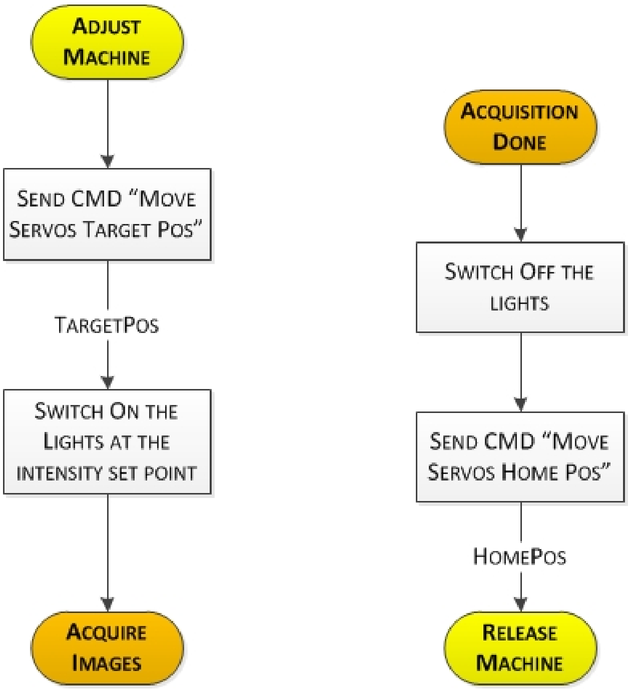
By using the tire virtual inspection, one expects to reduce the overall costs of the tire inspection process once operators can be faster by the fact that they only have to inspect the tire without handle it and the system might only show them parts of the tire image instead of the entire surface. It can also enhance the quality of detection by providing better inspection conditions. The virtual inspection can create additional advantages and flexibility for a company. By virtualizing the object of inspection, one or more operators



(a) Adjust machine (b) Release machine

Figure 3.7: Handling configuration flow chart

Figure 3.8: Tool available in the tire grabber applications to support the lighting setup



(a) Adjust lighting (b) Release lighting

Figure 3.9: Lighting configuration flow chart

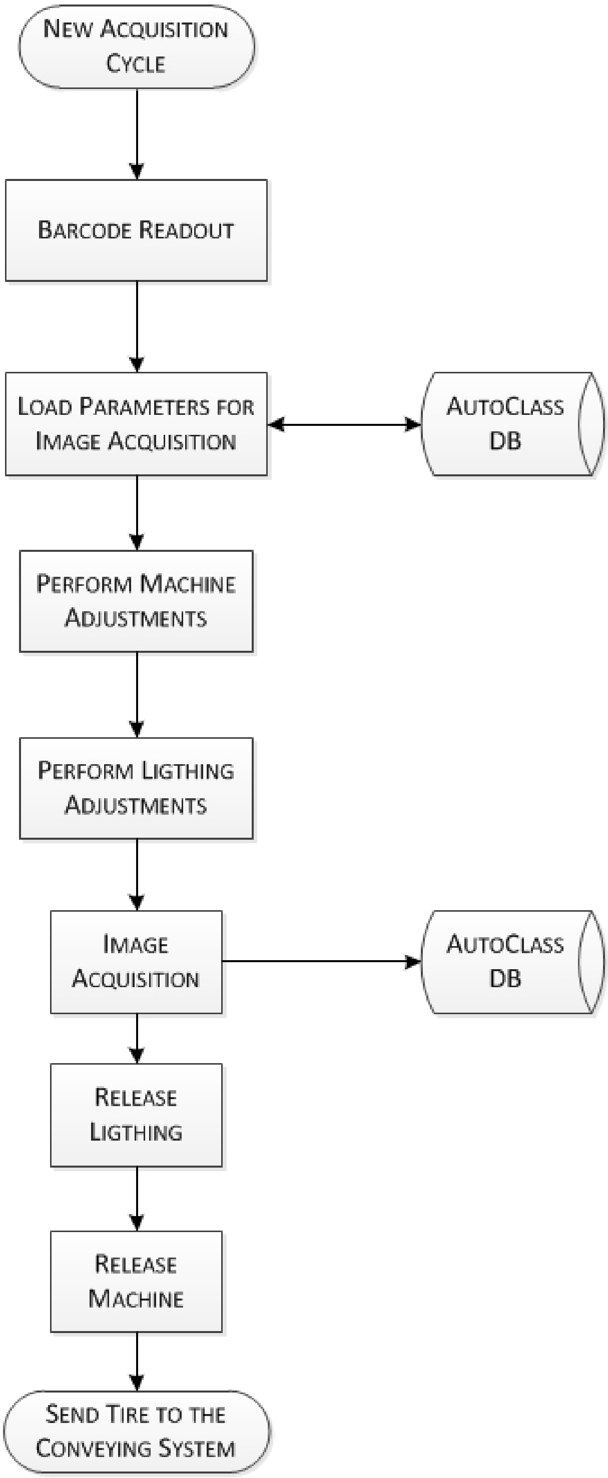


Figure 3.10: Suggested flow chart for the industrial implementation of the tire image acquisition station

can look to the same tire images. The system can store the images of each tire, resulting in a powerful tool for the Quality department with respect to product assessment and costumer complaints. The tire virtual inspection also allows personalized training system for each operator based on the images acquired. Moreover, with the aim of reducing the process mistakes and enhance the process traceability, the tire virtual inspection assures an integration between detection and decision as well as quicker detection and reaction to potential problems in the manufacturing process.

However, such a significant process change might be restricted by the inherent reluctance to change by humans and for the technology adoption issues. One of the most doubts when adopting this approach is the importance of haptics in the tire inspection process. Currently, operators make an extensive use of haptics to assess the tire quality, especially in hidden areas for their vision (e.g. tire interior or buttress). Nevertheless, the design of the interface under the virtual inspection environment shall be done in order to overcome these issues.

The tire virtual inspection workstation will be composed by a desktop. The interface between the application and the operator might be done with a joystick, a mouse, a keyboard, or a touch screen technology. The decisions upon the most suitable interface shall be done by performing additional experiments. Using touch screen technology seems to be suitable for the interface although some aspects related to its use, in particular to its maintenance shall be carefully analyzed in order to avoid undesired issues. The details about the interface design are presented in Chapter 5 and an overview of the prototype station installed in the plant is shown in Figure 3.11.

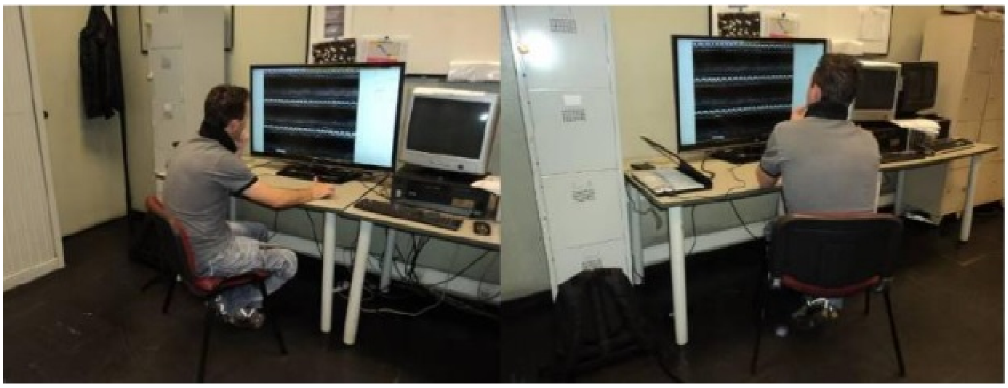


Figure 3.11: Virtual Inspection station: overview of the prototype

3.2 System Validation

One of the key aspects whenever a new system is developed is its validation. In one hand, one must prove the concept and its suitability to solve the problem in hands. In the other hand, in cases where the objective is to improve the actual process, a comparison with the actual performance is required.

The proposed solution comprises some sub-processes, each of them with its particular characteristics, with different impacts in the overall solution. The system validation must not only prove that each sub-system fullfils the requirements for which it has been developed but also that the overall system, as a composition of the diverse sub-systems, can achieve the desired performance as a whole.

3.2.1 Methods for System Validation

The methods used for the system validation will only focus on two sub-systems: the tire image acquisition station and the tire virtual inspection.

Regarding the tire image acquisition station, three main questions arise:

1. What is the cycle time of the tire image acquisition process and is it compatible with the cost savings objectives?
2. Is the tire image acquisition station able to process all tires, independently of its dimensions?
3. Do the images contain all the relevant information for an accurate detection of the imperfections?

In order to answer to the first question, one shall first establish the target criteria that enables the system performance to be aligned with the cost savings objectives. The target for the total acquisition process time has been identified, under the AutoClass project, to be between 5 to 15 seconds. To validate the performance of the system with respect to this feature, one has to incorporate the measurement of the time elapsed between the starting command and the signal provided by the system whenever the acquisition is finished. In addition, the time correspondent to the tire image acquisition is also measured. This is done to gather the time spent in the system while the tire is rotating in order to validate the expected time for the tire image acquisition which is dependent on the tire dimensions.

To answer to question 2, a variety of tires with many different dimensions (tread width, rim size, and sidewall height) are tested in the tire image acquisition station. The ability of the prototype to process the tires guarantees that the handling solution as well as the image acquisition systems are adequate for the tire image acquisition station.

The answer to the third question is something quite sensitive to the user who evaluates the tire images. In order to overcome this constraint, one uses the results of the virtual inspection to validate the adequate quality of the images obtained in the tire image acquisition station.

One of the most important aspects to be taken into account for the system validation process is the definition of the sample. It shall accurately represent the overall population (tire production in the plant) but shall also guarantee the reliability of the results one wants to gather. In this sense, in order to answer to question 2 and 3, at least 3 tires from the same article shall be selected. Three is the minimum number of instances that guarantees 95% level of confidence in the results obtained. For each imperfection, three tires shall be selected, each of them with the following criteria:

- One tire with an imperfection just below the rejection criterion
- One tire with an imperfection with an average behavior
- One tire with an imperfection just above the scrap criterion

The selection of the tires with imperfections must be done by experts like the graders.

At the same time, the sample shall guarantee a ratio of 9:1, i.e. 9 tires OK for 1 tire NOK, once the manufacturing process produces a ratio of 90% OK tires and 10% NOK tires. The number of NC codes in the plant is about 70, although some of the NC codes only show up rarely. Nevertheless, the total number of NOK tires shall be around 200 tires, i.e. the number of OK tires shall be 1800. In total, the prototype shall process 2000 tires randomly selected in order to validate the tire image acquisition system.

Regarding the validation of the tire virtual inspection system, there are two main questions to answer:

1. Are the inspectors capable of inspecting tires in the virtual environment with a comparable level of quality?
2. Is the cycle time of the tire virtual inspection compatible with the cost savings objectives?

To answer to these questions, the same sample used for the validation of the tire image acquisition station is considered for the validation of the tire virtual inspection system.

In order to answer to both questions, the tire virtual inspection system is able to store all the relevant information to perform the correct analysis: inspection time, user's decision, and imperfection marking location. The inspection time is measured and compared with the target (pointed to be between 7 to 13 seconds according to the cost model developed under the AutoClass project). The decision taken for each image is recorded as well as the regions of potential NC marked by the users. The regions of NC tagged by the operators are then compared with the reference regions marked in the tire image acquisition station.

3.2.2 Design of Experiments

The DoE is a critical step for the system validation. In one hand, one wants to be able to fulfill the requirements for the system validation, but on the other hand one must take into account the restrictions imposed by the manufacturing process. Interference with the standard process flow must be minimized in order to reduce the impact of the experience in the process performance.

The very first issue to consider is the selection of tires taking into account the requirements for the sample size and characteristics. The trigger for the tire selection is the grading station where all NOK tires are driven. At each day of the experiment, a list of the desired NC codes to be segregated are delivered to the grading station. Roughly six different tires for two different NC codes are requested and separated. Identifying the tires and the respective cavity where they are produced, three more tires from each of the cavities where the NOK tires were produced are especially marked to be easily identified in the tire inspection process. One assumes that those tires have a high probability to be classified as OK. Additionally, six other cavities are randomly selected and in each of them four tires are tagged in the same way as the previous. Once again, it is assumed that those tires have a high probability to be classified as OK. All the tires are inspected and assessed by the VI and the grader. The tire quality grade evaluated by the actual tire inspection process is the reference information for the overall system validation. The procedure shall last until the sample size is achieved, always trying to guarantee a ratio of 9 tires OK for each NOK tire.

Everyday, around 50 tires are scanned in the prototype with a roughly ratio of 9:1. For the tires with imperfections, the NC code and its location in the respective image is stored in the DB according to the assessment done by the graders. The image acquisition time and the total process time (includes the tire handling) is registered for further analysis. The images are then passed to the tire virtual inspection system where 6 operators, two from each shift, previously trained to work with the interface, perform the tire inspection based on the information provided in the tire images. The decision and the location of the NC is stored in the DB. The operators are randomly selected in each shift with the only concern of guaranteeing similar performances (rejection rates and inspection pace) among them. The comparison between the NC location of the reference and the ones tagged by the operators in the tire virtual inspection system allows to analyze the accuracy of the image information.

For the validation of the virtual inspection system, an additional group of six operators, the control group, are randomly selected to perform the tire inspection like in the current inspection process. The same sample of tires is used both for "physical" inspection and for virtual inspection, and both timings and decisions are registered. The six operators from the control group are selected with the same approach followed to the ones in the virtual inspection group, guaranteeing some uniformity among them and choosing two operators per shift. At the end, the performance of each group is compared.

Each session for both groups shall last around 45 to 60 minutes, depending on the inspection pace of the operators. In total, in each shift, one expects to take 4 hours of productivity from the tire inspection process.

3.2.3 Statistical Analysis

The amount of data to be generated along the experiment is considerably high. The data manipulation shall be done in order to get the appropriated information for the analysis and to be able to take conclusions about the correctness of the validation process and the proof of concept one expects to reach.

All the data registered along the process is stored in the AutoClass DB which as a structure like the one presented in Appendix A. From the information stored in the DB is then possible to generate a set of reports that enables the analysis of the results and the possibility to perform the system validation.

For the tire image acquisition system, one will analyze the influence of the tire dimensions in the image acquisition time as well as in the overall process timing. The average values will be taken once the standard deviation tends to be minimal. The sample size and the number of acquisitions for each NC code are also obtained.

In the virtual inspection system, both the decisions and the inspection times are stored. Due to abnormal behaviors (e.g. breaks in the middle of the sessions, energy shutdowns, etc.) the median value of the inspection time will be considered. In addition, the reports to be generated will also take into account other important aspects that can influence the performance of the virtual inspection like the tire quality grade, the image length size, or the tire surface in analysis. The changes in the virtual inspection interface design are also identified to understand the impact of those changes in the overall performance. Once the experiment will last for around 40 sessions, it will be also possible to verify the influence of the experience (learning curve) in the tire virtual inspection system performance.

Chapter 4

Technology Solutions Analysis

One of the key aspects one faced along the project is the need of select the most suitable technologies for each application. This issue becomes even more critical considering the fact that multiple technical solutions can be applied and they shall be integrated simultaneously. Moreover, the particularity of developing a research project that aims to provide a prototype able to be tested in an industrial environment which means the capacity to work under agressive environment conditions and guaranteeing the necessary feasibility, consistency and reliability, needs also to be taken into account. One has also identified the added-value of providing the decision-maker a suitable tool so that he/she is able to decide either to proceed to the next step, i.e. perform the industrialization of the solution suggested in this document, and in which conditions to realize it.

The literature is extensive with respect to technology selection processes, it is also true that very small attention is addressed to the transition between the prototyping phase and the industrialization phase. The aim of the proposed methodology is to have an integrated approach to the technology selection despite the specific context in which the technology selection process is performed.

4.1 Technology Selection, Integration and Deployment Methodology

In order to fulfill the expectations and the requirements for the technology selection process, one has developed a methodology for technology selection, integration and deployment. The methodology is presented in Figure 4.1.

One might summarize the methodology in two main phases: the technology selection phase and the context analysis phase. The technology selection phase comprises the identification of the most suitable technical solutions for the problem in hands as well as a

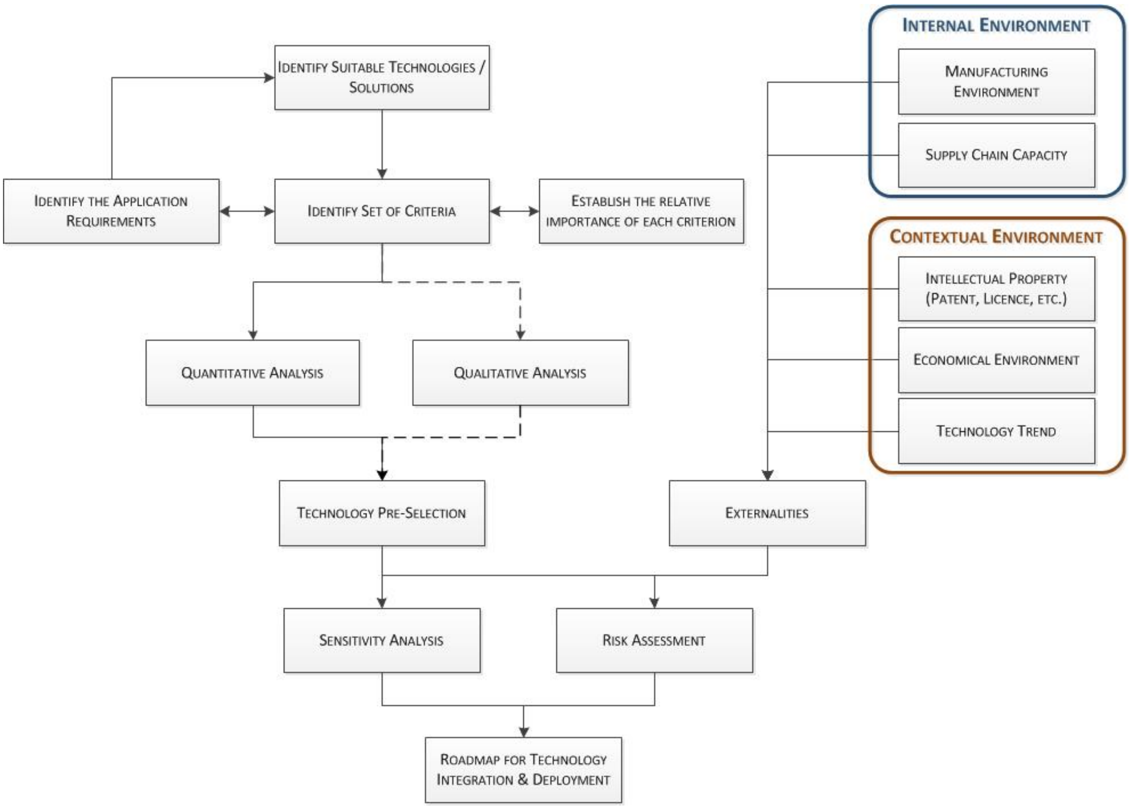


Figure 4.1: Technology Selection, Integration & Deployment Methodology

comparative analysis between the different solutions. The approach used at this part of the methodology is the AHP (Figure 4.2). The AHP allows a structured approach for organizing and analyzing complex decisions as the technology selection process. It is intended not to provide the optimal decision but the one that is more suitable for the problem in hands and that better fulfills the goals. It provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its factors, for relating those factors to overall goals, and for evaluating alternative solutions.

The context analysis phase intends to identify the internal and external enviromental factors that might contribute positive and negatively for the successful integration and deployment of the pre-selected technology. Combining the pre-selected technologies and the external enviromental factors it is possible to perform a risk assessment and a sensitivity analysis in order to offer the decision-maker an overall context in which the decision will have impact.

The final decision shall always be done by the decision-maker based on his/her risk profile and perception of the internal and external context. The methodology aims to facilitate the decision and provide enhanced knowledge to the decision-maker but not to replace him/her.

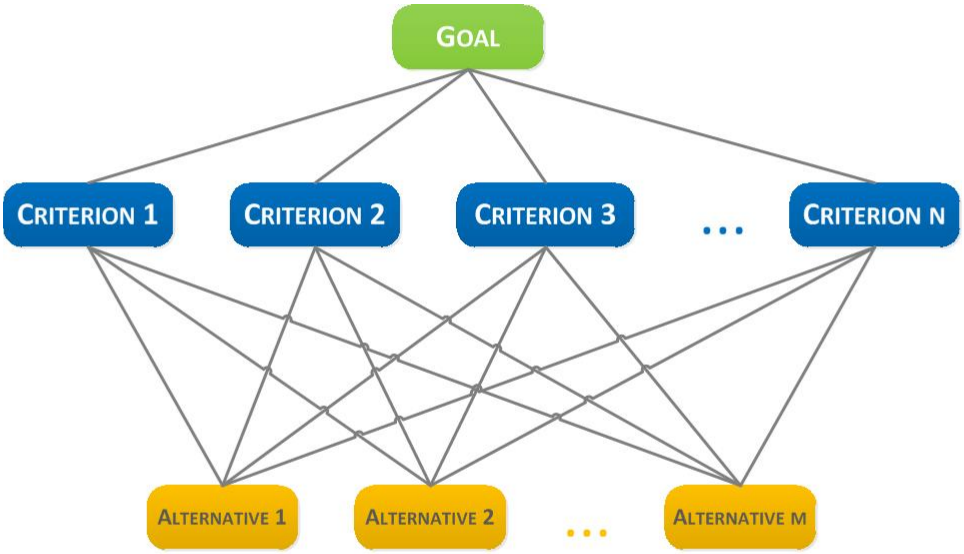


Figure 4.2: AHP methodology: general approach

4.1.1 Technology Pre-Selection Process

The technology pre-selection process intends to identify the possible technical solutions for the application in consideration and, at the end, to select the most suitable solution that better answers to the challenges imposed by the application and that also takes into account other important aspects like the cost, for instance.

The very first step to perform is to identify the application requirements, i.e. what are the needs that are critical to assure. In a inspection process, for instance, one has to assure that the object to be inspected cannot be modified or damaged but, at the same time, guaranteeing that the solution is able to correctly enhancing the features one is looking for. Other important requirements to take into account are process related: process time, space available, interface with other systems, etc. This is an essential step for the overall selection process, since all the inputs are inherent from the identification of the application requirements.

Finalizing the identification of the application requirements it is now possible to search for suitable technical solutions available. These technical solutions can vary from individual sensors to integrated systems that can partly or fully fulfill the application requirements. The vast number of technical solutions available for the user can significantly increase the amount of time spent in this process. However, it is up to the user responsible for this task to determine the amount of time that is spent in this step as well as the criteria to conclude the searching procedure. Moreover, the user shall also be aware that technology evolution will bring new or enhanced technical solutions that better fits in the application requirements.

Combining the application requirements and the suitable technical solutions identified in the previous process steps, one can identify the set of criteria that will be used to perform a comparison among the different technical solutions. One would like to be able to rank the criteria in order of importance, and to assign to the criteria some relative ranking indicating the degree of importance of each criterion with respect to the other criteria. If the number of criteria is relatively low (less than 3) then one might establish the relative importance (0% to 100%) of each. However, in the presence of multiple criteria in which is not so evident the relative importance of each and where inconsistencies might become significant, a systematic approach is required. Pairwise comparison is one way to determine how to evaluate alternatives by providing an easy and reliable means to rate and rank decision-making criteria. The use of pairwise comparison allows the user to establish the relative importance of each criterion to another, measuring at the same time the consistency level of the overall result.

In the pairwise comparison method, criteria and alternatives are presented in pairs of one or more referees [35]. One has to assess individual alternatives, deriving weights for the criteria, constructing the overall rating of the alternatives and identifying the most suitable one. Stating the alternatives by $\{A_1, A_2, , A_n\}$, where n is the number of alternatives in comparison, the correspondent weights by $\{w_1, w_2, , w_n\}$, and the matrix of ratios of all weights by

$$W = \left[{}^{w_i}\!/_{w_j}\right] = \begin{bmatrix} {}^{w_1}\!/_{w_1} & {}^{w_1}\!/_{w_2} & \cdots & {}^{w_1}\!/_{w_n} \\ {}^{w_2}\!/_{w_1} & {}^{w_2}\!/_{w_2} & \cdots & {}^{w_2}\!/_{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ {}^{w_n}\!/_{w_1} & {}^{w_n}\!/_{w_2} & \cdots & {}^{w_n}\!/_{w_n} \end{bmatrix} \tag{4.1}$$

The pairwise comparisons' matrix $A = [a_{ij}]$ symbolizes the intensities of the decision-maker's preference between individual pairs of alternatives (A_i *versus* A_j, for all $i, j = 1, 2, \cdots, n$), where the intensity values are selected from a given scale (see Table 4.1). The decison-maker compares pairs of alternatives for all possible pairs of the n alternatives given. A comparison matrix A (4.2) is obtained, where each element a_{ij} establishes the preference weight of A_i got by comparison with A_j.

$$A = [A_{ij}] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1j} & \cdots & a_{1n} \\ {}^{1}/_{a_{12}} & 1 & \cdots & a_{2j} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots & & \vdots \\ {}^{1}/_{a_{1j}} & {}^{1}/_{a_{2j}} & \cdots & a_{ij} & \cdots & a_{in} \\ \vdots & \vdots & & \vdots & & \vdots \\ {}^{1}/_{a_{1n}} & {}^{1}/_{a_{2n}} & \cdots & a_{in} & \cdots & 1 \end{bmatrix} \tag{4.2}$$

If the matrix A is absolutely consistent, then $A = W$ [86] and, for this particular case, the principal eigenvalue (λ_{max}) is equal to n. However, having an absolutely consistent matrix becomes difficult to obtain when the number of alternatives grows as well as the subjectivity analysis of the decision-maker is present. In this case, Saaty has established the Consistency Index (CI) as:

Table 4.1: Pairwise comparison intensity values and correspondent meaning

Intensity Value	**Definition**
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate value

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{4.3}$$

In order to measure the level of inconsistency, Saaty [86] proposes a definition for the Consistency Ratio (CR) as:

$$CR = \frac{CI}{RI} \tag{4.4}$$

where RI is the average value of CI for random matrices using the Saaty scale obtained by [35]. Saaty establish that only for CR < 0.1 the matrix can be considered as consistent.

Finally, with the aim of translating technical features into quantitative meanings, one shall select one of the technical solutions as reference for comparison and attribute a quantitative value for the remaining options with respect to the reference solution, based on a scale presented in Table 4.3.

The number of technical solutions can be significant high and one shall group the tech-

Table 4.2: RI values from [35]

n	RI value
3	0.5245
4	0.8815
5	1.1086
6	1.2479
7	1.3417
8	1.4056
9	1.4499
10	1.4854
11	1.5141
12	1.5365
13	1.5551
14	1.5713
15	1.5838

Table 4.3: Quantitative values to evaluate technical solutions

Value	Definition
1	Much worst than reference
1	Worst than reference
3	Equivalent to reference
4	Better than reference
5	Much better than reference

nical solutions by categories. In the case of an inspection system, the user might differentiate the object handling to be inspected (conveying systems, manipulators, etc.) and the technologies used for the inspection task. Although one solution for handling can conflict with the technology for inspection, one cannot compare technical solutions for different though complementary functions.

Based on the number of technical solutions identified by category, one can decide to perform a previous qualitative analysis over them, before a mandatory quantitative analysis. A qualitative analysis can be done in order to reduce the number of solutions to a more reasonable number. Although the qualitative analysis is more subjective and provides some hints about the usefulness of a certain solution, it might be convenient to use in order to become the quantitative analysis lighter. However, it is important to notice that one can disconsider some solutions at this preliminary step that can still be interesting to be analyzed.

At the end of the technology pre-selection process, one can expect a list of the suitable solutions identified in the beginning ranked according to their level of importance which is dependent on the criteria previously established.

4.1.2 Externalities Analysis

After pre-selecting the most promising technical solutions for the application, it is now time to perform an overall analysis over the context (environment) in which the application will take place. The decisions over the application or the technical solutions will be affected by the environment in which is inserted and each factor can have different impacts and probabilities to happen. Tavana and Banerjee [36] decompose the environment into three main categories: internal environment, transactional environment and contextual environment. Tavana and Banerjee [36] refer to Internal Environment as “factors within the organization that are controllable“; Transactional Environment as “the layer closest to the organization including factors that have direct transactions with the organization on a regular basis and are semi-controllable“; finally, the Contextual Environment as “factors outside the organization with which the organization interacts indirectly and are essentially uncontrollable“.

A simplification of this decomposition is suggested. The combination of Internal and Transactional Environment can be advantageous once it is not always clear the difference between these two categories.

For each of the environments (internal and contextual), one has to choose the factors that can influence the decision. In an industrial application, for instance the following factors can be used for analysis:

- Internal Environment
    - Manufacturing environment
    - Supply chain capacity
- Contextual Environment
    - Intellectual property (patent, license, etc.)
    - Economical environment

- Technology trend

In order to calculate the strategic value and the strategic risk related to each alternative, a seven-step procedure is followed ([36]):

1. Define environment-related weights
2. Identify opportunities and threats within each environment
3. Define weights associated with opportunities and threats
4. Develop subjective probabilities for each alternative
5. Calculate the strategic value for each alternative
6. Calculate the strategic risk for each alternative
7. Evaluate potential strategies

For each environment factor, one has to identify the opportunities and threats that might affect the decision, as well as the relative importance of each with respect to the others. Once again, in order to have a consistent weight attribution for each environment category and, in each category, for each factor, one suggests the use of pairwise comparison for the same reasons mentioned in 4.1.1. The identification of opportunities and threats are application dependent since these opportunities and threats shall derive from it, i.e. an expectation about the positive and negative impact the alternatives might have that could influence the decision-maker.

Evaluating the probability of occurrence for each potential opportunity and threat is a subjective assessment often used in strategic management, One makes use of qualitative expressions to manifest the feeling about the chance a certain factor has to happen and then convert it to numerical probabilities as suggested in the literature (see Table 4.4).

With the aim of executing the 5, 6, and 7 steps of the procedure, Tavana and Banerjee [36] use an algebraic model to calculate the strategic value of each alternative, the strategic risk for each alternative, and to evaluate the potential strategy.

The strategic value of an alternative corresponds to the attractiveness of an alternative taking into account the total threat value and the total opportunity value. The total threat / opportunity value is computed by the sum of the multiplication of the relative weight of each type of environment to the relative weight of each factor within that environment and the subjective probability of that factor for the selected alternative. A certain alternative will become more attractive as the strategic value is higher. More significant risks are associated to higher threat values for an alternative.

Table 4.4: Probabilistic expressions and perceived probability estimates [36]

Expression	**Probability**
Impossible	0.0
Small possibility	0.1
Small chance	0.2
Somewhat doubtful	0.3
Possible	0.4
Toss-up	0.5
Somewhat likely	0.6
Likely	0.7
Very likely	0.8
Quite certain	0.9
Certain	1.0

To evaluate the potential strategy, one has to calculate the strategic value per unit of risk. Assuming that decision-maker is risk neutral, the most suitable alternative is the one with highest strategic value per unit of risk, i.e. higher strategic value increases the attractiveness of an alternative, while higher risk diminishes it.

Table 4.5 provides the variables (weights, probabilities, and output results) used in the algebraic model. i represents the internal ($i = 1$) and contextual environment ($i = 2$). Table 4.6 shows all the variables used in the algebraic model and the correspondent definition.

The final goal of running this model is to get the highest strategic value per unit of risk, i.e. maximizing E^m (see equation (4.5)) one will get the most promising alternative. One shall notice that alternatives with negative strategic value per unit of risk mean that those alternatives are not satisfactory once their total threat value prevails over the respective total opportunity value. The equations (4.5) to (4.17) formulate the algebraic model used to obtain the most suitable alternative.

$$E^m = \frac{V^m}{S^m} \tag{4.5}$$

where

$$V^m = U^m - T^m \tag{4.6}$$

Table 4.5: Algebraic model variables used for evaluating potential strategies

Opportunities

Subjective weight of the environment W_{u_i}	Subjective weight of the factor $F_{u_{ij}}$	Probability of occurrence($P^m_{u_{ij}}$) $m = 1, 2, \cdots, q$		
		m = 1	m = 2	m = q
W_{u_1}	$F_{u_{11}}$	$P^1_{u_{11}}$	$P^2_{u_{11}}$	$P^q_{u_{11}}$
	$F_{u_{12}}$	$P^1_{u_{12}}$	$P^2_{u_{12}}$	$P^q_{u_{12}}$
	$\ldots$	$\ldots$	$\ldots$	$\ldots$
	$F_{u_{1j}}$	$P^1_{u_{1j}}$	$P^2_{u_{1j}}$	$P^q_{u_{1j}}$
W_{u_2}	$F_{u_{21}}$	$P^1_{u_{21}}$	$P^2_{u_{21}}$	$P^q_{u_{21}}$
	$F_{u_{22}}$	$P^1_{u_{22}}$	$P^2_{u_{22}}$	$P^q_{u_{22}}$
	$\ldots$	$\ldots$	$\ldots$	$\ldots$
	$F_{u_{2j}}$	$P^1_{u_{2j}}$	$P^2_{u_{2j}}$	$P^q_{u_{2j}}$
Total Opportunity Value (U^m)		U^1	U^2	U^q

Threats

Subjective weight of the environment W_{t_i}	Subjective weight of the factor $F_{t_{ij}}$	Probability of occurrence($P^m_{t_{ij}}$) $m = 1, 2, \cdots, q$		
		m = 1	m = 2	m = q
W_{t_1}	$F_{t_{11}}$	$P^1_{t_{11}}$	$P^2_{t_{11}}$	P^q_{t-11}
	$F_{t_{12}}$	$P^1_{t_{12}}$	$P^2_{t_{12}}$	$P^q_{t_2}$
	$\ldots$	$\ldots$	$\ldots$	$\ldots$
	$F_{t_{1j}}$	$P^1_{t_{1j}}$	$P^2_{t_{1j}}$	$P^q_{t_{1j}}$
W_{t_2}	$F_{t_{21}}$	$P^1_{t_{21}}$	$P^2_{t_{21}}$	$P^q_{t_{21}}$
	$F_{t_{22}}$	$P^1_{t_{22}}$	$P^2_{t_{22}}$	$P^q_{t_{22}}$
	$\ldots$	$\ldots$	$\ldots$	$\ldots$
	$F_{t_{2j}}$	$P^1_{t_{2j}}$	$P^2_{t_{2j}}$	$P^q_{t_{2j}}$
Total Threat Value (T^m)		T^1	T^2	T^q
Strategic Value (V^m)		V^1	V^2	V^q
Standard Deviation (S^m)		S^1	S^2	S^q
Strategic Value per unit of risk (E^m)		E^1	E^2	E^q

Table 4.6: Algebraic model variables and the respective meaning

Variable	Definition
E^m	Strategic value per unit of risk ($m = 1,2,\cdots,q$)
V^m	Total weighted strategic value of the m^{th} strategic alternative ($m = 1,2,\cdots,q$)
S^m	Standard deviation associated with the m^{th} strategic alternative derived from all opportunity and threat factors in the two environments ($m = 1,2,\cdots,q$)
U^m	Total weighted opportunity value of the m^{th} strategic alternative ($m = 1,2,\cdots,q$)
T^m	Total weighted threat value of the m^{th} strategic alternative ($m = 1,2,\cdots,q$)
V_u^m	Variance of the value of the m^{th} strategic alternative derived from all opportunity factors in the two environments ($m = 1,2,\cdots,q$)
V_t^m	Variance of the value of the m^{th} strategic alternative derived from all threat factors in the two environments ($m = 1,2,\cdots,q$)
W_{u_i}	The i^{th} environment opportunity associated weight ($i = 1,2$)
W_{t_i}	The i^{th} environment threat associated weight ($i = 1,2$)
$F_{u_{ij}}$	The j^{th} factor opportunity associated weight for the i^{th} environment ($j = 1,2,\cdots,N_{u_i}; i = 1,2$)
$F_{t_{ij}}$	The j^{th} factor threat associated weight for the i^{th} environment ($j = 1,2,\cdots,N_{t_i}; i = 1,2$)
$P^m_{u_{ij}}$	The m^{th} opportunity associated probability of occurrence of the j^{th} in the i^{th} environment ($m = 1,2,\cdots,q; j = 1,2,\cdots,N_{u_i}; i = 1,2$)
$P^m_{t_{ij}}$	The m^{th} threat associated probability of occurrence of the j^{th} in the i^{th} environment ($m = 1,2,\cdots,q; j = 1,2,\cdots,N_{t_i}; i = 1,2$)
N_{u_i}	Number of opportunity factors in the i^{th} environment ($i = 1,2$)
N_{t_i}	Number of threat factors in the i^{th} environment ($i = 1,2$)

$$U^m = \sum_{i=1}^{2} W_{u_i} \left(\sum_{j=1}^{N_{u_i}} F_{u_{ij}} P_{u_{ij}}^m \right) \tag{4.7}$$

$$T^m = \sum_{i=1}^{2} W_{t_i} \left(\sum_{j=1}^{N_{t_i}} F_{t_{ij}} P_{t_{ij}}^m \right) \tag{4.8}$$

$$S^m = \sqrt{V_u^m + V_t^m} \tag{4.9}$$

$$V_u^m = \sum_{i=1}^{2} W_{u_i} \sum_{j=1}^{N_{u_i}} \left[\left(P_{u_{ij}}^m - U^m \right)^2 F_{u_{ij}} \right] \tag{4.10}$$

$$V_t^m = \sum_{i=1}^{2} W_{t_i} \sum_{j=1}^{N_{t_i}} \left[\left(P_{t_{ij}}^m - T^m \right)^2 F_{t_{ij}} \right] \tag{4.11}$$

restricted to

$$\sum_{i=1}^{2} W_{u_i} = 1 \tag{4.12}$$

$$\sum_{i=1}^{2} W_{t_i} = 1 \tag{4.13}$$

$$\sum_{j=1}^{N_{u_i}} F_{u_{ij}} = 1 \tag{4.14}$$

$$\sum_{j=1}^{N_{t_i}} F_{t_{ij}} = 1 \tag{4.15}$$

$$0 \leq P_{u_{ij}}^m \leq 1 \tag{4.16}$$

$$0 \leq P_{t_{ij}}^m \leq 1 \tag{4.17}$$

The case study presented in 4.2 will translate, more clearly, the application of this algebraic model.

4.1.3 Sensitivity Analysis

The sensitivity analysis is an essential tool for the decision-maker to have an overall perspective about the prospective scenarios he/she might face. Since the context is not perfectly known, in particular, the trends are not perfectly forcasted, it is of the most importance to establish different prospective scenarios with more or less positive/negative impacts. The relative importance of each opportunity and threat factors, as well as the importance of the internal and contextual enviroments shall be measured and tested. The strategic value per unit risk result will deeply depend on those variables and it might result in completely different suggested alternatives.

4.1.4 Risk Assessment

One has mention in 4.1.2 that depending on the decision-maker risk profile one can either get the highest strategic value per unit of risk when he/she is risk neutral, or using an utility function in case he/she is risk averse / prone. In the last situation, the utility function shall be build-up upon the characteristics of the decision-maker which are, in general, the combination of many people inside an organization.

Nevertheless, even considering a risk neutral decision-maker, it is still important to perform a risk assessment of the results obtained, especially when two or more alternatives provide meaningless differences in the strategic value per unit of risk. Several approaches and tools might be followed (Flag Model, Monte Carlo analysis, etc.). One suggests a combination of risk analysis with sensitivity analysis (see 4.1.3).

By observing the evolution of the strategic value per unit of risk, the decision-maker would have a better impression about the real risk associated to the set of alternatives. In the end, the decision-maker profile will have a decisive impact on the alternative adopted. In fact, with this kind of approach, one is able to overpass the need of building an utility function, giving the decision-maker all the conditions to take the decision that is more adequated to his/her risk profile.

4.2 Case Study

In order to validate the methodology presented above, a case study of a technical solution selected for the AutoClass project is provided hereinafter. In particular, this case study is focused on the tire image acquisition station already presented in Chapter 3.

Due to the high complexity associated to the suggested inspection process, one decided to split the technology pre-selection process in two main groups: tire handling (4.2.1) and technologies for tire inspection (4.2.2, 4.2.3, and 4.2.4).

4.2.1 Tire Handling

Handling tire is a task performed several times along the process line of a tire manufacturer. The handling can be done both on a cured tire or on a green tire (tire not yet cured). The key aspect one is looking for is the way the tire is handled as well as the adaptability to the tire inspection application.

Other sources of search were the handling solutions used in the tire manufacturing process, not only in Portuguese plant but also considering other plants' solutions, observing all possible manners of handling a tire that can be suitable for the tire image acquisition station. Additionally, one has also the possibility to participate in the Tire Technology Expo 2011, held in Cologne, in February 2011. At this exhibition, one could be in contact with several technology providers under the tire industry which enlarge significantly the number of possible solutions to be considered.

One shall notice that tire image acquisition station will comprise tire handling and equipment handling. Two main options can be considered: the tire is fixed and the image acquisition equipment is moving, or the tire is rotating and the equipment is fixed. In both approaches, one has to take into account the equipment handling. Even when the tire is rotating, some equipment handling is expected in order to place the equipment in the desired position.

4.2.1.1 Tire Handling Requirements

The very first step of the technology pre-selection process is to identify the requirements that shall be considered for the application. The following requirements were identified for the the tire handling solution one is looking for:

- Tire / Equipment with low level of vibrations
- Tire / Equipment rotates at a constant and controllable speed
- The handling solutions shall be adaptable for all tire dimensions
- Guarantee a stable image acquisition for the different tires
- Guarantee constant lighting conditions for the different tire surfaces
- Avoid the existence of hidden surfaces
- Tire image acquisition process from all tire surfaces in less than 5 seconds
- The interface with the conveying system shall be fast and accurate

- Make use, as much as possible, of existent company's handling solutions

With respect to the tire dimensions, the diversity of tire dimensions in the plant is significant. The dimensions that mostly influence the design of the structure are the rim size, the tread width and the external tire radius. Table 4.7 show the range of each tire dimension in order to have an idea about the complexity associated to this requirement.

Table 4.7: Range of tire dimensions currently manufactured in the plant

Tire Dimension	**Min**	**Max**
Tread Width (mm)	125	285
Rim Size (inches)	14	20
Tire Radius (mm)	177.80	254.00
Tire External Radius (mm)	276.80	394.35

4.2.1.2 Tire Handling Solutions

The sources of information used in this process allowed to identify the following tire handling solutions:

- HS1: ContiSeal Laser Marker from *4Jet* (Figure 2.1)
- HS2: DOT read-out application - from *Bytewise* (Figure 2.7)
- HS3: Bead Lubricant Applicant (MU) (Figure 2.2)
- HS4: Trimming Machine - from *Matteuzzi* (Figure 2.8)
- HS5: Uniformity Machine Test Area (Figure 2.3)
- HS6: InspectoMat (Figure 2.4)
- HS7: ContiSeal Sealant Applicant - from *Promera* (Figure 2.5)
- HS8: Manual Bulge Measurement Machine
- HS9: X-ray Test Machine (Mont Vernon & Puchov) - from *YXLON* (Figure 4.3)
- HS10: ContiSeal Tire Washing Machine - from *Fuco* (Figure 2.6)

Some of the handling solutions presented above are not used for tire inspection. However, one is more focused on the handling capabilities which can perfectly fit on the handling requirements already identified in 4.2.1.1

Figure 4.3: X-ray test machine handling solution

4.2.1.3 Tire Handling Solutions Criteria for Comparison

With a considerable number of tire handling solutions to analyze, it is crucial to determine a set of criteria for comparison. These criteria shall be identified based on the application requirements and inputs from experts in such kind of processes. For that reason, one has collected the inputs from Engineering department that has considerable experience in designing, specifying, and validating new machines for the tire industry. The list of criteria used for tire handling solutions' comparison is the following:

- HC1: Mechanical complexity (tire handling)
- HC2: Mechanical complexity (equipment handling)
- HC3: Vibrations in the different directions (X, Y, and Z)
- HC4: Interface with conveying system
- HC5: Space needed
- HC6: Maintenance (tire handling)
- HC7: Maintenance (equipment handling)
- HC8: Guarantee of constant lighting conditions
- HC9: Equipment placement
- HC10: Access to different tire surfaces (tread, sidewall (inside and outside), bead, and interior)
- HC11: Cost

4.2.1.4 Qualitative Analysis

The number of handling solutions identified suggests to perform a qualitative analysis in order to eliminate potential weak solutions before computing a quantitative analysis. In this way, two main variables were considered to group the handling solutions: tire position and tire / equipment relative position.

For tire position, one has two options: either the tire is in vertical position or the tire is in the horizontal position. When the tire is in horizontal position, the deformation of each tire sidewall is different due to gravity. This effect can even be more significant on tires with soft rubber.

The tire / equipment relative position means which one is fixed and which one is rotating. Either the object of inspection (tire) is rotating or the inspection equipment. Due to the geometry of the object of inspection, it is not interesting to have the tire and the equipment fixed. This will mean a multiplication of inspection equipment which will turn into a non-effective solution from the cost perspective.

The handling solutions can then be grouped in the way shown in Table 4.8. From the list of handling solutions identified, none of them is assigned to the group Tire fixed / Equipment rotating - Tire in Vertical position.

Considering the handling solutions grouped in the way presented above, one can perform a qualitative analysis over the criteria identified before, for the four groups. A general consideration is done despiting some particular solution that can have better / worst performance in some criterion. The analysis is performed considering three different values: 1 point if the group has positive performance in a specific criterion; 0 points if the performance is neutral; and -1 points when the group of solutions has negative performance. The results of this analysis as well as the summary of the scoring is shown in Tables 4.9 and 4.10 respectively. The values obtained in this analysis result in the combination of inputs from the development team and the engineering department of the company. Scoring is a tool suggested by Ulrich and Eppinger [170] to perform a preliminary qualitative analysis in product development processes.

One might note that the group with no handling solutions assigned is the one with the lowest score. The negative score indicates that this approach seems to be not suitable for the tire inspection application, and one can conclude that this is most probably the reason why none handling solution has been identified for this group.

Moreover, one observes that the group Tire rotating / Equipment fixed (in both tire positions) is the most promising one. However, only two handling solutions do not fit in this group. For that reason, they will not be disconsidered in the quantitative analysis.

Table 4.8: Handling solutions grouped according to tire position and tire/equipment relation

		Tire Position	
		Horizontal	*Vertical*
Tire / Equipment relative position	*Tire fixed / Equipment rotating*	HS1	
		HS2	
	Tire rotating / Equipment fixed	HS3	HS5
		HS4	HS6
			HS7
			HS8
			HS9
			HS10

Table 4.9: Qualitative analysis of handling solutions

		Tire Position		
		Horizontal		*Vertical*
Tire / Equipment relative position	*Tire fixed / Equipment rotating*	1	Mechanical Complexity (tire handling)	0
		-1	Mechanical Complexity (equipment handling)	-1
		1	Vibrations in X direction	1
		1	Vibrations in Y direction	1
		1	Vibrations in Z direction	1
		1	Interface with conveying system	-1
		-1	Space Needed	-1
		1	Maintenance (tire handling)	1
		-1	Maintenance (equipment handling)	-1
		-1	Guarantee of constant lighting conditions	0
		-1	Equipment placement	-1
		-1	Access to different tire surfaces	-1
	Tire rotating / Equipment fixed	1	Mechanical Complexity (tire handling)	0
		0	Mechanical Complexity (equipment handling)	1
		1	Vibrations in X direction	1
		-1	Vibrations in Y direction	-1
		-1	Vibrations in Z direction	-1
		1	Interface with conveying system	-1
		-1	Space Needed	1
		1	Maintenance (tire handling)	0
		1	Maintenance (equipment handling)	1
		-1	Guarantee of constant lighting conditions	0
		1	Equipment placement	1
		1	Access to different tire surfaces	1

Table 4.10: Qualitative scoring of handling solutions

	Tire Position		
	Horizontal		*Vertical*
Tire fixed / Equipment rotating	6	Scoring (positive)	4
	0	Scoring (neutral)	0
	-6	Scoring (negative)	-6
	0	**Total Scoring**	**-2**
Tire rotating / Equipment fixed	7	Scoring (positive)	6
	0	Scoring (neutral)	0
	-4	Scoring (negative)	-3
	3	**Total Scoring**	**3**

4.2.1.5 Quantitative Analysis

A quantitative analysis is necessary to determine the most suitable handling solutions for the tire image acquisition station.

The first step consists in determining the relative importance (weights) of each criterion. In order to obtain these weights, one has to perform a pairwise comparison (Table 4.11) over all the criteria selected. The pairwise comparison takes into account the inputs from the engineering department which has significant experience in the design of handling solutions for the tire industry.

From the values of Table 4.11 one might obtain the relative importance of each criterion as well as the consistency ratio for this analysis. The values are shown in Table 4.12 where one observes that CI is lower than 0.1. One assumes that the relative importance of the vibrations across each direction is the same, i.e. the weight for X, Y, and Z is the same. The same approach is followed for the sub-criterion access to different tire surfaces.

Computing the quantitative analysis for the 3D solutions and the respective criterion weight, one obtains the ranking of solutions shown in Table 4.13.

4.2.1.6 Proposed Solution for Tire Handling

The result from the quantitative analysis shows clearly that that the ContiSeal Sealant Applicant handling solution is most suitable one for the tire image acquisition system.

Table 4.11: Pairwise comparison of the handling solution criteria

	HC1	**HC2**	**HC3**	**HC4**	**HC5**	**HC6**	**HC7**	**HC8**	**HC9**	**HC10**	**HC11**
HC1	1	1	1/5	1/7	1/2	1	1	1/9	1/5	1/9	1/5
HC2	1	1	1/5	1/7	1/2	1	1	1/9	1/5	1/9	1/5
HC3	5	5	1	1/3	5	5	5	1/5	1	1/7	5
HC4	7	7	3	1	7	7	7	1/3	3	1/3	5
HC5	2	2	1/5	1/7	1	2	2	1/7	1/4	1/9	1/2
HC6	1	1	1/5	1/7	1/2	1	1	1/9	1/5	1/9	1/6
HC7	1	1	1/5	1/7	1/2	1	1	1/9	1/5	1/9	1/6
HC8	9	9	5	3	7	9	9	1	5	1	5
HC9	5	5	1	1/3	4	5	5	1/5	1	1/4	3
HC10	9	9	7	3	9	9	9	1	4	1	7
HC11	5	5	1/5	1/5	2	6	6	1/5	1/3	1/7	1

Table 4.12: Criterion relative weight for handling solutions

Criterion	**Relative Weight**	**CR:** 0.0581
Mechanical complexity (tire handling)	1.92%	
Mechanical complexity (equipment handling)	1.92%	
Vibrations in the different directions	9.15%	
Interface with conveying system	14.94%	
Space needed	3.04%	
Maintenance (tire handling)	1.91%	
Maintenance (equipment handling)	1.91%	
Guarantee of constant lighting conditions	24.30%	
Equipment placement	8.52%	
Access to different tire surfaces	25.86%	
Cost	6.53%	

Table 4.13: Handling solutions’ ranking

Handling Solution	**Ranking**
ContiSeal Sealant Applicant - Promera	3.98
X-ray test machine - YXLON	3.54
Uniformity Machine Test Area	3.19
ContiSeal Tire Washing Machine - Fuco	3.18
ContiSeal Laser Marker - 4Jet	3.01
DOT read-out applications - Bytewise	3.01
InspectoMat	3.00
Manual Bulge Measurement Machine	2.90
Bead lubricant applicant (Uniformity Machine)	2.85
Trimming machine - Matteuzzi	2.80

Nevertheless, there are two items in which this solution still needs to improve: the interface with the conveying system, and the guarantee of constant light conditions.

Regarding the first criterion, one shall take into account that tires are usually transported in the horizontal position, which means that tires need to turn into the vertical position. One possibility is to build the same structure rotated 90° in order to have the tire in the horizontal position. Nevertheless, the final decisions regarding this topic shall only be taken when the final location of the tire image acquisition station is attributed. One shall have the fastest interface with the conveying system possible once the operation of tire in/out cannot compromise the process time.

In order to guarantee even better constant lighting conditions, one suggests the use of grips (two per sidewall) with the aim of allowing more uniform lighting conditions for the interior and for the sidewall. The design of these grips shall also take into account that equipment will be placed inside the tire and these grips shall not interfere with the equipment.

4.2.2 2D Vision

2D vision solutions look an obvious choice for the image acquisition system. 2D vision solutions are widely used in industrial applications, in particular for product quality assessment. In this sense, several 2D vision solutions are available in the market with a significant amount of different features, from the resolution or type of sensor, to the frame rate capabilities (number of frames per second (fps)) as well as camera interfaces (communication, I/O, etc.) and trigger type.

Regarding the type of sensor, one can find two main technical solutions: Charge-Coupled Device (CCD) or CMOS. The shift to CMOS technology has pushed machine vision's limits even further, with significant impacts on the performance level and solution costs (Figure 4.4) [22].

With respect to communication, the range of available technologies vary from the USB - USB2 or USB3 - CameraLink or GigE.

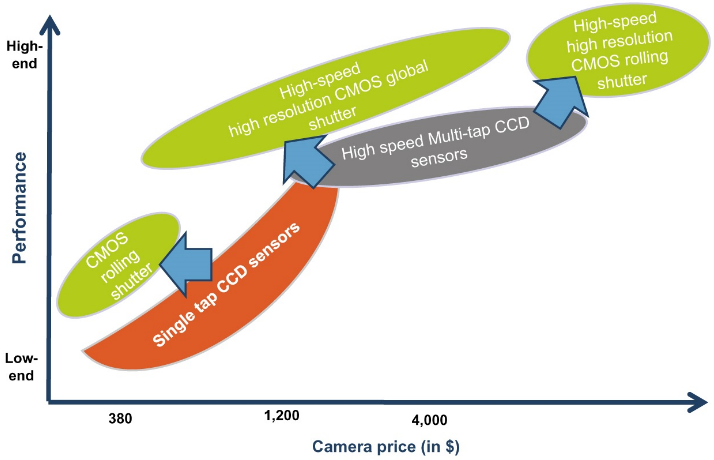


Figure 4.4: The shift to CMOS technology with impact on machine vision's limits (*source: I-Micronews* [22])

4.2.2.1 2D Vision Requirements

With the aim of selecting the most suitable 2D vision solution, the following requirements were identified:

- Image resolution of at least $0.5mm/px$
- External trigger controllable by hardware
- Linux and Windows environment compatible

To obtain the desired image resolution, there is a combination of sensor resolution, camera frame rate, image ROI, camera distance to the object, and lens focal length. The camera distance to the object will vary according to object dimensions, and lens focal length.

For the application in hands, the tire is rotating at a constant speed of $612.5mm/s$ (see 4.2.6 for details about the calculation). In order to have at least $0.5mm/px$, the camera shall work at 700 fps, with an image ROI of 2 pixels height. The value obtained is a compromise between the maximum camera frame rate, the necessary resolution for the tire image, and the requirements regarding the acquisition time. The optimal ROI height of 1 pixel is only possible with a camera with higher frame rate or even using a linear camera. Both solutions are much more costly than the 2D camera solution chosen for this application. Larger ROI height means higher acquisition time although less demanding camera frame rate. However, the larger the ROI height the lower are the guarantees of constant lighting conditions in all image ROI.

4.2.2.2 2D Vision Solutions

The number of 2D vision solutions available in the market is extensive. One has search, in first place, for cameras with GigE interface. GigE allows the use of standard drives, as well as high transmission rates and easy integration in architectures that require networking approach. Due to the research and development characteristics of AutoClass project, one decides to have as much flexibility as possible, thus choosing 2D vision solutions that can be developed under Linux operating system environment, cameras with external trigger controlled by hardware, and disconsidering smart cameras.

Along the development, new 2D vision solutions were showing up. In particular, one has payed attention and select one solution with USB3 interface due to its high transmission rates and plug-an-play characteristics.

Moreover, the approach followed to select the most suitable technology includes testing the cameras. For that reason, one selects three different 2D vision solutions:

- Prosilica Allied Vision Technologies (AVT) GC780 (Figure 4.5)
- Imaging Development Systems (IDS) μEye UI-5240SE (Figure 4.6)
- Point Grey Flea3 (Figure 4.7)

Figure 4.5: AVT Prosilica GC780 camera (*source: AVT Prosilica* [23])

Table 4.14 presents the main features of the 2D vision solutions considered to be used in the image acquisition system.

Figure 4.6: IDS μEye camera (*source: IDS* [24])

Figure 4.7: Point Grey Flea3 USB3 camera (*source: Point Grey* [25])

4.2.2.3 Proposed Solution for 2D Vision

From the 2D vision solutions presented above the only one that is able to reach the image resolution required with the object tangential speed of $612.5 mm/s$ is the AVT Prosilica GC780 camera. One can observe in Figure 4.8 (data provided by the AVT supplier in the technical manual [23]), the camera can reach the $700 fps$ for ROI with less than 5 pixels height.

4.2.3 3D Vision

Nowadays, the current tire inspection process is done by operators that make use of their sensors (visual, tact, etc.) to take decisions over the tire grading. With 2D vision solutions one intends to obtain the visual aspect of the tire as well as visual imperfections it might contain. However, as in the current tire inspection process, the use of complementary sensors is important. In particular, when depressions (positive or negative) are in place.

Table 4.14: 2D vision solutions: main features (*sources:* [23], [24], and [25])

Feature	**GC780**	**μEye UI-5240SE**	**Flea3**
Resolution (pix × pix)	782 × 582	1280 × 1024	1280 × 1024
Sensor Type	CCD	CMOS	CMOS
Max Frame Rate at full resolution	64 fps	50 fps	60 fps
Interface	GigE	GigE	USB 3.0

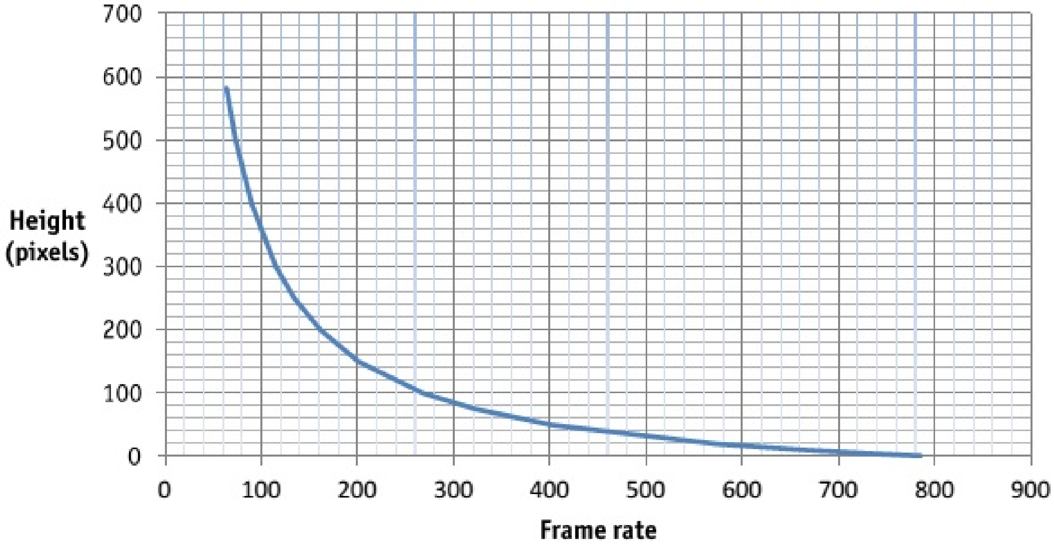


Figure 4.8: Maximum frame rate versus image height for GC780 (*source: AVT* [23])

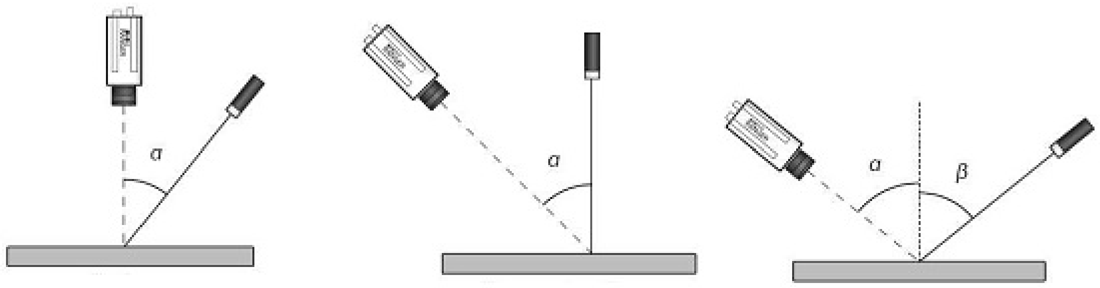
These depressions can be blisters (air or material), blemishes or imperfect material joins. Although 2D vision might be enough for many situation, the need of having 3D data seems to be important. 3D vision solutions can complement the information provided by the 2D vision solutions, enhancing the information gathered with the height profile of the object. The use of this technology can somehow *simulate* the tact used by the operators currently.

Nevertheless, one has to take into account that this technology is generally more expensive than 2D vision solutions (especially when compared with the 2D vision solutions described in 4.2.2.2). Additionally, the use of laser light requires special attention to its use in order to not provoke any kind of injury for the user, mainly in the eyes. The size of 3D vision solutions shall also be considered once it can compromises its use in some applications.

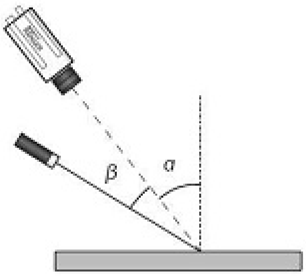
When adopting the 3D laser scanner technology, one shall select the most suitable triangulation geometry. There are four different triangulation geometries:

Ordinary (Figure 4.9a): It is adequate for multi-scan setup and for box-like objects with high walls. Provides the highest height profile resolution among the different geometries. Its performance depends on diffuse reflections and it gets miss-register.

Reverse ordinary (Figure 4.9b): It gives the easiest calibration. Due to its equidistant profiles only requires calibration for X and Z axis. It is the only geometry without miss-register. The performance depends on diffuse reflections and it has slightly lower height profile resolution than ordinary geometry.



(a) Ordinary (b) Reverse ordinary (c) Specular



(d) Look-away

Figure 4.9: 3D geometry types (*source: SICK IVP* [26])

Specular (Figure 4.9c): It is adequate for 2D gloss measurement and crack detection on shiny surfaces as well as for 3D on dark, matte objects. This geometry gives saturation behavior on sensor if mirror criterion is fulfilled ($\alpha = \beta$), i.e. it is not suitable for 3D on bright or shiny objects.

Look-away (Figure 4.9d): It is less affected by stray reflections but it has low height profile resolution. It requires strong laser beam light and it has more occlusion effects.

The most common 3D coordinate system definition establishes that X axis is orthogonal to object movement (width); Y axis is along the object movement; and Z axis is along the laser's optical axis (see Figure 4.10).

One might expect an output image from the 3D laser scanner solution identical to the one shown in Figure4.11.

4.2.3.1 3D Vision Requirements

With the aim of selecting the most suitable 3D vision solution, the following requirements were determined:

- Image resolution (along the direction of acquisition) of at least 0.3 $mm/profile$

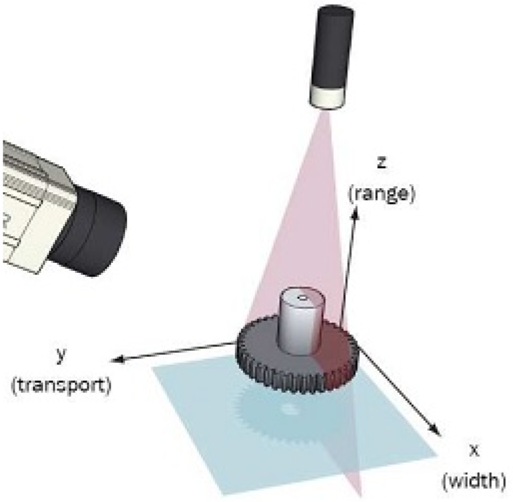


Figure 4.10: 3D coordinate system for reverse ordinary geometry (*source: SICK IVP* [26])

- Image resolution (height profile) of at least 0.2 mm/px
- External trigger controllable by hardware
- Linux and Windows environment compatible
- Flexible camera vs laser position
- Acquire data from tire surfaces in less than 5 seconds

The resolution along the direction of acquisition and for the height profile are obtained with the aim of capturing the minimal features (dimensions) of the imperfections and to gather the information regarding the lettering used for the tire identification.

In order to calculate the correspondent resolutions in the different directions, one has to first calculate the Field Of View (FOV) width by:

$$FOV_{width} = \frac{sensor\ width}{focal\ length} \times working\ distance \tag{4.18}$$

Equation (4.18) can also be used to calculate the most suitable focal length or the working distance, knowing the remaining parameters.

The average resolution in Z direction (direction where one gets the height profile data) for the ordinary geometry is given by:

$$Z_{res} = \frac{\Delta Z}{subpixel\ resolution} \tag{4.19}$$

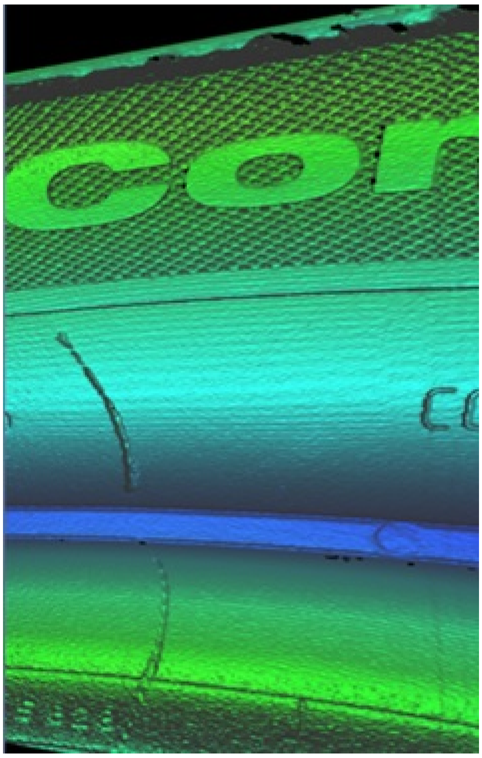


Figure 4.11: 3D image output enhancing an imperfection in the sidewall

where

$$\Delta Z \approx \frac{\Delta X}{\tan \alpha} \tag{4.20}$$

where α is the angle between the camera and the laser beam. The sub-pixel resolution depends on the algorithm used in the peak detector.
The ΔX is calculated by:

$$\Delta X = \frac{FOV_{width}}{sensor\ height} \tag{4.21}$$

Finally, the resolution in the direction of the object movement (given in $mm/profile$) is given by:

$$\Delta Y = object\ speed \times cycle\ time \tag{4.22}$$

Where the cycle time (in microseconds) is a camera parameter.

4.2.3.2 3D Vision Solutions

The following 3D vision solutions were considered for the application in hands:

- SICK Ranger E5540 (Figure 4.12)

- LMI 3D Gocator 2340 (Figure 4.13)

- Photonfocus MV1-D2048x (Figure 4.14)
- Bytewise VHSLE4-080-050-030-660-N (Figure 4.15)

Figure 4.12: SICK Ranger E5540 camera (*source: SICK* [27])

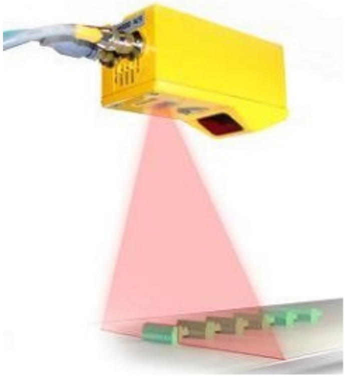


Figure 4.13: LMI3D Gocator 2000 Family Laser Scanner solution (*source: LMI Technologies* [28])

Figure 4.14: Photonfocus MV1-D2048 camera (*source: Photonfocus* [29])

Table 4.14 presents the main features of the 3D vision solutions considered to be used in the image acquisition system.

The solutions provided by LMI (Figure 4.13) and by Bytewise (Figure 4.15) are 3D laser scanner integrated solutions that combines a camera and the respective laser. This means that the relative position between the camera and the laser is defined a priori, giving no chance for the end user to adapt the laser scanner solution to the application in hands in

Figure 4.15: Bytewise 3D Laser Scanner solution (*source: Bytewise* [30])

Figure 4.16: Laser solution (*source: Z-LASER* [31])

Table 4.15: 3D vision solutions: main features (*sources:* [27], [28], [29], and [30])

Feature	**SICK Ranger E**	**LMI 3D Gocator**	**Photonfocus**	**Bytewise**
Frame rate vs resolution	20 000 Hz @ 1536×128	855 Hz @ 1280×128	2382 Hz @ 2048×128	
Sensor Resolution	1536×512	1280×	2048×1088	
Trigger type	Internal/External	Internal/External	Internal/External	External
Built in processing capabilities	Peak detector	Configurable X Re-sampling, built in measuring types	Peak detector	Peak detector
Intensity image outputs	Yes	Yes	Yes	No
2D image output	Yes	No	No	No
Price	9000 €	9000 €	5000 €	25 000 €

order to optimize the results. On the other hand, this kind of integrated solution avoid the need of camera calibration which is very relevant for the end user.

In the two other 3D solutions considered for the application (SICK Ranger E5540 and Photonfocus MV1-D2048x) one needs to use an external laser as light source. In this case, one has chosen the Z10M18S-F-635-lg90 laser from Z-Laser (Figure 4.16). This solution provides a 635 nm laser light, 10 mW power and it is class 2M. This laser has two main advantages: it allows an external trigger to control the laser emition and it has an analog input to control the laser light intensity.

4.2.3.3 3D Vision Solution Criteria for Comparison

The following criteria were considered for the 3D vision solutions comparison:

- C1: Frame Rate vs. Resolution
- C2: Sensor Resolution
- C3: Trigger Type
- C4: Built-in Processing Capabilities
- C5: Intensity Image Output
- C6: 2D Image Output
- C7: Windows / Linux Compatibility
- C8: Software Developer's Kit (SDK) Integration
- C9: Laser vs. Camera Position Flexibility
- C10: Calibration
- C11: Maintenance
- C12: Cost

4.2.3.4 Quantitative Analysis

In order to perform a quantitative analysis, one has to select one of the solutions as the reference. In this case, the option for the reference is the Bytewise 3D Laser Scanner solution once it was the first solution tested along this process. For that reason, all values for each criterion will be 3, taking into account the scale presented in Table 4.3.

Table 4.16 provides the quantitative analysis of each 3D solution tested for this case study, as a result of the consensus achieved in the development team.

On the next step, one calculates the relative importance of each criterion in order to obtain the respective weight of each (see Table 4.17) and then apply it to get a ranking of the 3D solutions in analysis.

Table 4.16: Quantitative analysis of the different 3D solution tested

Criteria	**3D Solutions**			
	SICK Ranger	*LMI Gocator*	*Photonfocus*	*Bytewise*
Frame rate vs resolution	5	2	4	3
Sensor resolution	2	1	3	3
Trigger type	5	5	5	3
Built-in processing capabilities	3	5	3	3
Intensity image output	5	5	5	3
2D image output	5	3	3	3
Windows / Linux compatibility	4	5	2	3
Integration (SDK)	4	4	2	3
Laser vs camera position flexibility	5	3	5	3
Calibration	2	3	1	3
Maintenance	2	3	2	3
Cost	4	4	5	3

Table 4.17: Pairwise comparison of the 3D solution criteria

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**
C1	1	1	3	7	7	8	3	2	5	6	4	6
C2	1	1	3	7	7	8	3	2	5	6	4	6
C3	⅓	⅓	1	3	3	5	1	⅕	3	4	3	3
C4	⅐	⅐	⅓	1	⅓	1	⅕	⅐	¼	⅓	⅓	⅕
C5	⅐	⅐	⅓	3	1	5	⅓	⅕	2	4	4	3
C6	⅛	⅛	⅕	1	⅕	1	⅕	⅐	⅓	⅓	¼	⅕
C7	⅓	⅓	1	5	3	5	1	⅓	3	4	5	4
C8	½	½	5	7	5	7	3	1	7	5	7	5
C9	⅕	⅕	⅓	4	½	3	⅓	⅐	1	⅓	3	⅓
C10	⅙	⅙	¼	3	¼	3	¼	⅕	3	1	3	2
C11	¼	¼	⅓	3	¼	4	⅕	⅐	⅓	⅓	1	¼
C12	⅙	⅙	⅓	5	⅓	5	¼	⅕	3	½	4	1

From the values of Table 4.17 one might obtain the relative importance of each criterion as well as the consistency ration for this analysis. The values are shown in Table 4.18 where one observes that CI is lower than 0.1.

Computing the quantitative analysis for the 3D solutions and the respective criterion weight, one obtains the ranking of solutions shown in Table 4.19.

Table 4.18: Criterion relative weight for 3D solutions

Criterion	**Relative Weight**	**CR:** 0.0963
Frame rate vs resolution	19.73%	
Sensor resolution	19.73%	
Trigger type	8.15%	
Built-in processing capabilities	1.74%	
Intensity image output	5.99%	
2D image output	1.56%	
Windows / Linux compatibility	9.36%	
Integration (SDK)	17.55%	
Laser vs camera position flexibility	3.71%	
Calibration	4.43%	
Maintenance	3.09%	
Cost	4.96%	

Table 4.19: 3D solutions' ranking

3D Solution	**Ranking**
SICK Ranger E5540	3.83
PHOTONFOCUS MV1-D2048x	3.26
LMI 3D Gocator 2340	3.14
Bytewise	3.00

4.2.3.5 Proposed Solution for 3D Vision

From the results obtained in the quantitative analysis, one decides to choose the SICK Ranger E5540 solution for the tire image acquisition station. The camera will be installed in a ordinary geometry configuration in order to get the highest resolution possible in the Z axis, so more detailed and accurate data is expected. In addition, one uses a laser beam solution provided by Z-Laser with the characteristics mentioned in 4.2.3.2.

4.2.4 Thermal Infrared

Most of the thermal radiation emitted by objects near room temperature is infrared. Infrared thermal-imaging cameras are used to detect heat profiles in objects where temperature measurement is essential.

Cured tires have a temperature around 90º C. In the presence of excess of material with different densities, air or material blisters, cracks or blemishes, one expects to have different temperature profiles in those regions. This is the main motivation for using this technology for tire inspection. However, the use of this technology requires that the tire is still warm (more than 35º C) in order to allow the detection of temperature variations in the specific regions where imperfections are placed. Below this limit, the use of thermal infrared technologies becomes meaningless.

4.2.4.1 Thermal Infrared Requirements

In order to identify the most suitable technology for the application, one has determined the following requirements for the thermal infrared solutions:

- Acquire data from the different tire surfaces in less than 5 seconds
- Be able to identify tire imperfections when the tire temperature is above 35º C

As referred above, the usefulness of the thermal infrared solutions is achieved when the tire temperature is above 40º C. This is a constraint that needs somehow to be granted by the process. If the tire arrives to the acquisition station with a temperature below 35º C, then one cannot use the data from the thermal infrared for analysis.

4.2.4.2 Thermal Infrared Solutions

The following thermal infrared solutions were identified and tested:

- FLIR A315 (Figure 4.17)

- Gobi-384 Uncooled smart thermal camera (Figure 4.18)

The thermal infrared solutions have some of the features presented in Table 4.20

Table 4.20: Thermal infrared camera solutions features (*sources:* [32] and [33])

Feature	**FLIR A315**	**Gobi-384**
Frame rate	60 Hz	50 Hz
Sensor resolution	$320 \times 240 pixels$	$384 \times 288 pixels$
Object temperature range	-20 to +120º C	-20 to +120º C
Thermal sensitivity	< 0.05º C @ +30º C / 50 mK	≥ 50 mK @ 30° C
Price	8000 €	5000 €

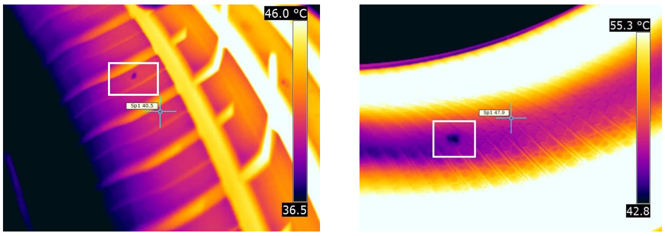
Figure 4.17: FLIR A Family thermal infrared camera (*source: FLIR* [32])

Figure 4.18: Gobi 384 thermal infrared uncooled camera (*source: Xenics* [33])

4.2.4.3 Thermal Infrared Results

One ran some tests with both thermal infrared solutions and examples of the results one might expect are shown in Figure 4.19. The imperfection in the tire caused a temperature difference in the tire surface which is *visible* in each image (Figure 4.19a and Figure 4.19b) highlighted with the white square.

Not all imperfections can be obtained with this technology since those imperfections will not have different material densities and thus no significant temperature variation with



(a) Blemish in tread (b) Air blister in interior

Figure 4.19: Example of images obtained with thermal infrared technology

respect to the neighborhood. Besides that, tires with an average temperature below 35º C do not manifest significant temperature variations that can highlight the imperfections.

Although the promising results one can get with this technology, some significant constraints turn this technology not suitable for the application. The main constraint is the frame rate. One has tested cameras with 50/60 Hz, i.e. with this frame rate, one will take a full image of an entire tire surface in more than 45 seconds. There are other thermal infrared solutions with higher frame rates (100/200 Hz) that can be enough for this application. However, the 100/200 Hz cameras are very costly (prices around 25 000 €). Moreover, once the process shall guarantee that tire surface temperature is above 35º C which is not possible all the time, the adoption of this technology becomes very risky. The technology evolution expected for the near future might become this technology suitable for this application. The integration of this technology in the tire image acquisition system shall only occur if the technology fullfils the application requirements, it shows better results than the technologies already in place and the cost / benefit analysis shows that the decision is the more convenient. The trend for the next 5 years (see Figure 4.20) shows that a 23% growth is expected which will imply significant cost reductions [34].

4.2.5 Proposed Solution for Tire Image Acquisition Station

The solution adopted for the tire handling allows a constant tangential speed of the tire, guaranteeing at the same time low level of vibrations. In fact, with the adjustments that can be done in the machine, both the presser and the moving wall can be adjusted in such a way that the tire is rotating smoothly and at a controllable speed.

The design of the prototype allows the user to test a wide range of tires, from 14 inches to 20 inches, with tread widths from 145 mm to 310 mm. Tires with tread width lower than 145 mm (e.g. spare tires that have 125 mm tread width) cannot be tested in the prototype due to design constraints. This limitation must be overtaken in the industrial implementation of the solution.

The tangential speed is controllable. In order to reach the acquisition target time, one has

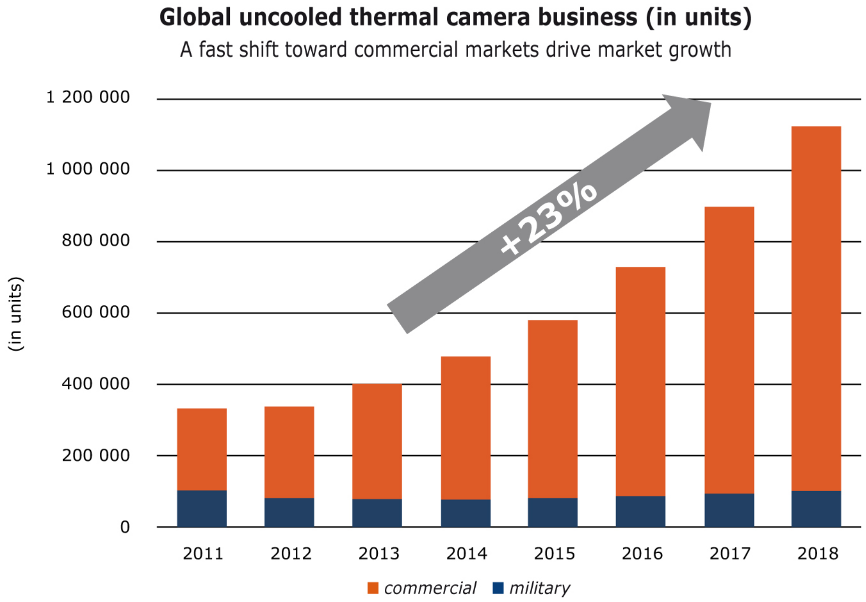


Figure 4.20: Thermal infrared camera business trends (*source: I-Micronews* [34])

established the tire tangential speed to 612.5 mm/s. The maximum acquisition time for the set of tires produced in Lousado plant is 4.224 seconds (see 4.2.6).

The vision technologies used for each tire surface are shown in Table 4.21. The 2D vision solution adopted is the AVT Prosilica GC780. The 3D vision solution used is the SICK Ranger E5540.

For each sidewall (inside and outside), one 2D camera is applied. One single 3D laser scanner solution is used for each sidewall and each bead in simultaneous. Only part of the sidewall (the one in which the DOT and mold number are placed) is covered by the 3D vision technology. In fact, in this region, one will get information from the 2D and from the 3D vision technologies.

In the tread region, one 2D camera is used. In order to perform the tire identification, another 2D camera, in this case a color camera (AVT Prosilica GC780C) is used to gather the color lines information from the tire.

In the interior, two 2D cameras are used, each of them covering half of the internal region. Along the tests performed in the prototype, the cameras for the interior were placed making use of the manipulator ABB IRB120. The cameras are placed inside the tire in a position that can guarantee that all the surface is covered and the external lighting does not affect the image acquisition. For the industrial implementation, one suggests the use of two linear actuators to handle the cameras (and lighting) for the interior, once this option is less expensive and can produce the same level of performance. One linear actuator will be used to adjust the vertical position of the cameras, and the second one will guarantee the correct positioning of the cameras according to the distance between the beads. For the 2D vision solutions, white lighting source is required. Once one is acquiring images at 700 fps, in order to get images with high quality, powerful light is required. One decides to choose a Light Emitting Diode (LED) array from Bridgelux with 4000 lumen and neutral white color (ref: BXRA-N4000-00LE).

Table 4.21: Vision technology selection for the tire image acquisition station

Tire Surface	**Technology**
Sidewall	2D & 3D
Bead	3D
Tread	2D
Interior	2D

With the aim of having flexible and adjustable lighting positioning for the different surfaces, one used servo motors in the prototype. Servo motors are very interesting for its linear movement and lightweight features. For the prototype purposes, one used the servo motors from the Bioloid kit. For each sidewall, one has build-up a 3-axis configuration that makes possible the light to point to a specific spot and with a pre-determined angle of incidence. For the tread, a 2-axis configuration is used allowing to adjust the light with different angles of incidence. For the interior, only one servo is used to adjust the light to different points of incidence, keeping always the same angle of incidence.

The 3-axis configuration is set-up as illustrated in Figure 4.21. Two possible configurations are considered for the joint L_1 - L_2: elbow up (Figure 4.22) or elbow down (Figure 4.21). Elbow up position will get the value 0 and elbow position down will get the value 1. The axis 1 is responsible to point the light to a specific position (X_a) in the tire surface (Figure 4.23). Axis 2 and axis 3 are responsible for guaranteeing the desired light incidence angle (θ_i) with the tire surface.

In the application, one wants to specify the light angle of incidence as well as the incidence point. With that aim, the inverse kinematics of the 3-axis configuration needs to be gathered. Using the variables shown in Figure 4.21, one can calculate the correspondent angles for each axis using the equations (4.23) to (4.27).

$$\theta_1 = \arctan\left(\frac{D_i}{X_a}\right) \tag{4.23}$$

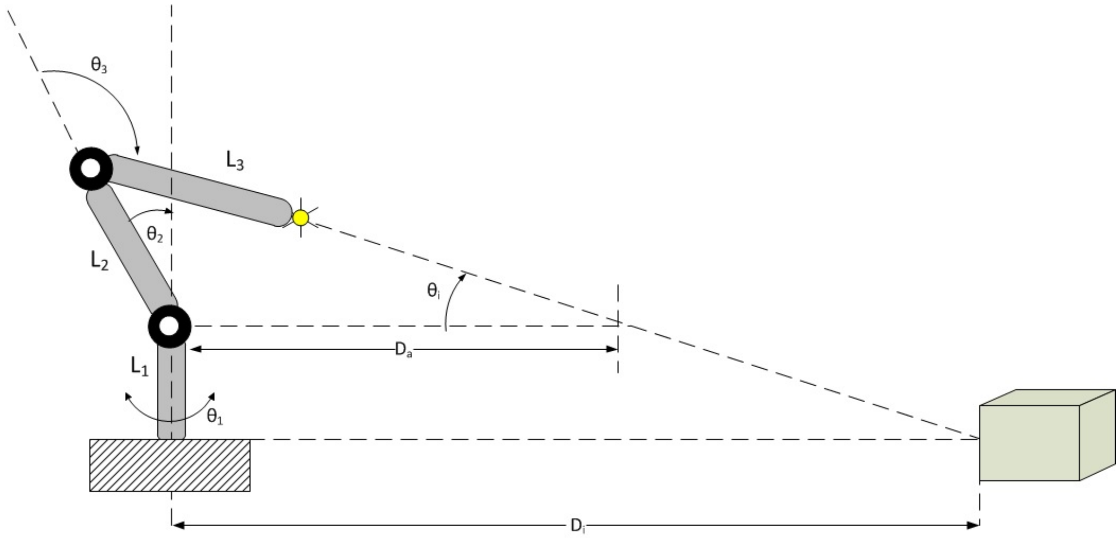


Figure 4.21: 3-axis configuration (elbow down): variables used for inverse kinematics

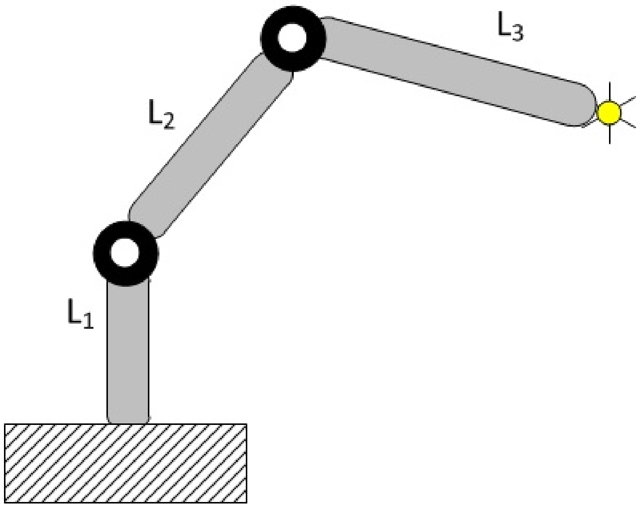


Figure 4.22: 3-axis configuration (elbow up): variables used for inverse kinematics

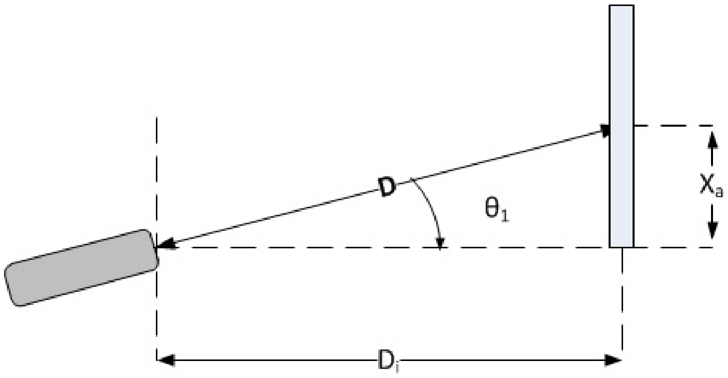


Figure 4.23: 3-axis configuration: representation of the light incidence point in the object

$$D = \frac{D_i}{\cos\theta_1} \tag{4.24}$$

$$D_a = D - \frac{L_1}{\tan\theta_i} \tag{4.25}$$

$$\theta_3 = \frac{\pi}{2} \times Elbow\,Config + (-2 \times Elbow\,Config + 1) \times \arcsin\left(\frac{D_a \times \sin\theta_i}{L_2}\right) \tag{4.26}$$

$$\theta_2 = \theta_3 - \theta_i - \frac{\pi}{2} \tag{4.27}$$

where:

- L_1: length of axis 1
- L_2: length of axis 2
- L_3: length of axis 3
- D_i: distance to the object for $\theta_1 = 0$
- D: distance to the incidence point
- D_a: distance calculated at the joint $L_1 - L_2$

The values of θ_1, θ_2, and θ_3 are mechanically restricted to the following limits:

$$-150^\circ < \theta_1 < 150^\circ \tag{4.28}$$

$$-140^\circ < \theta_2 < 130^\circ \tag{4.29}$$

$$-130^\circ < \theta_3 < 130^\circ \tag{4.30}$$

Although the distance of the light source to the tire is not constant for all angles, one might control the light intensity to compensate that effect.

The 2D camera for the tire sidewall is placed at 500 mm far from the tire surface (working distance), 840 mm height from the floor, and uses a 16 mm focal length lens. For the tire tread, the 2D camera is located at 600 mm far from the tire surface and 170 mm from the fixed structure wall, using a 12 mm focal length lens. In the interior, each 2D camera is

placed according to tire dimensions and uses a fish-eye lens of 2 mm focal length.
The appropriate lens (focal length) is selected by applying the equation (4.31).

$$f = \frac{Working\ Distance \times Sensor\ Width}{FOV_{Width}} \tag{4.31}$$

where the $Sensor\ Width = 6.5\ mm$ for the AVT Prosilica GC780.
The 3D laser scanner solution is positioned 300 mm above the rolling axes directly pointing to the bead. It uses a 12 mm lens and the angle between the camera and the laser beam, α is 30º, in an ordinary geometry.

4.2.5.1 Drawings

The tire handling solution selected for the tire image acquisition station is the ContiSeal Sealant Applicant solution. Some adaptations were done in order to incorporate some of the features one would like to enhance. A general view of the tire handling solution is presented in Figure 4.24. The drawings were provided by NPSantos which was responsible for the execution of the prototype.

The tire is introduced manually in the structure, between the two walls. One of the walls is fixed and the other one is adjustable according to tire tread width. The adjustment is done with an electrical linear actuator that guarantee a certain position (distance to the fixed wall). The two rolling axes on the bottom are responsible for the tire rotational movement. They are linked by a transmission belt that guarantees the same tangential speed in both. The rolling axes are actuated by a DC motor with a encoder incorporated which speed is controllable by a speed variator. Although a wide range of tires can be tested, a constant linear speed is achieved. The distance between the two rolling axes is 370 mm. In order to have only one 2D camera for the tread surface, it is required to elevate the structure guaranteeing that the two rollings axes are at a distance of 800 mm with respect to the floor.

The presser (Figure 4.26a) on the top part of the structure is composed by a pneumatic actuator. The pressure is adjustable from 0 to 4000 mbar. When the pressure is applied, the rolls drop until the pressure is reached. The use of this presser is essential to guarantee low vibration of the tire in the Z direction. The pressure might vary from tire to tire. In most of the cases, one has used a pressure of 200 mbar.

One of the features one suggested to improve is the guarantee of constant light conditions. One suggests the use of grips which one will call Clip Mechanism (Figure 4.26b). The clip mechanism is composed by two sets of cylinders that will apply a constant force to the tire sidewalls. The minimum distance between the cylinders, in this case, is 200

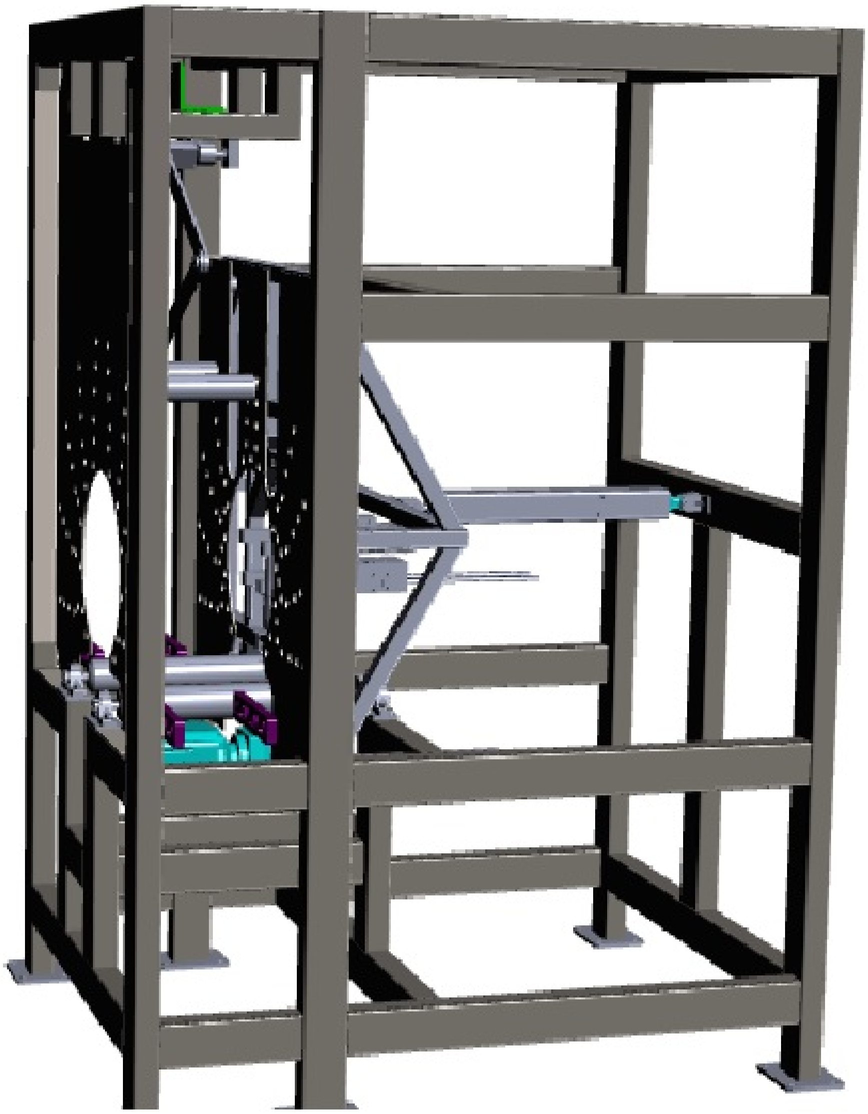
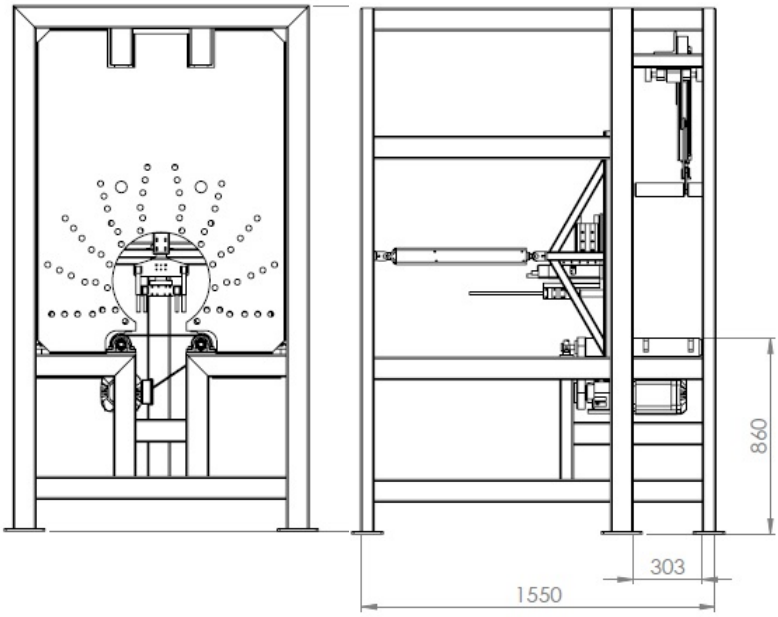
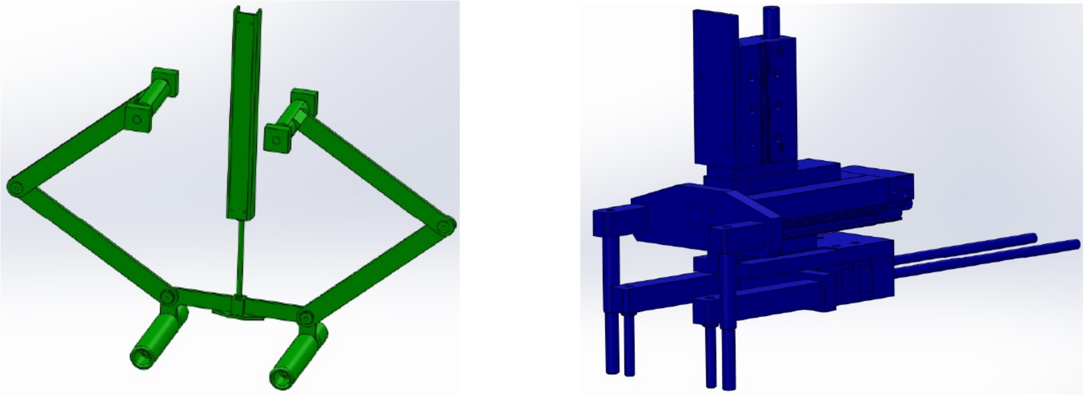


Figure 4.24: Tire handling solution used for the tire image acquisition station



(a) Front view (b) Side view

Figure 4.25: Tire handling solution: detailed views



(a) Tire Presser (b) Clip mechanism

Figure 4.26: Tire handling solution: mechanisms

mm. The experiments done until now revealed that the design of the clip mechanism needs to be improved. In one hand, the distance between the cylinders does not allow a good image acquisition of the interior due to significant constraints faced to positioning the light source in that region. In another hand, the time spent to adjust the clip mechanism is too long (more than 5 seconds), which compromises the total time desired for this process. For those reasons, the clip mechanism was removed and not considered in the tests developed along the experience.

4.2.5.2 Cost Analysis

Table 4.22 provides the list of equipment used in the prototype as well as the unit cost of each equipment. One shall note that the unit costs of the 2D cameras already include the cost of the lens; the unit cost of the 3D camera already includes the cost of the laser beam; the lighting source unit cost includes the cost of the heat sink, the socket and the electronic board used for light control.

The total investment cost for the prototype is about 98 500 €.

Table 4.22: Tire Image Acquisition Station: technologies used and unit cost

Technology	**Quantity**	**Unit cost**
Tire handling structure	1	50 000 €
AVT Prosilica GC780	5	1500 €
AVT Prosilica GC780C	1	1500 €
SICK Ranger E5540	2	10 000 €
Computer	2	1000 €
ABB IRB120	1	16 000 €
Kit Bioloid	1	700 €
Lighting source	8	100 €

For the industrial implementation of this solution one might expect a slightly lower cost due to the use of linear actuators instead of the manipulator ABB IRB120. However, a more expensive solution for the light positioning system is expected once the servo motors from Bioloid kit are not suitable for an industrial implementation. The final configuration of the light sources for the different tire surfaces will depend on the option adopted for the tire handling. The solution can be used only for a set of tires (based on the tire rim, for instance) or can be the same for all tires. Flexibility can be achieved either by a pre-determined number of light sources positioned in certain places, guaranteeing that all possible tires acquired in that station are covered by that lighting scheme or adjustable lighting position is used. The choice from one or another will depend on the number of different configurations needed and the cost/benefit analysis for each solution.

Regarding operational costs, one will assume maintenance costs around 10% of the total investment cost, i.e. yearly maintenance costs of around 10 000 €. With respect to energy costs, Table 4.23 shows the power consumption per unit provided by the supplier. Based on actual energy prices in Portugal, one might expect total energy costs per year around 7500 €.

Table 4.23: Power consumption per unit for technology used in the tire image acquisition station

Technology	**Power Consumption**
Tire handling structure	200 W
AVT Prosilica GC780	2.8 W
AVT Prosilica GC780C	28 W
SICK Ranger E5540	7 W
Computer	200 W
Lighting source	8 W

4.2.6 Results

The results obtained from the experiments realized in the prototype might be analyzed in two main aspects: the quality of the images and the acquisition time per tire. The quality of the images is somehow a subjective analysis. It can be seen from different angles, like the tire stability while rotating, the information gathered from the tire, etc. One of the ways to better assess the quality of the images is the feedback received from the virtual inspection. If the operators can identify the imperfections on the tire image, this means that the important information is placed in the the image. Besides, when the tire images are acquired, one shall verify if the tire image is properly acquired, i.e. if the information is visible (especially in tires with imperfections) as well as if the image fluctuations caused by tire vibrations are not significant. Another way to verify the quality of the images is to get an histogram of the intensity values for each image and guaranteeing a reasonable balance among the different tire surfaces.

Examples of tire images obtained in the prototype are shown in Figure 4.27, Figure 4.28,

Figure 4.29, and Figure 4.30. One can observe that the tire rotates with very low vibrations in the different directions.

Regarding the 3D image acquisition, one wants to gather the relevant information placed in the tire sidewall and bead, especially the characters that are needed for tire identification. The mold number characters are the smallest ones (despite the safety warning text), and they shall be used as reference for the image quality obtained. Figure 4.31 gives an example of the output obtained with the SICK Ranger E5540 camera.

Figure 4.27: 2D image captured from tire sidewall (inside)

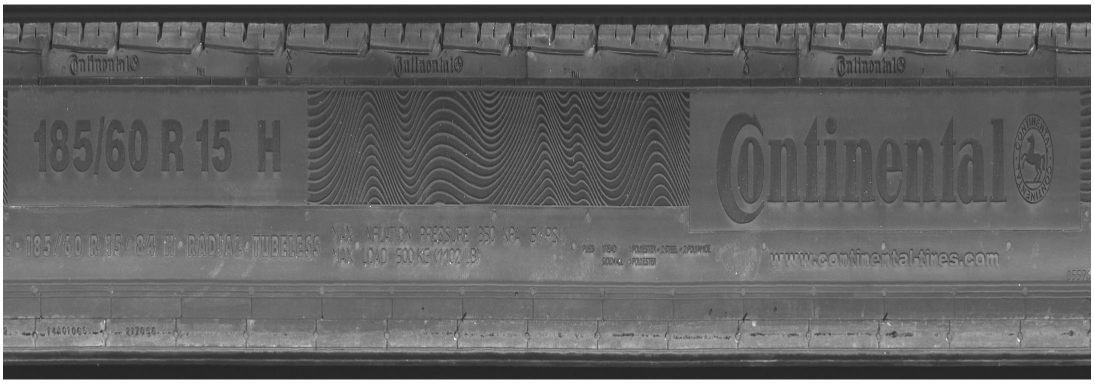


Figure 4.28: 2D image captured from tire sidewall (outside)

One of the most critical aspects in the tire image acquisition station is the process time. It will define the number of machines needed when the solution is introduced in the production line. One has stated that the tire shall be acquired in less than 5 seconds, based on a cost model developed for AutoClass project. The acquisition time per tire depends on two main variables: external tire perimeter and tire tangential speed. To obtain the acquisition time, one shall use the equation (4.32).

$$Acquisition\ Time = \frac{External\ Tire\ Perimeter}{Tire\ Tangential\ Speed} \tag{4.32}$$

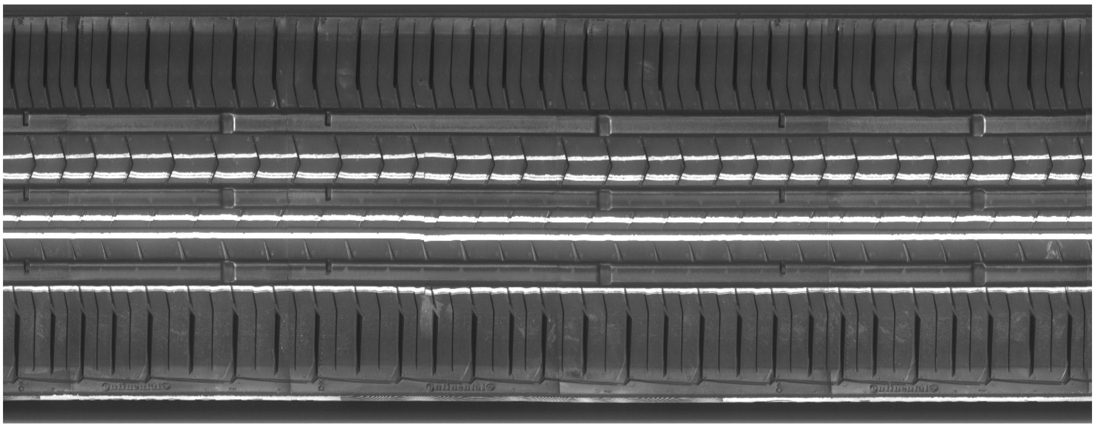


Figure 4.29: 2D image captured from tire tread

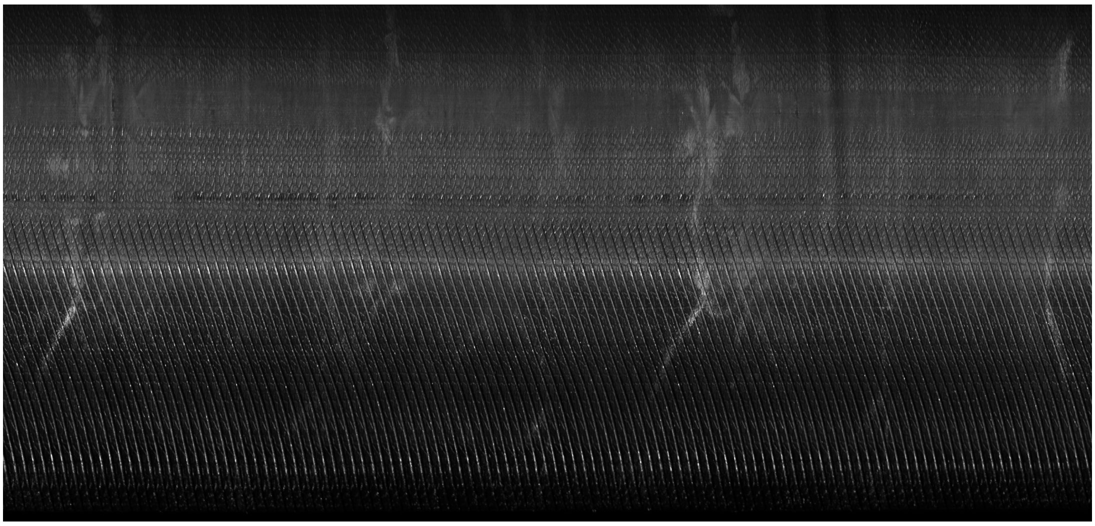


Figure 4.30: 2D image captured from tire interior

Figure 4.31: 3D image gathered from tire sidewall

where

$$Tire\ Tangential\ Speed = 612.5\ mm/s \tag{4.33}$$

The external tire perimeter directly depends on the tire dimensions: tread width, sidewall height (percentage of tread width), and rim size (in inches). In order to obtain the external tire perimeter, one shall use the equations (4.34), (4.35), and (4.36).

$$External\ Tire\ Perimeter = 2 \times \pi \times External\ Tire\ Radius \tag{4.34}$$

$$External\ Tire\ Radius = Tire\ Radius_{mm} + Tire\ Tread\ Width \times \frac{Tire\ Sidewall\ Height}{100} \tag{4.35}$$

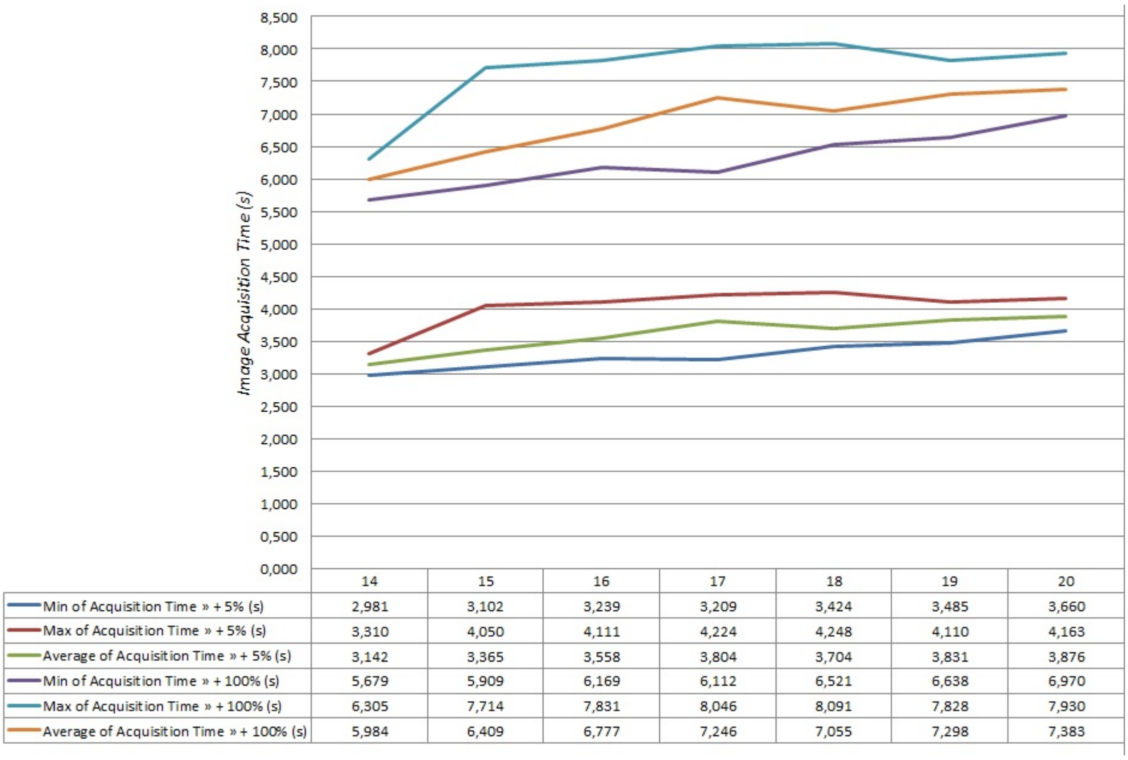
$$Tire\ Radius_{mm} = Tire\ Rim_{inch} \times 25.4 \times \frac{1}{2} \tag{4.36}$$

When the tire image is acquired, it is a good practice to acquire some additional tire portion besides one entire rotation. This shall be done in order to avoid that a certain imperfection exactly placed in the beginning of the acquisition cannot be acquired properly. In order to guarantee that situation, one suggests that 5% more tire surface shall be acquired. For the set of tires produced in Lousado plant, one might expect the time distribution presented in Figure 4.32, grouped by tire rim. The minimum, the maximum and the average acquisition time is provided for +5% and +100% tire surface acquisition. One can observe the time dispersion for each rim size and among the different rim sizes. For each rim size, one can obtain many different values depending on the sidewall height dimensions of the tire. In all cases, the tire acquisition per tire is lower than 5 seconds.

For the purpose of increasing the efficiency of the automatic tire detection algorithms, the reference tire (tire without imperfections of a certain article produced in a certain mold), shall be acquired twice in a row, i.e. double acquisition time is expected. However, the number of tires under these conditions is expected to be significantly smaller than the standard production, i.e. very small impact on process time is verified.

Tire image acquisition time is only a part of the total process time in the tire image acquisition station. One has to sum up the time spent in performing the necessary adjustments to accommodate the tire in the right conditions (wall movement, presser movement, and set tangential speed), the time required for equipment placement inside the tire, time for lighting positioning, and the overall process when the tire is released.

The results obtained in the overall process are around 7 seconds, with small variations according to the tire dimensions. The overall process is optimized in order to get the



	14	15	16	17	18	19	20
— Min of Acquisition Time » + 5% (s)	2,981	3,102	3,239	3,209	3,424	3,485	3,660
— Max of Acquisition Time » + 5% (s)	3,310	4,050	4,111	4,224	4,248	4,110	4,163
— Average of Acquisition Time » + 5% (s)	3,142	3,365	3,558	3,804	3,704	3,831	3,876
— Min of Acquisition Time » + 100% (s)	5,679	5,909	6,169	6,112	6,521	6,638	6,970
— Max of Acquisition Time » + 100% (s)	6,305	7,714	7,831	8,046	8,091	7,828	7,930
— Average of Acquisition Time » + 100% (s)	5,984	6,409	6,777	7,246	7,055	7,298	7,383

Figure 4.32: Acquisition time variation according to tire rim size (inches)

best process time possible and guaranteeing safety conditions for the equipment (e.g. the manipulator shall only go inside the tire when the tire is in the right place - when the wall movement is almost finished). The bottleneck is the presser adjustment. In order to accelerate this task, one suggests the use of electrical actuator.

One shall also take into account that these tests ran without the clip mechanism. The introduction of the clip mechanism will increase the total process time. The design of this mechanism shall be done in order to optimize this characteristic.

Another key aspect is the interface of the acquisition station with the conveying system. This process shall not introduce significant time to the overall process. The use of an intermediate buffer could be done in order to minimize this effect. The final design of the tire image acquisition station must take into account the interface with the conveying system. It has not been possible to test this feature since the prototype was installed apart from the conveying system.

Finally, the prototype is able to test a significant range of tires, except the spare tires which have tread widths lower than 150 mm. The handling solution for the prototype have some limitations that can be overcome by changes in the design of the presser as well as some attention needs to be payed for the design of the tool responsible to carry on the equipment for the image acquisition of the tire interior. The range of tires acquired along the experiments are shown in Table 4.24.

Table 4.24: Range of tire dimensions acquired in the tire image acquisition station

Tire Tim	Tread Range	Tires Acquired
14	155 - 185	134
15	165 - 205	296
16	195 - 235	395
17	205 - 275	152
18	215 - 265	239
19	225 - 275	92
20	245 - 275	72

4.2.7 Road map for Technology Integration and Deployment

At this stage, one has the technologies selected for the tire image acquisition system. In order to evaluate what is the most suitable alternative with respect to the ways of perform an industrialization of the solution, four alternatives were considered:

- A1: No industrialization
- A2: Implement the system only in Portugal plant
- A3: Implement the system in European plants
- A4: Implement the system worldwide

The four alternatives represent different scenarios of industrial implementation. The decision-maker can even decide by not industrialize the solution at all. The advantages and disadvantages of each alternative will be assessed in the following sections.

4.2.7.1 Externalities

One will consider two type of environment influences: internal and contextual. For this case study, one establishes the relative importance of each environment by the weights presented in Table 4.25. The values presented in Table 4.25 have a significant degree of uncertainty. However, it is expected that the internal threats might have more impact than the contextual ones. Regarding the opportunities, one expects not so significant differences in the contribution from internal and contextual environments.

Table 4.25: Opportunities and Threats relative importance for internal and contextual environments

	Environment	**Weight**
Opportunities	Internal	60.0%
	Contextual	40.0%
Threats	Internal	70.0%
	Contextual	30.0%

Internal Environment

The decision over the alternatives shall be done according to the following internal factors:

- *Opportunities*

IPC - Inspection Process Cost reduction by 50%: This is the main goal of the project. With the solution provided, it may be possible to achieve this objective. The opportunity can become even more interesting if the industrial implementation will be adopted in several plants of the company's group.

ESL - Employees Skill Level increase: The use of new technologies will provoke an increase in the employees' skill level. They will face new challenges but at the same time, they will be better prepared for future process changes.

BWC - Better Working Conditions: One of the most interesting outcomes of this solution is the possibility of enhance the actual working conditions, mainly related to ergonomic issues.

IRS - Improved Relationships with Suppliers: The complexity level of the technical solution presented will require a closer relationship with the suppliers in order to have a enhanced performance of the system and fulfilling the time requirements for the industrial implementation.

IPT - Improved Process Tracking: By identifying each tire the system is able to provide information about the mold number, i.e. the cavity in which the tire was cured. With this information is then possible to create a set of rules to highlight specific process alerts for vulcanization process, for instance. Moreover, the company is able to use the stored images for specific purposes (e.g. dedicated training sessions).

ICR - Improved Customer Relationship: By keeping the storage of the tire images, the company is able to provide quicker answers to possible customer complaints.

NPC - New Product Challenges: Product improvements and new areas of tire developments will create new challenges. The use of virtual inspection and technologies for tire acquisition can diminish the risks.

- *Threats*

EIL - Employee's Insatisfaction Level: The introduction of a new way of tire inspection in the production line may cause some mistrust degree on the employees because the new system might be seen as a threat for their job position.

CET - Cost of Employee Training: The suggested solution for tire inspection process requires a significant level of training to be provided. The number of operators involved in the new system will imply more or less investment in this subject.

ETA - Employees Technology Adoption issues: The new tire inspection process makes use of a set of new technologies and a necessary adaption is required by the operators. Once one is facing a process change, the adoption of new technologies by the employees might expect some obstacles.

LSR - Limited Supplier Range: The selection of suppliers is a key aspect to take into account. Regional supplier can provide a closer relation with the company, affording a better service. However, this can have some negative impact if the supplier is not able to implement the system worldwide.

EPR - Employee Placement Relocation: The enhancements introduced in the tire inspection process will lead to a reduction of the number of operators needed to execute the tire inspection. Additionally, the remaining operators have to be relocated in other tasks which can be seen by them as negative. This issue might be minimized if the inspectors perform multiple tasks in a rotational scheme.

In order to determine the relative importance of each opportunity factor for the internal environment, a pairwise comparison is computed and the results are shown in Table 4.26. The relative importance (weight) of each opportunity factor can then be extracted as well

Table 4.26: Opportunity factors pairwise comparison for the internal environment

	IPC	**ESL**	**BWC**	**IRS**	**IPT**	**ICR**	**NPC**
IPC	1	3	6	8	2	1	6
ESL	1/3	1	3	4	1/2	1/3	3
BWC	1/6	1/3	1	1	1/4	1/7	1
IRS	1/8	1/4	1	1	1/4	1/8	1/2
IPT	1/2	2	4	4	1	1/2	5
ICR	1	3	7	8	2	1	7
NPC	1/6	1/3	1	2	1/5	1/7	1

as the CR. As one can observe in Table 4.27, the CR is lower than 0.1, so the factors' weights obtained are reasonably consistent.

The same kind of computation was done for the threats in internal environment (see Table 4.28 and Table 4.29). Once again, one obtains a consistency ration lower than 0.1.

Table 4.27: Opportunity factors relative weight for the internal environment

Opportunity factor	**Relative Weight**	**CR:** 0.0674
IPC	29.13%	
ESL	11.24%	
BWC	4.15%	
IRS	3.46%	
IPT	17.12%	
ICR	30.36%	
NPC	4.54%	

Contextual Environment

The decision over the alternatives shall also consider the following contextual factors:

- *Opportunities*

WCL - Working Conditions Legislation: Due to the incidence of elder people (mainly in European countries) and an increase of retirement age, more attention is addressed to working conditions, mainly in areas in which physically

Table 4.28: Threat factors pairwise comparison for the internal environment

	EIL	**CET**	**ETA**	**LSR**	**EPR**
EIL	1	5	3	7	6
CET	1/5	1	1/4	2	3
ETA	1/3	4	1	4	3
LSR	1/7	1/2	1/4	1	1/3
EPR	1/6	1/3	1/3	3	1

demanding tasks are in place. Actual tire inspection process is one of them, and the introduction of the new tire inspection system can be beneficial for the operators, in first place, and for the company too.

CIP - Company Image Perception: The introduction of technology innovation in the inspection process might have positive impact in the company's image perception. Trustful customer relationships are always required in this industry and technical innovation can contribute for its enhancement.

IPM - Intellectual Property Management: Technology innovation is a powerful tool for company's competitiveness. In such a competitive industry where innovation is very valued being a step forward can create competitive advantage. Dealing with expectations management and Intellectual Property (IP) management is essential to maximize the advantages that can be obtained from a non-added value process as the tire inspection process.

PSI - Product Sales Increase: The company is facing an increase in market share and product sales. With process cost reduction expected by the introduction of a new tire inspection system, this will mean higher profit margins.

Table 4.29: Threat factors relative weight for the internal environment

Threat factor	**Relative Weight**	**CR:** 0.0816
EIL	49.73%	
CET	11.90%	
ETA	24.35%	
LSR	5.18%	
EPR	8.83%	

WER - Worldwide Economy Recover: Some economists forecast an economy recovery for the next years. Although the uncertainty level is high, this can have very positive impact in the industry in general, and for the company in particular.

- *Threats*

CPC - Competitor Patent Conflict: Introducing automation in the tire inspection process has been always a goal many tire manufacturers were seeking for. Significant investments have been done in this research area although none company has announced a new tire inspection system so far. However, since this is a research area where several developments were done in the past years, time management of IP management is crucial to avoid interfering with existent patents.

ICA - Investment Capital Availability: Due to actual economy situation, access to capital became more difficult. The level of investment capital will depend on the level of implementation of the new system worldwide.

LPC - Local Perception of the Company: The human resources management is a key issue to take into account with the introduction of the new tire inspection system. Once the number of operators needed in the new system is lower than actual process. Reducing the number of operators might have negative impact on local company's perception.

TPR - Technology Price Reduction: Technology evolution and technology mass production will lead to price reduction. The continuous introduction of automation in the industrial processes will have this impact. The perception of the right time to implement the system is essential. However, some of the technologies used in the new tire inspection process are already mature.

UTE - Unstable Tax Environment: Tax environment always play an important role in investment decisions. Due to the actual economical situation tax systems become less predictable and can lead to higher or lower risky decisions.

EEU - European Economy Uncertainty: Although economy recover is expected, the European economy perspective is still uncertain. The risk becomes higher when uncertainty is higher.

In order to determine the relative importance of each opportunity factor for the contextual environment, a pairwise comparison is computed and the results are shown in Table 4.30. The relative importance (weight) of each opportunity factor can then be extracted as well

Table 4.30: Opportunity factors pairwise comparison for the contextual environment

	WCL	**CIP**	**IPM**	**PSI**	**WER**
WCL	1	1/7	1/3	1/7	1/4
CIP	7	1	3	1	3
IPM	3	1/3	1	1/5	1/2
PSI	7	1	5	1	3
WER	4	1/3	2	1/3	1

as the CR. As one can observe in Table 4.31, the CR is lower than 0.1, so the factors' weights obtained are reasonably consistent.

The same kind of computation was done for the threats in contextual environment (see Table 4.32 and Table 4.33). Once again, one obtains a consistency ration lower than 0.1.

Table 4.31: Opportunity factors relative weight for the contextual environment

Opportunity factor	**Relative Weight**	**CR:** 0.0198
WCL	4.23%	
CIP	33.99%	
IPM	9.65%	
PSI	37.52%	
WER	14.61%	

Results of the algebraic model

After computing the relative weights of all factors (internal and contextual), it is now possible to apply the algebraic model presented in 4.1.2 in order to obtain the strategic value per unit of risk for each alternative.

A preliminary step consists of calculating the total opportunity value and the threat opportunity value as shown in Tables 4.34 and 4.35.

The remaining outputs from the algebraic model can then be computed and the results are shown in Table 4.36.

One observes that the most promising alternative, derived from the algebraic model is alternative A3 (Implement the system in European plants). This is the alternative that has

Table 4.32: Threat factors pairwise comparison for the contextual environment

	CPC	**ICA**	**LPC**	**TPR**	**UTE**	**EEU**
CPC	1	1/5	1/2	3	1/4	1/7
ICA	5	1	3	5	2	1/2
LPC	2	1/3	1	3	1/3	1/4
TPR	1/3	1/5	1/3	1	1/5	1/7
UTE	4	1/2	3	5	1	1/3
EEU	7	2	4	7	3	1

Table 4.33: Threat factors relative weight for the contextual environment

Threat factor	**Relative Weight**	**CR:** 0.0374
CPC	6.06%	
ICA	24.38%	
LPC	9.11%	
TPR	3.74%	
UTE	17.92%	
EEU	38.81%	

Table 4.34: Comparison of the strategic alternatives (Opportunities)

		Env. Weight	**Factor Weight**	**Alternatives**			
OPPORTUNITIES	**Internal Factors**	0.600		*A1*	*A2*	*A3*	*A4*
	IPC		0.291	0.10	0.90	0.90	0.90
	ESL		0.112	0.10	0.90	0.90	0.90
	BWC		0.041	0.40	0.90	0.90	0.90
	IRS		0.035	0.20	0.40	0.60	0.80
	IPT		0.171	0.10	0.90	0.90	0.90
	ICR		0.304	0.20	0.50	0.70	0.90
	NPC		0.045	0.50	0.70	0.80	0.90
	Contextual Factors	0.400					
	WCL		0.042	0.70	0.70	0.70	0.70
	CIP		0.340	0.00	0.40	0.70	0.90
	IPM		0.096	0.00	0.30	0.60	0.70
	PSI		0.375	0.40	0.50	0.70	0.80
	WER		0.146	0.50	0.50	0.50	0.50
	Total Opportunity Value (U^m)			0.200	0.633	0.759	0.848

Table 4.35: Comparison of the strategic alternatives (Threats)

		Env. Weight	**Factor Weight**	**Alternatives**			
THREATS	**Internal Factors**	0.700		*A1*	*A2*	*A3*	*A4*
	EIL		0.497	0.20	0.30	0.30	0.30
	CET		0.119	0.00	0.80	0.90	1.00
	ETA		0.243	0.00	0.60	0.70	0.80
	LSR		0.052	0.00	0.20	0.60	0.80
	EPR		0.088	0.00	0.50	0.60	0.70
	Contextual Factors	0.300					
	CPC		0.061	0.10	0.20	0.30	0.40
	ICA		0.244	0.20	0.30	0.50	0.70
	LPC		0.091	0.20	0.30	0.20	0.10
	TPR		0.037	0.50	0.50	0.50	0.50
	UTE		0.179	0.50	0.50	0.40	0.30
	EEU		0.388	0.50	0.50	0.50	0.30
	Total Threat Value (T^m)			0.182	0.436	0.490	0.514

Table 4.36: Algebraic model output results

	Alternatives			
	A1	*A2*	*A3*	*A4*
Strategic Value (V^m)	0.018	0.197	0.269	0.334
Opportunity Value Variance (V_u^m)	0.029	0.046	0.015	0.011
Threat Value Variance (V_t^m)	0.058	0.029	0.039	0.082
Standard Deviation (S^m)	0.295	0.274	0.232	0.305
Strategic Value per unit of risk (E^m)	0.061	0.719	1.159	1.095

the highest strategic value per unit of risk. However, the key question is: **Is alternative A3 always the most suitable option?**

4.2.8 Sensitivity Analysis

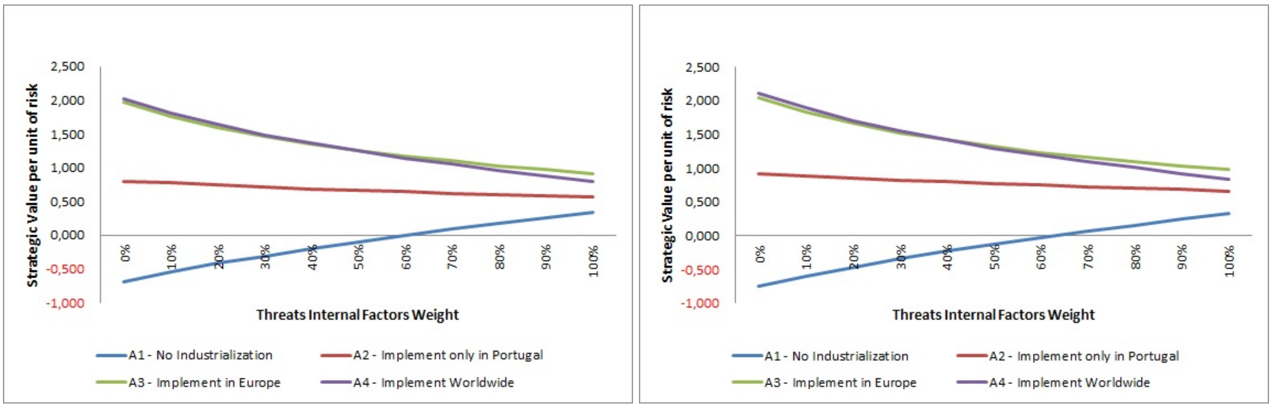
The analysis done until now establishes a specific value for each variable. However, uncertainty is inherent to each of the values (weights and probabilities) determined along this process. In order to overcome this limitation, several scenarios can be build up so the decision-maker will have wide and detailed perspective about the context in which he/she has to take a decision.

One of the aspects of analysis shall be the influence of the environment weight in the final result, i.e. in the strategic value per unit of risk. One started with internal environment weight for opportunities equal to 60% and internal environment weight for threats equal to 70%. By varying these two variables, one shall expect a variation of the strategic value per unit of risk with the trend shown in Figure 4.33.

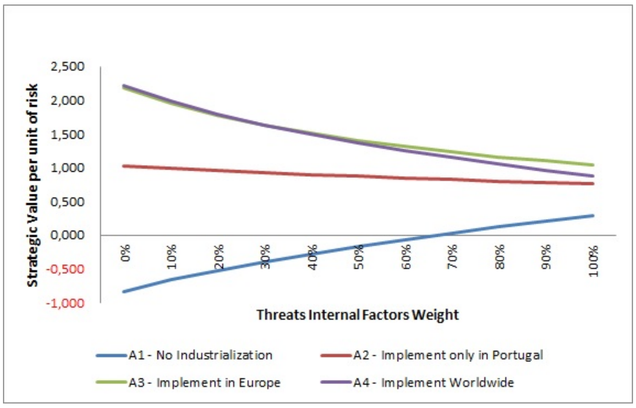
One might notice that the alternative A2 (Implement the system only in Portugal plant) is the one showing a behavior not significantly influenced by those variables. On contrary, the other alternatives revealed a behavior deeply dependent on those two variables. For alternative A1, for threats internal factor weights below 50%, one will always get strategic values per unit of risk negatives.

The most suitable alternative (A3 or A4) depends on the environment weight considered, although the strategic value per unit or risk of each of these alternatives do not differ too much. Another sensitivity analysis that one shall perform is to observe the influence of some opportunity / threat factor probabilities in the overall appreciation of each alternative. Figure 4.34 gives an idea about the influence of the IPC (Inspection Process Cost reduction by 50%) and EIL (Employee's Insatisfaction Level) factor probabilities in the strategic value per unit of risk for each alternative. The highest strategic value per unit of risk has non-linear dependence over the two variables as one can observe in Figure 4.34. The trend revealed in those charts enhance the importance of understanding the impact of the uncertainty in the attribution of these values. The impact of IPC shows the importance of this factor in the overall result as one might expect for a relative importance of 29.13%.

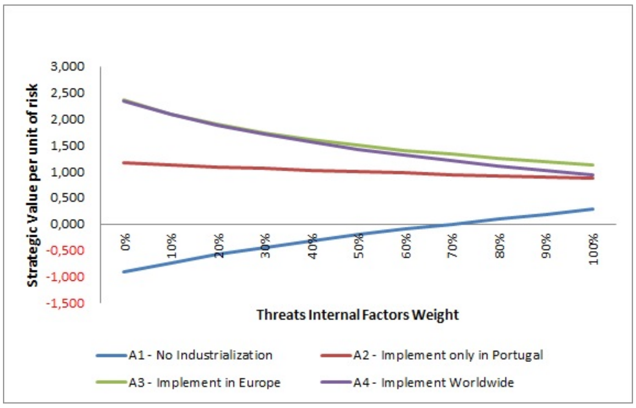
This kind of analysis shall be performed for as many variables as possible in order to get the most information possible. However, one suggests to perform the sensitivity analysis for the top 3 opportunity / threat factors in each environment (see the results obtained for ICR vs. EIL in Figure 4.35). This shall be enough to take the most adequate decision.



(a) weight = 50% (b) weight = 60%

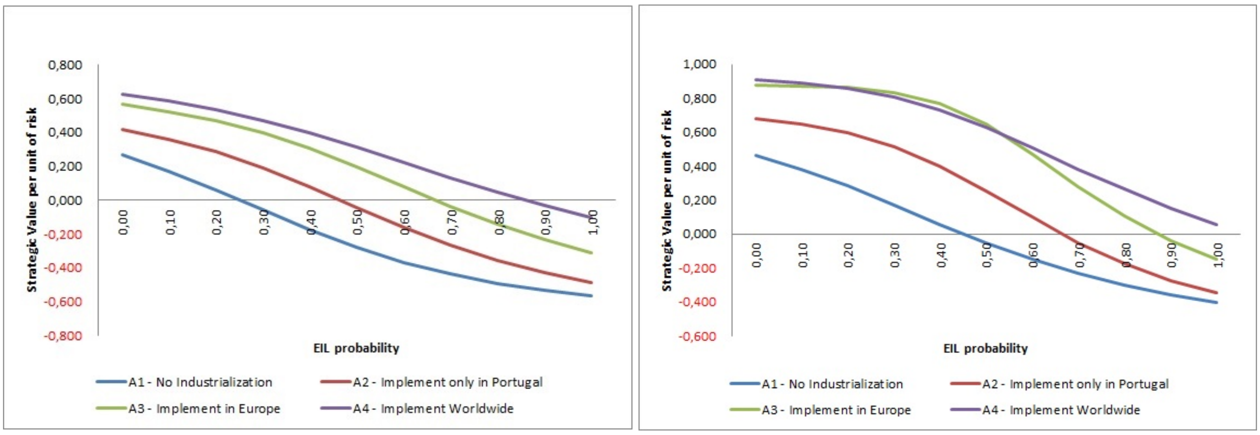


(c) weight = 70%



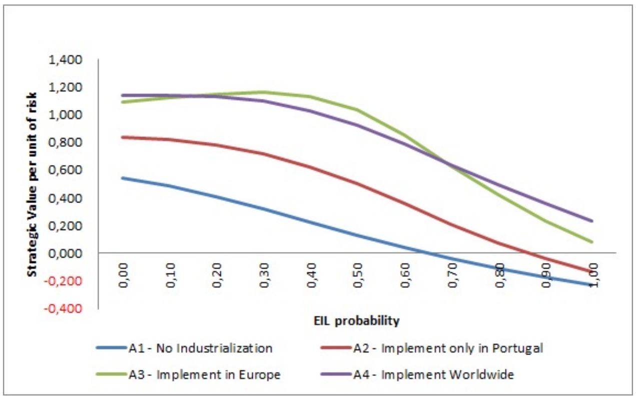
(d) weight = 80%

Figure 4.33: Opportunities vs Threats Internal Factor weights influence



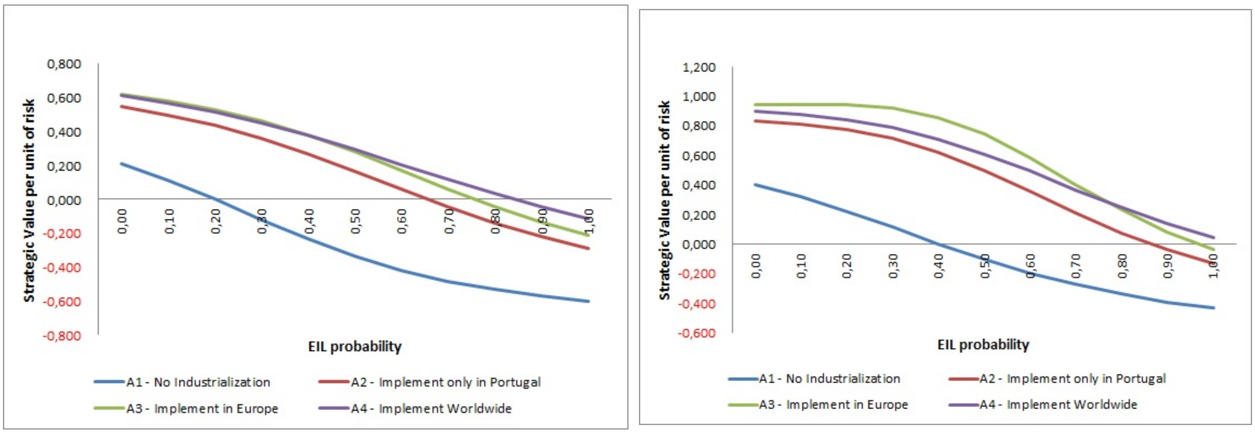
(a) IPC probability = 0.10

(b) IPC probability = 0.50



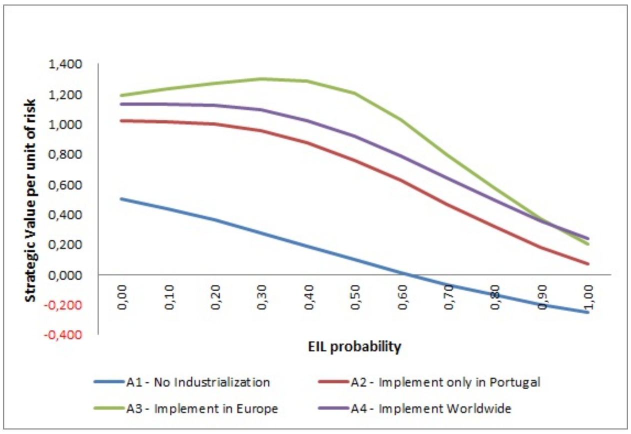
(c) IPC probability = 0.90

Figure 4.34: IPC vs EIL probabilities' influence



(a) ICR probability = 0.10

(b) ICR probability = 0.50



(c) ICR probability = 0.90

Figure 4.35: ICR vs EIL probabilities' influence

4.2.9 Risk Assessment

In the previous analysis, one could observe the influence of the different variables in the strategic value per unit of risk for each alternative. The trends manifested by each alternative revealed the influence that those variables have in the attractiveness and in the risk of each alternative.

The most suitable alternatives (A3 and A4) are also the ones with higher total threat value, which means that the inherent risk is also higher. The uncertainty measured by the opportunity / threat value variance is also more significant in those two alternatives. For a risk-averse decision-maker, these two alternatives might be seen as interesting but, at the same time, with high level of risk. Another way to analyze the results obtained in the sensitivity analysis is to measure the difference between the maximum and the minimum strategic value per unit of risk one gets: great differences mean higher risk.

4.2.10 Conclusions

The methodology presented in this section of the document has shown suitable for the case study described in 4.2. Such a complex technology selection requires structured, clear and extensive methodology. Although several steps are needed, this is also a guarantee of a suitable decision for a concrete application. The application of this methodology has proven to be effective in the prototype definition once the solutions adopted revealed to be suitable for the tire inspection process.

A successful implementation of this methodology requires the involvement of several players, from the engineering department, to the quality department, and industrial engineering department in order to better assess the different technologies and to define the most adequate set of requirements and respective criteria for comparison.

Regarding the deployment phase, one suggests that the company opts for the alternative A2 (Implement the system only in Portugal plant). Alternative A2 can be seen as a pilot experience reducing the risk of a wide implementation of this solution. Although the prototype has shown very promising results and alignment with the project goals, the transition from a prototyping phase to the industrial implementation phase requires a lot of attention due to the high risks involved in such a process change.

With the results observed with alternative A1 (No industrialization), the decision-maker can then decide the most adequate plan of industrial implementation in the other plants. One shall notice that the environment and factor weights as well as the probabilities of a certain factor to happen may vary among the different facilities. Technology adoption issues or employees' level of satisfaction can vary significantly according to the context.

The most interesting aspect of the approach followed for the new tire inspection system is the possibility to incorporate iteratively degrees of automation in the process while measuring its effects. This gives to the decision-maker a powerful tool to take the most suitable decisions.

Chapter 5

Human-Machine Interfaces

The solution proposed for the new inspection system gives high importance to the virtual inspection process. The virtual inspection process is an innovative approach to the tire inspection process breaking the rules of the standard approach followed in this kind of inspection where the human-based process is replaced by an automatic system.

The virtual inspection workstation is being designed to replace the standard manual inspection, but it can also go beyond the display of images and provide new tools that may optimize the inspection process. From the inspection point of view, the minimum requirement is that the same (if not better) detection rate is achieved using the workstation for interpretation instead of the physical object. From the process point of view, the minimum requirement is that the workstation improves efficiency (faster inspection) while reducing stress and fatigue for the operator and improving workflow.

The design of the virtual inspection interface shall pay special attention not only to the interaction between the operator and the application but also for the way the information is displayed in order to maximize the operator's performance. It shall also reduce the impact caused by such significant change in the tire inspection process.

5.1 HMI development methodology

The HMI development is a critical step in the overall development of the new tire inspection system. In one hand, the virtual inspection will be used for the tire quality assessment, and in the other hand, it is also a tool to gather information to validate the tire image acquisition system and to feed the automatic tire detection algorithms.

The drastic change in the inspection process requires a careful approach in order to minimize the effects of some reluctance to change by all the stakeholders involved in the process. For that reason, a close approach with the operators is followed so the interface design developed are aligned with their expectations and at the same time can fulfill the goals of the project.

With all these requirements, a structured approach to the problem must be followed. A methodology for the HMI development was designed and it is shown in Figure 5.1. The methodology follows an empirical approach [121] once it is based on the performances or opinions of users gathered in experimental situations.

To start the process, one has to identify the key features for the virtual inspection interface. As mentioned before, the interface seeks for effective and efficient tire inspection, but also as a platform for continuous process improvement.

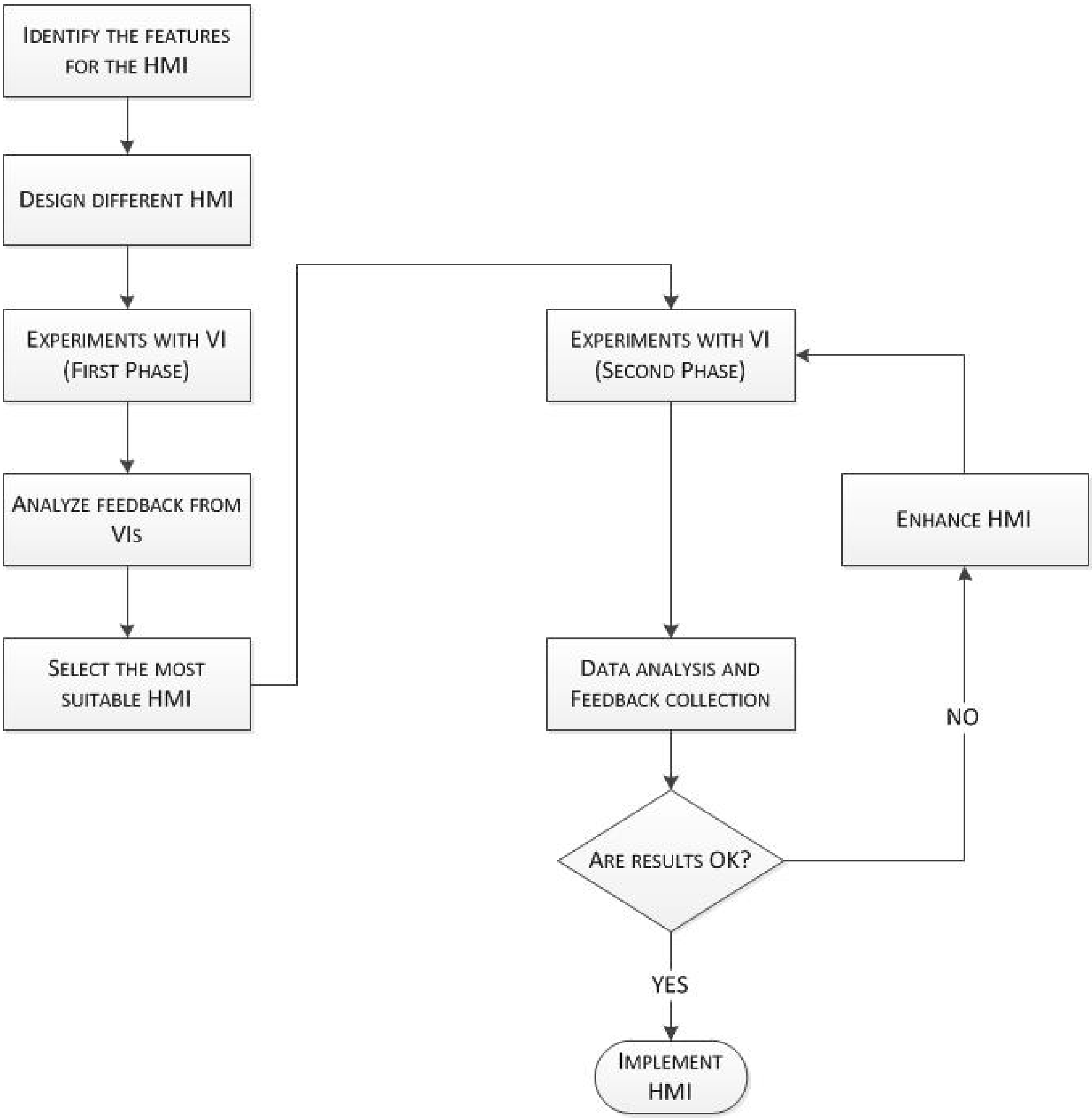


Figure 5.1: Methodology followed for HMI development

Based on the identified features, one shall design different interface designs that can go in the direction of the requirements for the virtual inspection process. It shall also take into account that the process change effects shall be minimized so one might expect good results in short term.

In order to perform the first phase of the experiments with the operators, one selected 8 visual inspectors, from the same shift, who are 30 years old (on average), and have an average time of experience in the visual inspection process of six years. One assumes that all operators involved in this first phase have a minimum experience with computers and HMI.

The methodology consisted in a 30 minutes sessions with each operator, with an introductory phase where the operators got in touch with the visualization tools developed so far (three in total), and they could play with the interfaces in order to get familiarized with them. The interfaces ran on a 42 inches screen, with 1920×1080 pixels resolution. A set of pre-selected tires were shown and one asked the operators to perform the tire inspection. For each tire image, the inspection time and the decision are registered for each visualization tool. Each operator that participated in this experiment has done two sessions. In the first session the objective is to understand the context and target of the study and to receive training in one mode. The second session will be focused on the usage of the second mode and to perform a comparison. The setup will consist of a standard desk equipped with a monitor which will be placed in front of the participant.

At the end of the experiment, a quick survey (Appendix B) is requested to be filled-in and an informal Question & Answer session is done with the aim of gather operators' feedback about the different visualization tools. An interview with a combination of open-ended and close-ended questions will be done to each operator. The open-ended questions will be used to capture the operators impression of the new tool as well as its main problems and to get suggestions on how to overcome them. The close-ended questions with a Likerts five-point scale will be used to describe the intensity of specific problems that the tool might have.

The results from this experience are then analyzed in order to identify the most suitable virtual inspection interface. With the feedback gathered from the experience, one might also develop some additional features to enhance the most suitable interface design.

When all the material is ready, the second phase of the experiments with operators can start. In the second phase, two operators from each week shift (six in total) are randomly selected. They will be asked to perform virtual inspection of a set of tires (around 40 tires which corresponds to 160 images), organized in sessions, each of them lasting between 30 to 60 minutes, depending on their inspection pace. The tires for each session are selected in order to guarantee a ratio of 9 to 1, i.e. nine tires OK for one tire with imperfections (tire NOK), once is the actual (average) ratio in the production flow. All the relevant information (inspection time, quality grade, imperfections' marking, etc.) is registered for further analysis. The experiments ran in a workstation with a 21.5 inches screen with 1920 × 1080 pixels resolution.

In a regular scheme (once per week) a so called "training session" is done with each operator with the aim of get their feedback for eventual interface enhancements. At the same time, some specific images are shown to them, so they are able to be more sensible to the way the imperfections are showing-up in the virtual inspection. Although they are well-trained and knowledgeable operators, the new virtual inspection process introduces some new features in the inspection process, especially in what concerns the imperfection perception. After a reasonable number of sessions (around 15 sessions) and number of different imperfections acquired, the weekly "training sessions" are replaced by a pre-determined number of images (roughly 10 images per session) where the type of imperfection is referred to the operator, so he knows in advance that a certain image has a specific imperfection (Appendix C). In this way, one intends to provide specific training to all operators, ableing them to perceive how the different imperfections manifests in the image.

Based on the feedback and the analysis of the results obtained, one might need to perform some adjustments in the interface design. When the results are aligned with the objectives, the cycle might finish.

5.2 HMI Features

The virtual inspection system to be developed was thinking to have two fundamental goals: provide a new decision-support tool for the tire inspection process, and define a platform to support and introduce new developments for a continuous process improvement. The first objective intends to improve the actual tire inspection process by means of reducing the inspection time and, at least, keep the same level of quality performance. The system shall also be seen as a platform in which the current and future developments can be tested and the results recorded in a straight forward way giving the possibility to take decisions over the time in order to introduce, iteratively, additional levels of automation to the overall system. The new visualization tools shall be able to serve as a validation both for the tire image acquisition system and for the automatic tire detection system.

An important aspect to be taken into account is the guarantee that the design production systems are cognitively compatible with the mental models of the workers. A comprehensive checklist of the criteria is presented by Fuchs-Frohnhofen *et al.* [126], in which workers shall be able to:

- Learn about and adapt easily to the system and its different uses
- Directly experience and manually influence the manufacturing process
- Make use of databases and decentralized information networks (but with protection of personal data)
- Simulate manufacturing processes before starting the “real“ process
- Develop communication and cooperation in groups and networks
- Maintain and repair the system
- Make use of the system’s self-explanation features and documentation

In the end, the HMI functions can be specified in the following global categories [117]:

- Supporting the accomplishment of all goal classes: **goal functionality**
- Supporting the transformation and usage of all available means: **means functionality**
- Supporting appropriate task perception and performance: **task functionality**
- Organizing sufficient and timely information, transfer from and to the technical system and all its subsystems with respect to goals, means, and tasks: **dialog functionality**
- Visualizing all process and systems states with respect to goals, means, and tasks: **presentation functionality**
- Avoiding or compensating for human errors: **human error-tolerance functionality**

Another important feature to take into account is the time operators will be using the virtual inspection. For an entire shift (8 hours), operators will be using the new visualization for at least 6.5 hours. Although the utilization time is not consecutive, some fatigue effects might be expected. Thus, the HMI shall also guarantee that fatigue effects along the time are minimized with respect to the system performance.

5.3 Interface Designs

Based on the features identified for the HMI, different interface designs were developed in order to create the most suitable solutions to achieve the determined goals. Three different interface designs were developed intending to enhance certain characteristics of the actual tire inspection process, but at the same time to get advantage of the new visualization tools to strengthen the process performance. The features of each interface design and the correspondent advantages and disadvantages are presented in the following sections.

5.3.1 Interface Design 1

The interface design 1 seeks to translate the actual tire rotation movement to the screen. The plannar image captured in the tire image acquisition station is shown to the user in a 1:1 scale, so none detail of the tire image is lost. In opposition to the current tire inspection station, the tire movement speed can be adjusted by the user, so each operator can define the most suitable speed for his inspection. The user has total control about the tire movement and can even stop or move the tire image backwards.

The interface design 1, shown in Figure 5.2, has the following features:

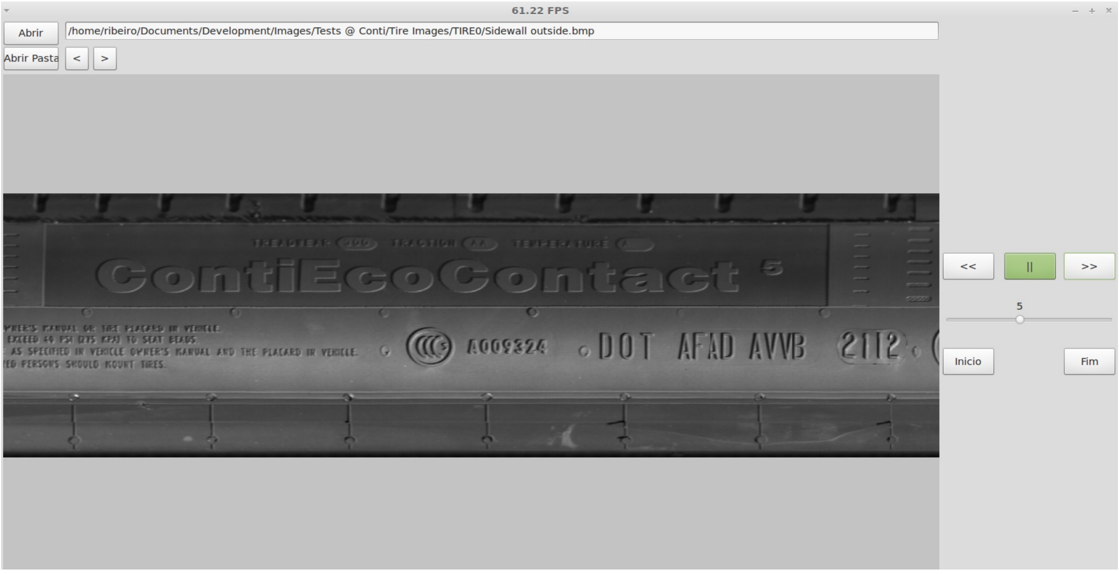
- Images of the different tire surfaces are loaded separately
- Images are moving on the screen (like a film) and the user can adjust its speed (backward and forward) with the mouse wheel
- The user can stop the image movement when needed
- The image is shown in 1:1 scale

This interface design has the following advantages:

- The tire is shown in a 1:1 scale, offering the best possible view of the image
- By controlling the tire movement speed, the operator can adapt the movement to his pace

However, the interface design 1 has the following disadvantages:

- The tire movement does not create the same effect has the one faced in the actual VI station
- The user has many ways of interacting with the interface



/home/ribeiro/Documents/Development/Images/Tests @ Conti/Tire Images/TIRE0/Sidewall outside.bmp

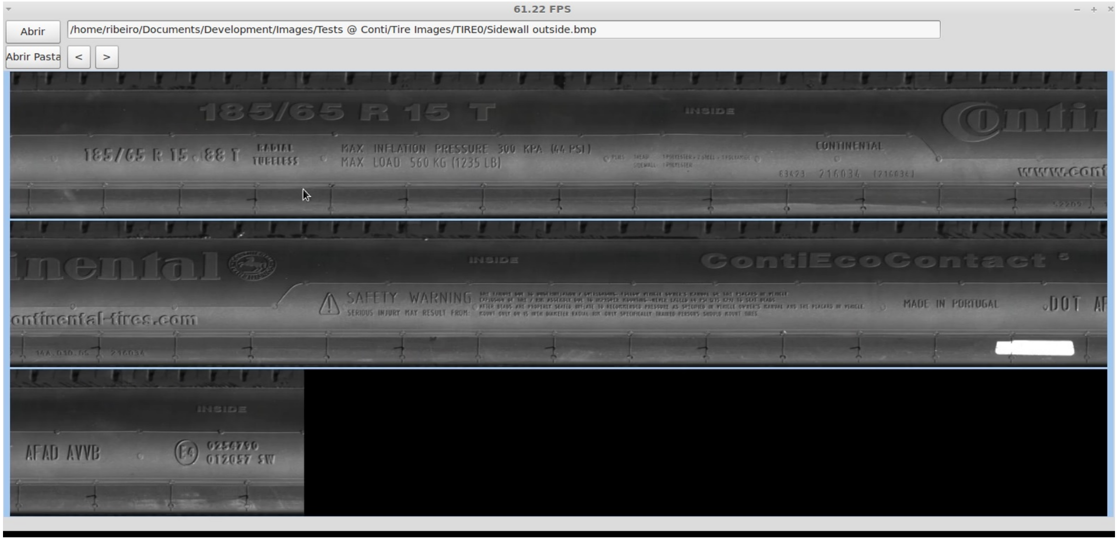
Figure 5.2: HMI design 1: tire image flowing on the screen

- The tire movement creates the flicker effect on the image
- The user has no perception about the region is looking at with respect to all tire surface

5.3.2 Interface Design 2

The aim behind the development of interface design 2 is to speed-up the inspection process. Instead of showing only a portion of the tire image, like in interface design 1, one shows the entire surface at glance. Although compromising some image quality due to loose some image information, the user is able to have a wide perspective of the tire surface. The information lost is bigger as bigger is the image length.
By observing the entire tire surface, the operator is able to identify specific tire points (e.g. different tire splices) as reference points where certain imperfections have a tendency to occur. Some extra image portions need to be added in the viewer edges in order to guarantee that a small imperfection is well seen.
The interface design 2, shown in Figure 5.3, has the following features:

- Images of the different tire surfaces are loaded separately
- An entire image of a specific tire surface is shown on the screen
- The image is split into a number of branches that guarantees the image aspect ratio
- The user can zoom in/out in a specific area of the image



/home/ribeiro/Documents/Development/Images/Tests @ Conti/Tire Images/TIRE0/Sidewall outside.bmp

Figure 5.3: HMI design 2: static view of the tire image split into layers

This interface design has the following advantages:

- All tire surface is shown at glance, so each operator will work at his own pace
- Possibility to show only parts of the tire where automatic inspection process has doubts
- Fewer operators interactions with the interface are required
- Possibility to show more than one tire surface at a time

However, the interface design 2 has the following disadvantages:

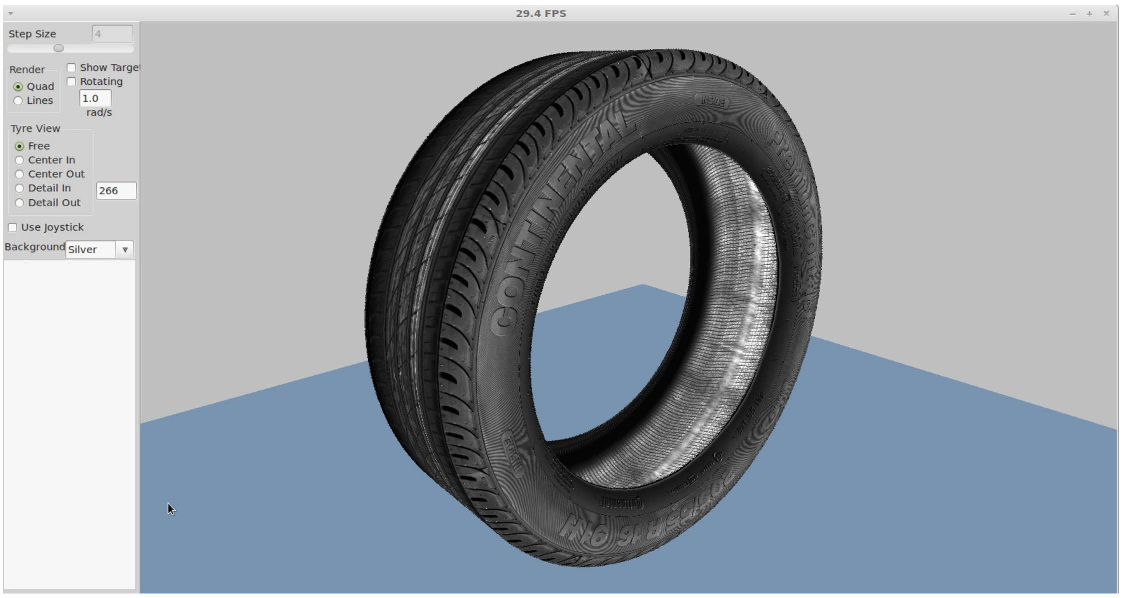
- The tire image is not in its ideal scale (although the user can zoom in to get it)
- The last branch is not completed in most of the cases
- The tire image occupies the entire screen, but the operators tend to look for the central part of the screen
- Extra image portions are added to avoid misleading decisions

5.3.3 Interface Design 3

The actual inspection process occurs in a 3D environment. The operator is able to inspect more than one surface at a time, and has an overall perspective of the tire, especially in the transition between the different tire surfaces. The idea behind the interface design 3 is to come-up with the actual context into the virtual environment. The 3D model

reconstruction of the tire is able to provide the user with the “real“ perspective of the tire enhanced by the fact that no obstacles are in place for the inspection and controllable lighting conditions are provided.
The interface design 3, shown in Figure 5.4, has the following features:

- The 2D images of the different tire surfaces are stitched to the tire 3D model
- Different tire views are available for the user
- The tire can rotate at a speed defined by the user
- The user can handle the tire and inspect the tire at the same time



Step Size 4

Render
● Quad
○ Lines

☐ Show Targe
☐ Rotating
1.0 rad/s

Tyre View
● Free
○ Center In
○ Center Out
○ Detail In
○ Detail Out
266

☐ Use Joystick

Background Silver

Figure 5.4: HMI design 3: 3D view of all tire surfaces

This interface design has the following advantages:

- The operator have a similar view as the actual process
- Possibility to inspect more than one tire surface at a time
- The operator has a full perspective of the tire

However, the interface design 3 has the following disadvantages:

- The tire handling requires some expertise of the operator due to more complex interactions

- The 3D model of the tire requires the use of additional technology (e.g. 3D laser scanner)
- A perfect image stitching may not be possible and this can create confusion to the operator
- Time spent in tire handling might be significant
- Most of the times, the information provided has a quite low effective resolution

5.4 Preliminary Results

At the end of the first phase of the experiments, one could collect the results from the experiences as well as the qualitative feedback the operators provided. Some of the feedback received form the operators are listed below:

- “This tool can help us a lot!”
- “I need more contact with the interfaces, but the first impression is very good.”
- “The quality of the images is better than when seen the tire at the VI station.“
- “This approach is much better than the actual process.“
- ”Tires are becoming bigger and heavier which make our job harder. In this way, this approach solves that issue.“
- “Sitting in front of the computer the entire shift will be tough.“
- “I am afraid I could not see some imperfections that I am used to detect by haptics.“

Regarding the inspection results, one will drive more effort for the inspection time performance of the operators. Nevertheless, in order to have a broader perspective of results, the performance regarding the decisions over the quality grade of the tire are also provided. Figure 5.5 shows the inspection time distribution of three different operators (indicated as VI1, VI2, and VI3) using interface design 2. The inspection time refers to the time spent to inspect and attribute a quality grade (OK or NOK) to each tire image. It is assumed that the distribution time follows a Gaussian curve, where the sample contains 75 images. One observes that VI1 and VI2 have similar performances with respect to inspection time, while VI3 is slower and has higher variation. Regarding the assessment of the the tire quality grade, Table 5.1 shows the results for the same three operators. The decisions are split into good decisions, false positive result, and false negative result. Good

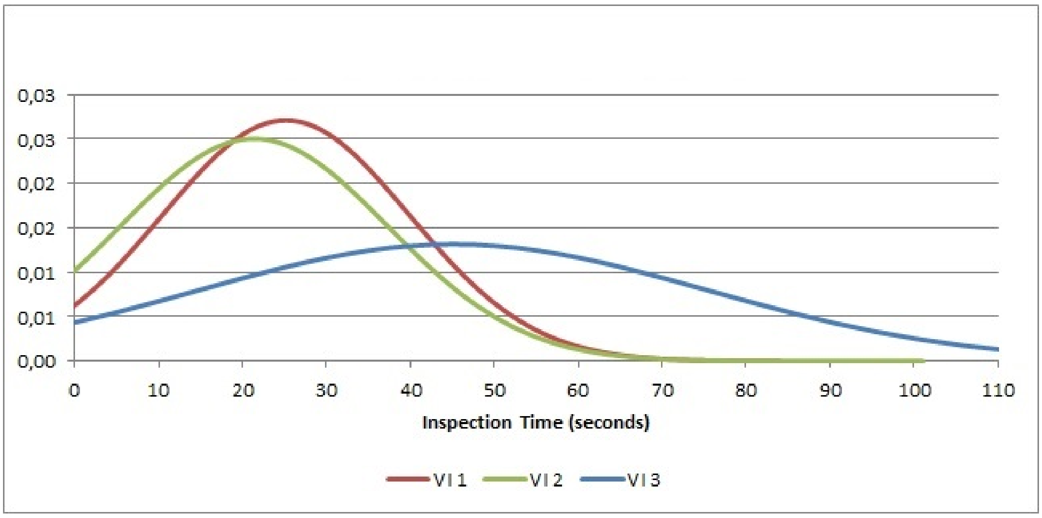


Figure 5.5: Inspection Time Distribution of 3 operators in the first phase of the experiments

decisions occur both when the operator considers the tire OK when the tire is effectively OK and when the operators rejects the tire when the tire is NOK. False negative result means that the operator considers a tire NOK when the tire is OK. Finally, a false positive result, the most critical one, means that a tire is classified as OK when, in fact, the tire is NOK. This result means that either the imperfection is not contained in the tire image or the operator was not able to identify it. From the results obtained, one has identified the following main outcomes:

Table 5.1: Results of the operator's decisions along the first phase of the experiments

Decision	**VI1**	**VI2**	**VI3**
Good	63.01%	68.49%	65.75%
False Positive	32.88%	0.00%	26.03%
False Negative	4.11%	31.51%	8.22%

- The tire image acquisition shall be improved, mainly in the buttress and tread regions
- Test the visualization tools with NCs actually detected by haptics
- Some operators could take decisions over certain images in about 3 seconds
- Interface design 2 has been the preferred one among the operators

- All the imperfections existent in the different tire images are contained in the image once at least one operator could take the right decision in all images
- The size of the screen shall not be so big since the operators have to be placed far from the screen and they have some difficulties to observe the entire image
- The screen resolution shall be kept
- Some ergonomic issues shall be fixed

Regarding the screen size, the 42” screen used in the first phase of the experiments imposes that the operator is at a minimum distance to the screen of 1.8 m [171]. For a 21“ screen, the distance drops to less than one meter (0.7 - 0.9 m).

The results showed that there is still room for improvement with respect to the interface design. However, the promising results obtained at this preliminary stage indicate that the approach followed is in the right direction to reach the goals. The operators were requested to use the application without previous dedicated training with the system and without being familiarized with the way imperfections are translated into the image.

There are also two ergonomic issues that need to be fixed: the room lighting conditions and the user vs. screen relative position. Figure 5.6 shows the effects caused by the direct light on the screen as well as the shining effects created by the screen type. These effects have a negative impact on the operator’s performance and capabilities along the time. For that reason, a non-shining screen and indirect room light shall be the options. The size of the screen and the wrong working distance (distance between the user and the screen) implies an inadequate view angle for the user, provoking wrong user posture with possible healthy problems (Figure 5.7). In this case, the design of the workstation shall take into account these aspects. The use of a 21” screen will also contribute positively for this issue.

The analysis of the results obtained in the first phase of the experiments also showed the need to perform some improvements in the interface design. The design shall also take into account that images have to be grouped in sessions, the need to record the imperfection location tagged by the operator, and to optimize the image distribution along the screen viewer. Figure 5.8 reveals the virtual inspection interface designed for the second phase of the experiments with the operators. The interface guarantees an optimal distribution of the tire image over the viewer, creating the necessary number of branches adequated to keep the image aspect ratio of the original image, to contain all the tire image in a single view. The optimization is done in order to minimize the difference between the viewer aspect ration and the image aspect ratio for a minimum of one branch and a maximum of five branches.

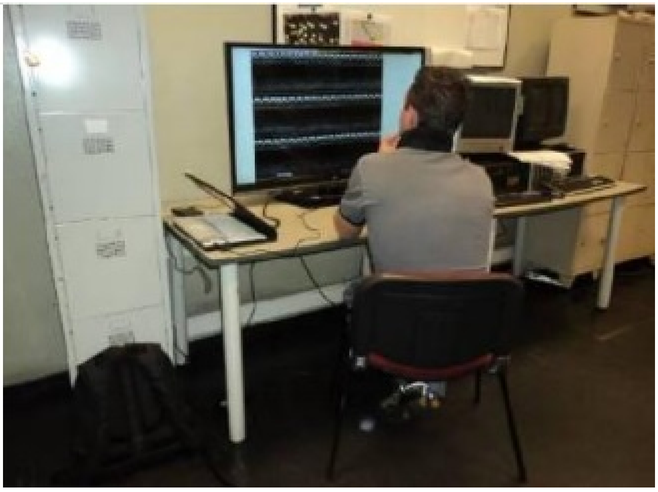


Figure 5.6: Room lighting effects on the screen

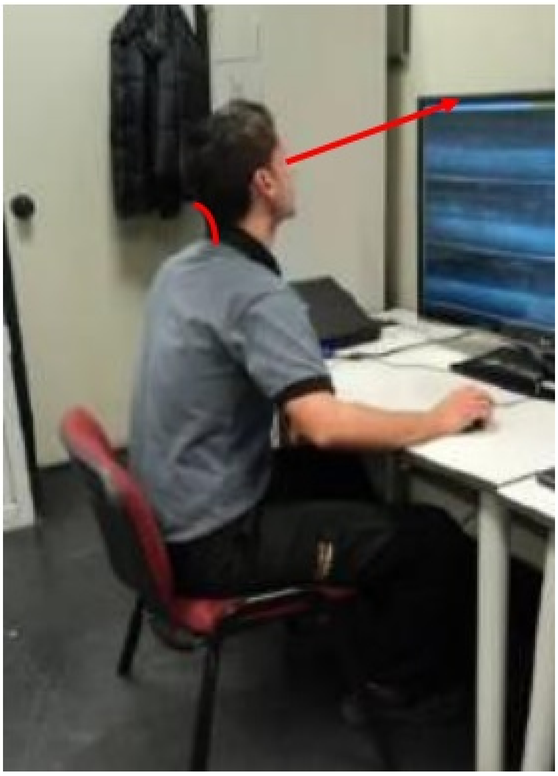


Figure 5.7: Inadequate view angle and screen size not adapted to the workstation

Utilizador: Jason Teixeira

Session: 2

Figure 5.8: Virtual Inspection interface: first version

The interface also contains additional information like the user name. The interaction of the user with the application is done with a mouse at this stage, where the left button is used to tag the imperfection on the image, and to press the buttons to proceed with the virtual inspection.

The user logins in the application with the employee's ID number, thus a unique user is accessing the virtual inspection application at each time. The application also has the possibility to incorporate a password for each operator, enhancing the guarantee of restricted access to the application.

5.5 Data Collection and Analysis

The second phase of the experiments intends to get the most relevant data for future implementation of the virtual inspection system. Each operator involved in the second phase of the experiments (6 in total) are randomly selected among the different shifts, identifying two operators per shift. The selection procedure also takes into account the vacation scheme and availability along the experiment. However, not all operators were able to complete all the sessions available due to medical absence or parental leave. Whenever the operator is foreseen to miss several days, one decided to select another operator to substitute him. Once one assumes that the performance among the operators is similar, this should not have significant impact in the results obtained.

The sessions contains a set of tire images from the different tire surfaces of each tire acquired in the tire image acquisition station. The set of tires are from many different articles, with different tire dimensions and having different tire imperfections with the aim of covering as much as possible all tire imperfection codes. The number of tires OK and NOK have a 9:1 ratio in order to have a sample with a representative population of the production.

To gather all the relevant data from the experiment, one has created a data structure as shown in Figure 5.9. The application records the following data:

- Session start time
- Session end time
- User ID
- Inspection time for each tire image
- Decision for each tire image (OK or NOK)
- All tags (regions where the operator marks the potential imperfection) associated to each NOK tire

For the purpose of the study provided in this document, one will pay attention to the inspection time for each tire image. The quality assessment is also analyzed in the AutoClass project. Some of the aspects that will be mentioned in this section have also contributions from the quality assessment study.

The inspection time (and the quality assessment) under the virtual inspection environment is influenced by three main factors:

- Quality of the tire images
- Interface design adequability
- Operator's training level

The quality of the tire images exclusively depends on the performance of the tire image acquisition station. The interface design can contribute positively or negatively for the inspection performance. The way the image is displayed and its quality as well as the interaction needed to take decisions will influence the inspection time each operator will spend for each tire image assessment. The operator's training level is related to the level of familiarization each operator has with the new visualization tool. The familiarization with the interface design is also important but confidence with the way the tire features are shown in the virtual environment plays a critical role. As more confident the operators

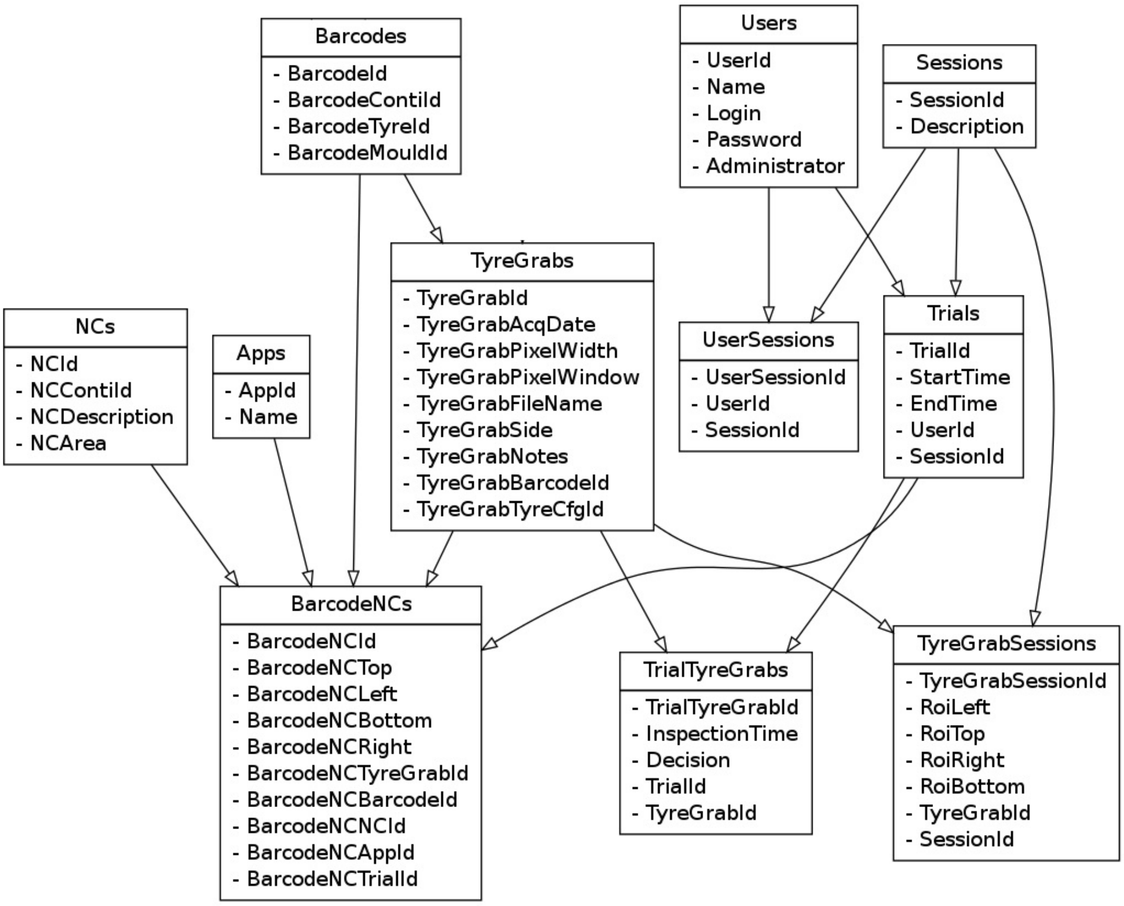


Figure 5.9: Data structure used for experiment data gathering

are the lowest inspection time is expected. The learning curve influence shall be visible in the results obtained although the total time spent by the operators in the experiments will not achieve one entire week of work. For reference, in the actual process, a new operator is trained for two months and after starting the inspection procedures in the production line he will need additional two months (in average) to reach the desirable performance of roughly 30 seconds per tire inspection. Taking into account that their current knowledge is not lost, the adaptation time required for the new inspection process shall also be significant.

The inspection time analysis will cover the influence of the following factors:

- Tire surface
- Tire image length size
- Tire grade (OK or NOK)
- Learning curve

For each tire (each tire is identified by its barcode), the operator will have four different images from each tire surface: sidewall outside, sidewall inside, tread, and interior. Each tire surface of a certain tire will be acquired with the same number of frames, thus the tire image length will be the same in all tire images of a specific tire. However, the information for each tire surface image will be very different. For the sidewall (inside and outside) the amount of data is significantly higher when compared with the tire images of the tread or the interior. For that reason, one shall expect a slightly different inspection time over the different tire surfaces. Figure 5.10 shows the influence of the tire surface in the inspection time for the group of operators involved in the experiment. One can observe that the hypothesis mentioned above is confirmed. The difference observe in the inspection time from the sidewall inside to the sidewall outside is explained by the fact that the sidewall outside surface is the one visible to the end-user and it is the surface where the VI spends more time and attention in the current inspection process.

The inspection time plotted in the graphics are the median values. The median values were selected in order to get rid of extreme tire image inspection times caused by a break in the middle of the session observed in several trials.

Another important aspect is the size (length) of the image showed to the operators. The image length depends on the tire dimensions. With the interface design chosen for this experiment phase, the longest the image length is the more shrunk image is expected, i.e. the number of branches tend to increase with the increase of image length. This means that the image data is “compressed” and one is losing image information. The effect that

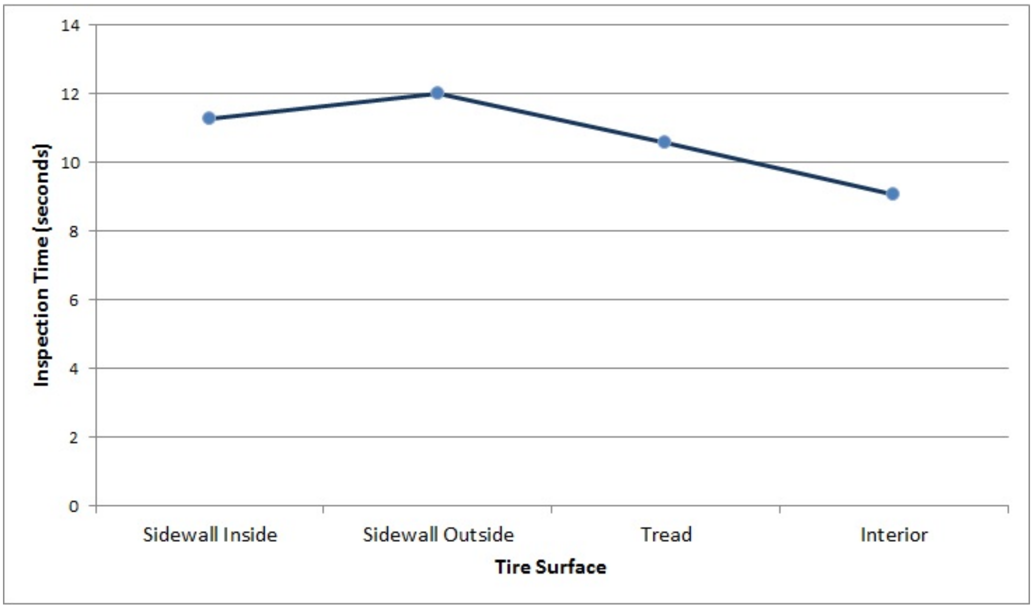


Figure 5.10: Inspection time influenced by tire surface viewed

is expected is that the operator will spend more time in images with higher length size, as one can observe in Figure 5.11. The graphic shows the image length size split in intervals of 1000 pixels for better assessment. The image length size influence is evident. The quantity of tire image showed to the operators in the virtual inspection environment will have impact in the overall inspection process time.

One is asking the operators to mark all the imperfections observed in the tire image. In one hand, one pretends to distinguish between the decision of accepting/rejecting a tire. On the other hand, it is also important to understand if the tags marked by the operators coincide with the reference tags or the tags generated by the automatic tire detection process. However, tagging a tire (draw a rectangle which contains the tire imperfection) is creating additional time of inspection. So, higher inspection time is expected for the NOK tires as it is shown in Figure 5.12.

This is a very important aspect to consider for the interface enhancement. The way the operators indicate the imperfection location shall be improved in order to reduce the time impact verified along the experiment.

The results shown in Figure 5.13 are the results obtained by one operator involved in the experiment with respect to the quality assessment of the tire images. Although at least one operator could correctly assess the quality grade of each NOK tire, the results show that something needs to be done in order to enhance the performance of virtual inspection.

The outcome from the results provided above implied two main changes: intensify the training sessions and change the interface design. The training sessions are important for the operators to perceive the way the imperfection is featured in the tire image once in

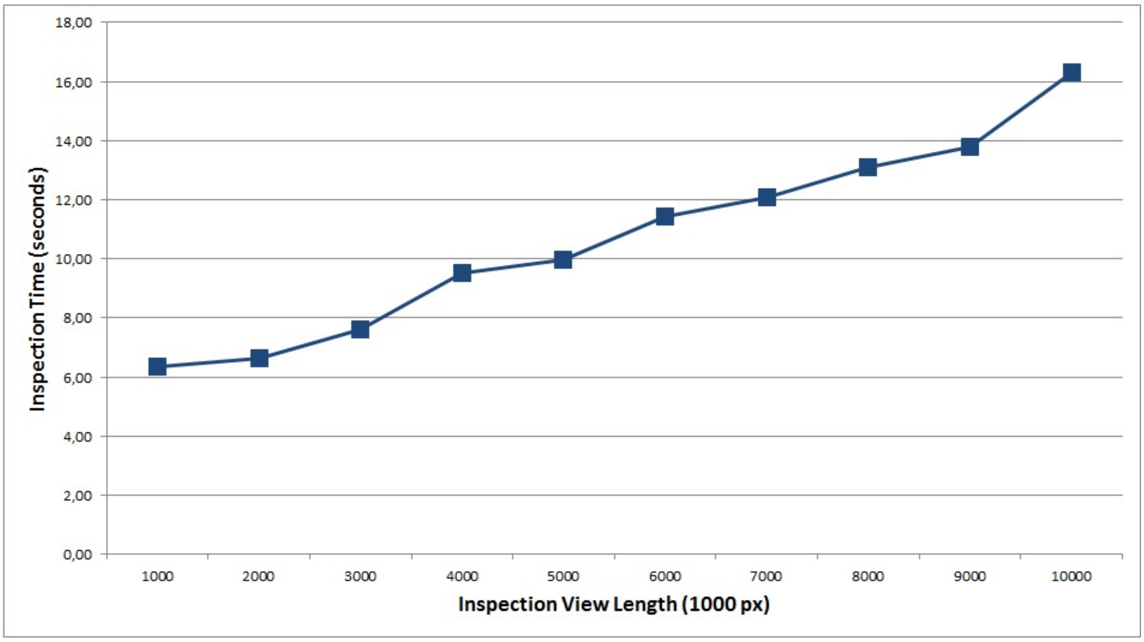


Figure 5.11: Inspection time influenced by the image length

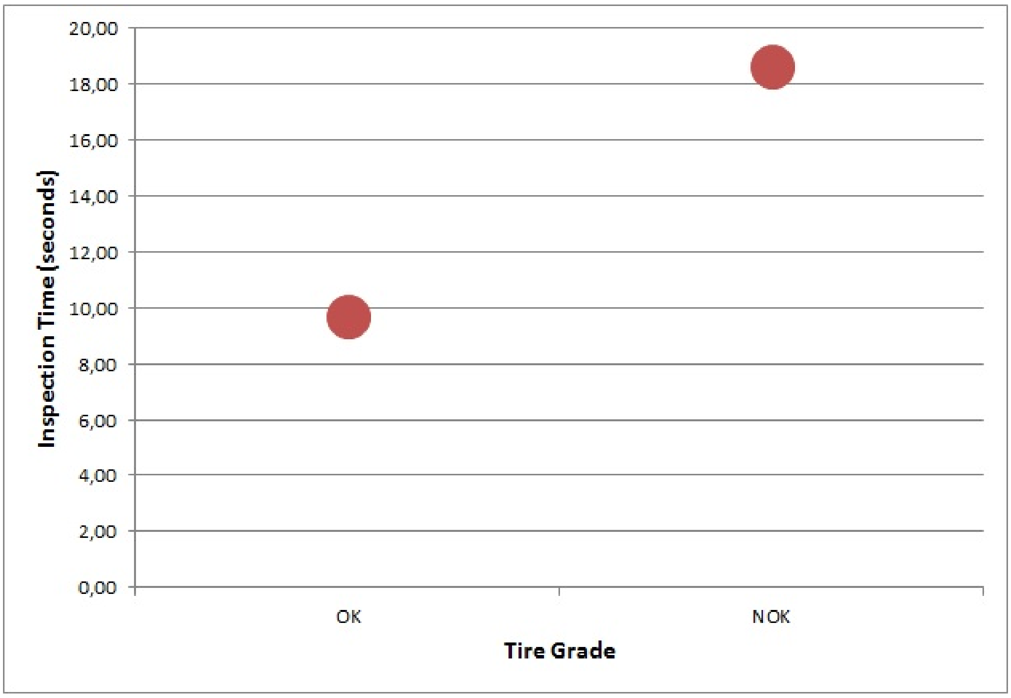


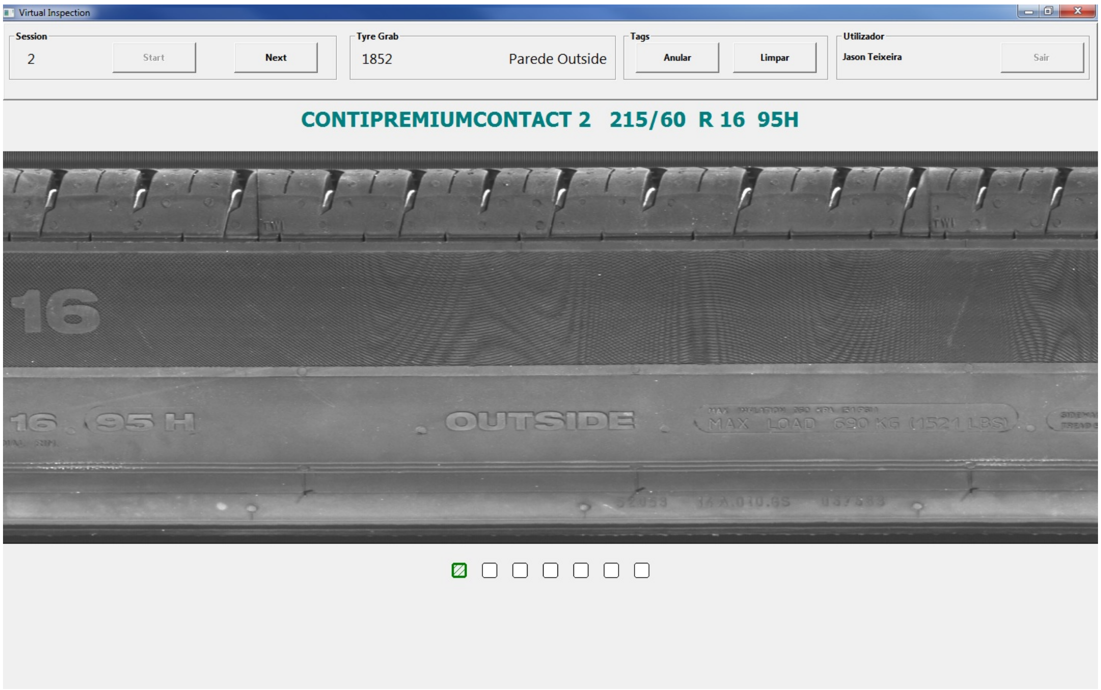
Figure 5.12: Inspection time distribution by tire grade

Figure 5.13: Quality assessment results from one operator

certain cases it is slightly different from the actual process (e.g. blisters or tire breakers misaligment). The introduction of 10 tire images of NOK tires in the beginning of each session has this purpose. Each tire image has an unique tire ID and the correspondent imperfection is indicated to the operator. The operators are requested to identify the NC in the tire image and tag it. In this way, the operator can understand how a certain imperfection looks like in the new environment.

Another important development is the design interface improvement. The feedback from the operators is that in some cases the tire images are very "small" in size, constraining the performance of the operator and obliging him to zoom in several times, especially in the bead and buttress areas in the sidewall images. Another important aspect referred by the operators is the importance of having additional information about the tire under inspection which can facilitate the decision. Taking into account those aspects, one has developed an enhanced interface design as shown in Figure 5.14.

In the new interface design, the image is showed in a 1:1 scale, and the image is divided in different slices depending on the image length size. The user navigates along the image with the mouse wheel in both directions. The way the user tags the imperfections is the same as in the previous version. The interface design makes use of the entire screen width in order to maximize the quantity of image showed. Some extra image (100 frames) are showed in each image slice transition in order to guarantee that an imperfection located in that region is not neglected. The inspection time in the new version is expected to not increase significantly, although more information is showed and some time is required



Session 2

Tyre Grab 1852 Parede Outside

Tags

Utilizador Jason Teixeira

CONTIPREMIUMCONTACT 2 215/60 R 16 95H

Figure 5.14: Virtual Inspection interface: enhanced version

to navigate along the entire image. However, once the information in the image is more clear (no information is lost), one expects that the operator will reduce the inspection time required for each image piece. Figure 5.15 shows the results obtained along the experiment considering the different environments operators faced.

The different features of the enhanced version of the Virtual Inspection design interface

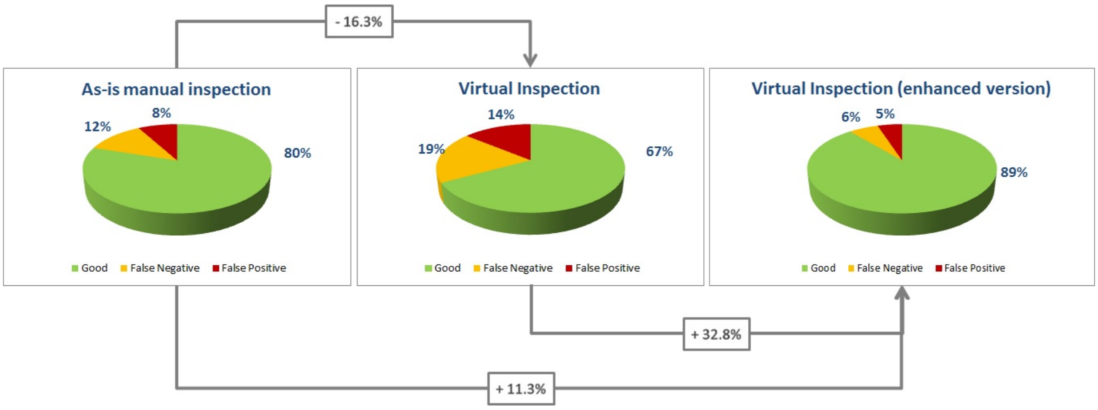


Figure 5.15: Virtual Inspection results comparison for the enhanced design version

(Figure 5.16) are the following:

1. **Session number**: number indicating the actual session under inspection. It is also used to guide operators through the training sessions sheets.

2. **Session Start button**: the operator presses this button to start the session.
3. **Next image button**: the operator presses this button whenever he wants to inspect the next image.
4. **Tyre Grab ID**: the ID number of a specific tire image. This information is used for the list of images included in each training sessions.
5. **Tire surface description**: it is important for the operators to know in advance the tire surface they are analyzing. This is especially important for the images of the tire sidewall (e.g. the barcode must be always in the sidewall inside surface).
6. **Tags menu**: when the operator tags an imperfection in the tire image, he is able to remove the last tag or all tags marked in that specific tire image.
7. **User Name**: the name of the operator is shown.
8. **Logout button**: at the end of each session, the user might logout or start a new session (if available).
9. **Tire information**: the tire name, tire dimensions, and speed index is shown to the operator. This kind of information can improve their decision process, once operators develop cognitive skills that relates tires to the tendency of certain imperfections occurrence.
10. **Progression Bar**: the number of squares indicate the number of tire image pieces. The ▨ indicates the actual piece view; The 🟩 indicates the tire image pieces already viewed by the operator; The ☐ indicates the tire image pieces not viewed yet by the operator.

In order to better assess the influence of the tire image length size, one has prepared special sessions for the operators in which the set of tire images are exactly the same. The difference among them is the image length size of each. In session 17, the entire tire image is showed. In session 29, 80% of the image length size is presented to the operators. Sessions 30 (60% of the image), 31 (40%), and 32 (20%) have continuous size decrease up to show only 20% of the image length to the operators in session 32. The idea is to directly compare the inspection time results evolution in the different sessions to gather the contribution of this variable to the virtual inspection time output. The results obtained for the above mentioned sessions are plotted in Figure 5.17. One pays attention to the images with imperfections, guaranteeing that they are contained in the image showed to the operators in each session.

Session: 2

Tyre Grab: 1852

Parede Outside

Tags

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Figure 5.16: Virtual Inspection interface: details of enhanced version

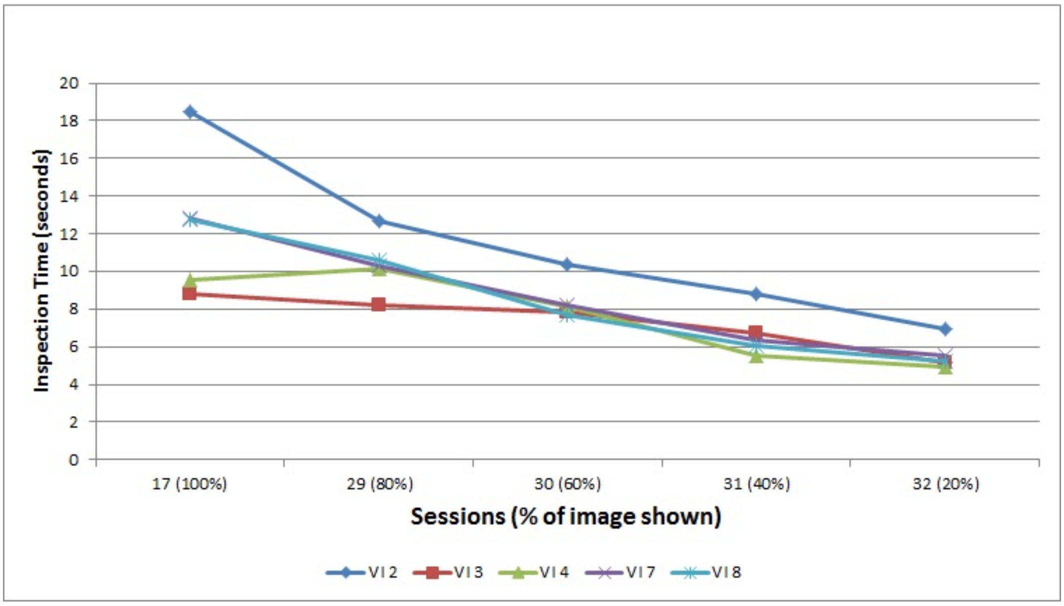


Figure 5.17: Inspection time of the same tire images with different lengths

5.6 As-is and Proposed Solution Comparison

Along the phase two of the experiments, the same number of operators were randomly selected to perform the so called “physical” inspection of the tire. In fact, these operators will only perform the visual inspection of the tires exactly in the same conditions as today. However, in order to have reasonably similar data for analysis, the operators are asked to inspect tires already trimmed, and they do not need to identify the tire. In thus way, both “physical” and virtual inspection users will only inspect the tires.

The same set of tires are assessed by both groups in each session. The results obtained in each group are shown in Figure 5.18 (virtual inspection) and Figure 5.19 (“physical” inspection). In the “physical” inspection, the inspection time corresponds to the time spent to inspect the entire tire. In the virtual inspection, the measured time is per tire image. To compare both results, one can multiply the inspection time of virtual inspection by four (the number of tire images per tire).

The results showed clearly the influence of the experience in the inspection time. In “physical” inspection, operators are performing the tire inspection exactly in the same way as they are used to while in virtual inspection operators need to adapt to the new reality. However, the trend verified in the inspection time in virtual inspection has shown that even better performance might be achieved with time and training.

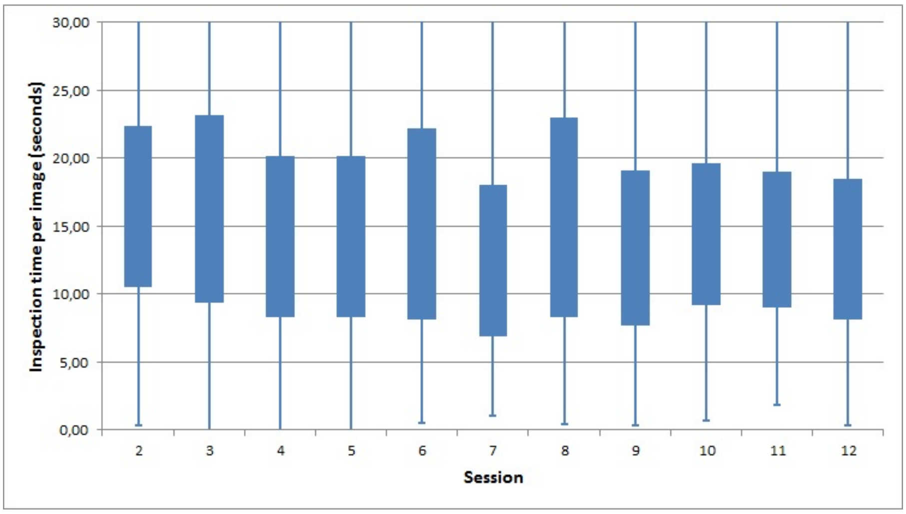


Figure 5.18: Virtual Inspection: inspection time (per image) distribution for each session

It is important to highlight that the working conditions (with respect to ergonomic conditions) are considerably different in the two environments. The study realized under the Ergos project, in particular the results of the workstation assessment (see Appendix D), showed that operators are exposed to physical demanding tasks with the possibility of developing future healthy issues. The new approach for the tire inspection process by means

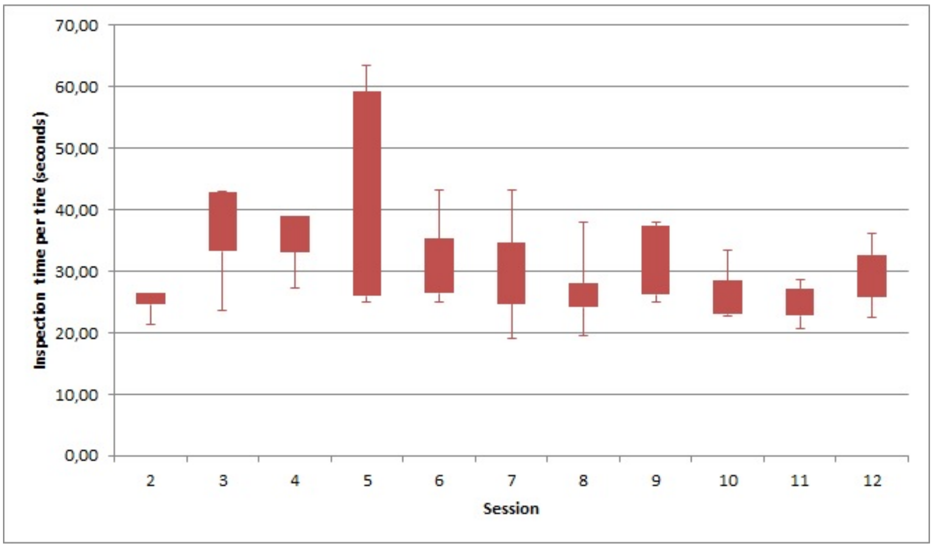


Figure 5.19: Physical Inspection: inspection time (per tire) distribution for each session

of virtual inspection, minimizes significantly these risks. Nevertheless, some aspects shall be taken into account like the schedule of operator's breaks and the possibility to perform other tasks along the shift or in different days in a rotating scheme.

5.7 Conclusions

The results gathered along the different phases of the experiments gave very important outputs with respect to the development of HMI for the virtual inspection of tires. The first one is that the methodology followed for the HMI development has proven to be the right one taking into account the problem in hands and the context in which the development was done. The contribution of the operators knowledge revealed in the feedback sessions and in the results obtained along the experience provided important hints that significantly enhanced the development of the HMI solution. The changes in the interface design performed along the experiment revealed the need of a close interaction with the final users in order to obtain the best results. The interpretation of the feedback provided by the operators is essential to identify the key features that need to be improved or changed.

The results of the virtual inspection regarding the inspection time is influenced by several variables: tire surface, tire grade, tire image length, operator's level of confidence with the application, and training. The influence of each variable has been presented in 5.5. The results showed that there are still room for improvement. Regarding the tire images, the image length size shall not exceed one screen width size so one can expect inspection time per image lower than 5 seconds. In order to keep the image quality, showing in a 1:1

scale, the quantity of image (length size) to show to the operators in the virtual inspection tool shall be not bigger than 20% of the total image. To achieve that value, one expects that the automatic tire detection system output is able to clearly identify areas of the tire image that do not need to be shown to the operators in a range of 80% of the total image length size. This means that the tire automatic detection system is able to "cut" 80% of the total image length, once these areas are correctly analyzed by that system. In that case, the operators are asked to inspect only 20% of the total image length. Although the objective is quite demanding, the results obtained so far by this system show that it is possible.

Another important contribution for the results is the level of confidence of the operators with the new system. The significant change in the inspection context requires some time and training for the operators to reach the same level as the one they have in the actual system. The time spent by the operators in each session do not allow significant improvements from one session to another. Training is essential to promote the level of confidence and to speed-up the inspection process. In Figure 5.20 (median inspection time per session considering all operators involved in each session) one can observe the influence of the operator's experience along the experiment. The inspection time per image increase from session 7 to session 8, and from session 9 to session 10 are influenced by the feedback sessions occurred between them. At this phase of the experiments, the development team performed feedback sessions where the operators were observing images with imperfections where the detection ratio was not good. One assumes that in the next session, the operators were more cautious so they will not miss potential NOK tires. This also evident in the results of the quality assessment showed in Figure 5.13. This is also evident in the study presented by Longenecker *et al.* [169] where they conclude that "work force training was a primary vehicle for enhancing work performance".

The trend verified from session 16 to session 17 is affected by the change in the interface design occurred at that time. The adaptation to the new interface design and the expected slightly increase in the inspection time is observed.

Nevertheless, one could observe an inspection time reduction trend of about 0.5 seconds per session. Taking into account the different aspects around the change in the inspection system environment, the necessary adaptation and the poor level of experience in the new interface, one might observe the learning curve effect in the results.

From session 19 to session 24, operators were asked to perform training sessions with pre-selected images with imperfections. Sessions 25 to 32 are the ones where the operators are asked to inspect the same tire images with consecutive lower image length sizes. Session 33 is again a standard session. The results show clearly a significant improvement in the inspection time. One might assume the contribution of the training sessions and the

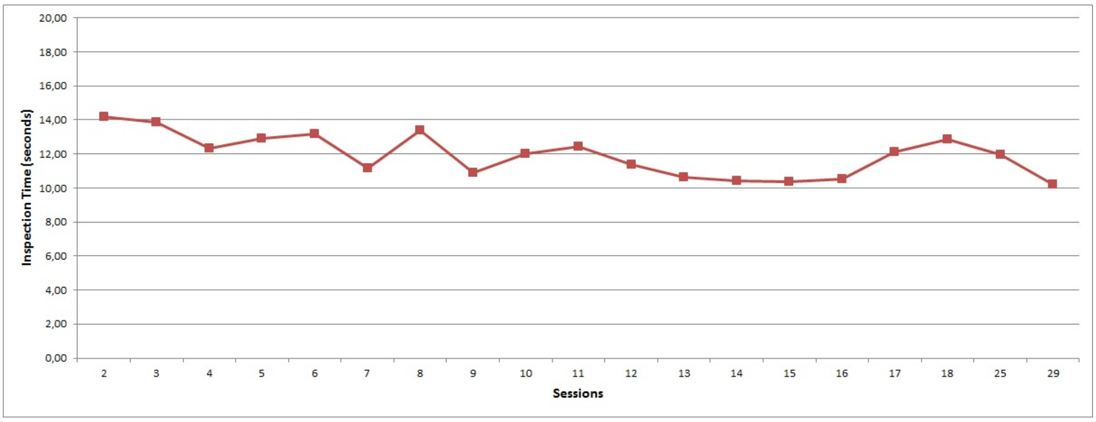


Figure 5.20: Inspection time evolution along the experience: operator's experience influence

increasing level of experience of the operators (Figure 5.21).

Regarding the interface design, the improvements introduced along the experiment result in enhancements in the quality assessment. Regarding the inspection time, the changes were not done to reduce the inspection time. However, the image size length plays a crucial role in the inspection time results. The focus of the development shall be in the automatic detection system in order to guarantee the minimal image length size possible. The experiments ran in a workstation with a Full High Definition (HD) screen and the interaction was done with a mouse and the keyboard. With the aim of obtained the best performance one suggests the use of a touch screen solution. A capacitive multiple touch screen solution like the HP TouchSmart 610 All-in-one Station seems the most suitable technology for this kind of application. The multiple touch screen allows a better use of the interactions of the operator with the application, and will speed-up some of the tasks that are not optimized in time like the imperfections marking or the navigation among the

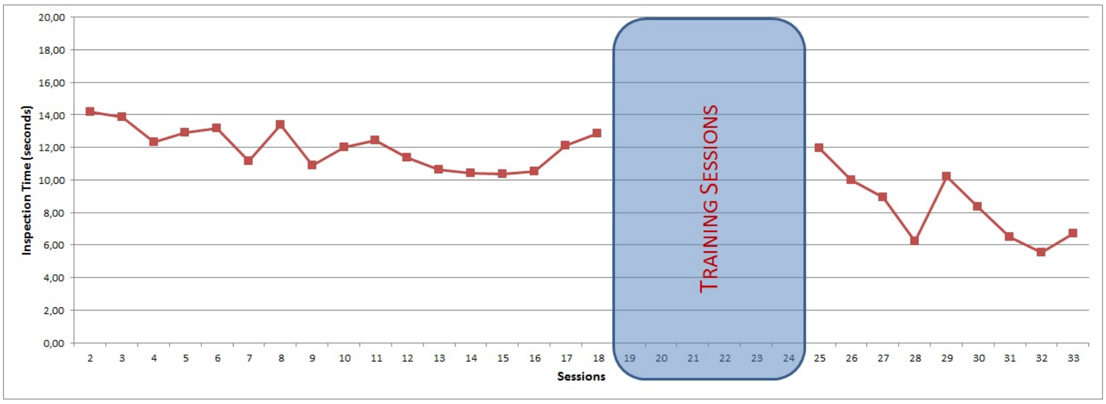


Figure 5.21: Inspection time evolution along the experience: operator's experience influence

different image slices. With the broadly dissemination of touch screen applications in the several contexts, an easy adaptation of the operators to the new interface is expected.

One of the main advantages of the virtual inspection is the ergonomic conditions enhancements that it can provide. The study realized by the Ergos project by *PlanyCorpo* company showed some room for improvement with respect to the workstation design. Two alternative designs are suggested: in one, the operator is sitting in an adjustable chair, ergonomically designed, as shown in Figure 5.23; in the second option, the operator is semi-sitting and workstation shall be adjustable to the operator's height (Figure 5.22). The room where the inspection process is performed shall have indirect light to overcome the issues observed in experiments phase one (see Figure 5.6).

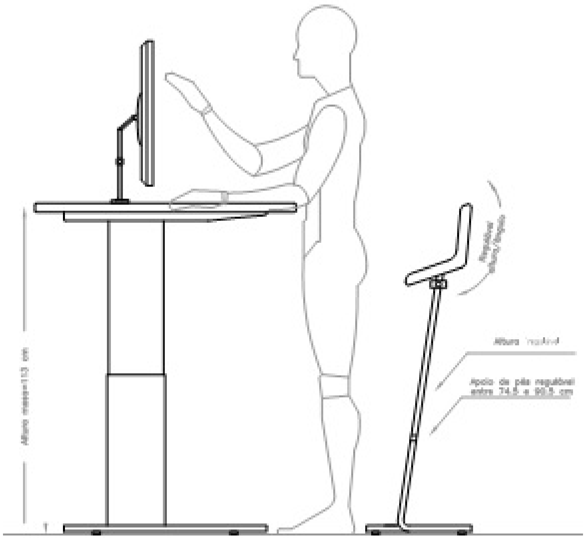


Figure 5.22: Final workstation design: semi-sitting position

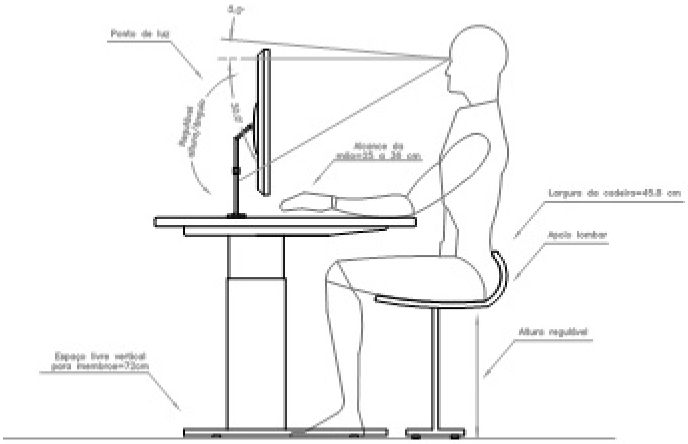


Figure 5.23: Final workstation design: sitting position

Chapter 6

Decision Model for Tire Inspection Solution

The solution presented for the inspection process improvement comprises the combination of an automatic system and a human-based system. The most suitable level of automation to be implemented is not an easy issue to solve once it depends on the performance of each system and also the interrelation between the two systems. In one hand, the automatic system provides some level of uniformity for the quality decisions, but on the other hand, the triggers for the quality assessment are not very objective due to the nature of the object to be inspected which introduces additional complexity in the process quality control and enhance the product variability. The automatic system can either reject a significant quantity of tires that are OK or accept tires with imperfections within the rejection criteria due to incorrect definitions of the thresholds. This also gives some idea about the level of flexibility an automatic system might have. To establish the right level of automation for the system it is also of the most importance to understand the dynamics of the virtual inspection system. The tool designed to assist operators to take the best decisions depends also on the operator's performance which is influenced by a set of variables inherent to each individual but also affected by the context in which they are included.

In order to manage the complexity associated to the inspection solution proposed as well as the uncertainty associated to the output of each system, one develops a decision model to allow the decision-maker to choose and to configure the system with the features that better fullfils the requirements, the needs and the objectives of the company taking into account not only the process costs but also the ability to turn the overall solution more flexible, more reliable and more predictable.

6.1 Automatic tire detection system characterization and model

The automatic tire detection system has only few references along this document although it is analyzed in a detailed way in AutoClass project. Nevertheless, the performance and the design of this system influences the overall performance of the new tire inspection solution. For that reason, one rehearses a proposal for model that can translate the main features of this system that influence the subsequent system (the virtual inspection system) and has impact on the results that might be expected for the tire inspection solution. The automatic tire detection system is much more than a set of algorithms to determine the quality grade of the object of inspection. It is rather an intelligent system that takes into account other important variables of the process and it is evolving in time with additional sources of information, seeking for enhanced levels of accuracy and achieving better levels of confidence about the decisions taken along the time.

The model to characterize the automatic detection system is presented in Figure 6.1. The model intends to enhance the capability of this system to evolve with time and with more accurate data. In order to take a decision over a tire image that is under analysis, the system will make use of reference tire images stored in the DB of the same article. Moreover, it shall also consider the influence of the other historical data (e.g. NC occurrence, tendency for an article to have a specific NC, etc.), respecting the rejection criteria defined by the Quality department, specific tire-related data (e.g. winter tires have softer rubber which can have impact in the tire image, barcode location in the sidewall, etc.), and process-related inputs like quality trends for that article or sudden problems in the production line (e.g. leaking bladder) that can affect the quality of the tire.

The weight of each variable shall dynamically be adjustable along the time and with the circumstances. Each variable is expected to have a normal distribution, with a mean value and a standard deviation known for a specific article. Each variable shall follow a fuzzy logic principle with the aim of building-up a decision system based on neural networks, for instance. This can generate a system that is constantly adapting to the reality and taking into account the historical background. In this way, the system is inherently gifted with the properties of flexibility and adaptability.

Finally, in order to have an increased level of confidence on the decisions taken by the system, the decision process shall also be influenced by the actual level of confidence of the system. The weight of this variable shall increase with the time once this feature is expected to evolve. To determine the decision's level of confidence, the system shall also consider the inputs received by the virtual inspection decisions. In the first instance, these

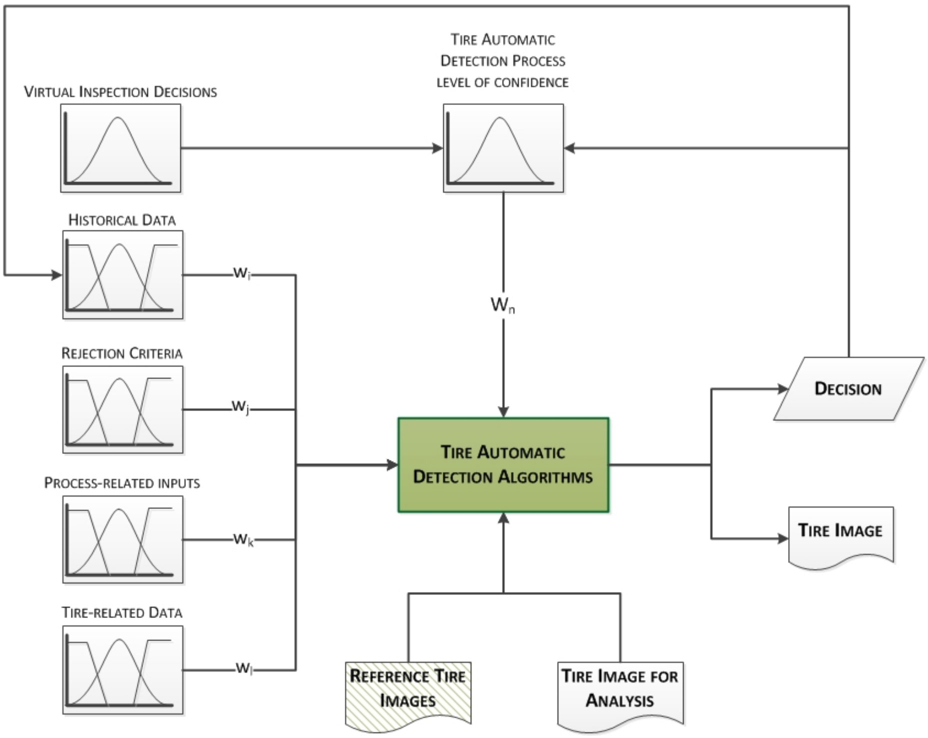


Figure 6.1: Automatic Tire Detection model: overview of the different elements

decisions will serve as a validation tool for the automatic tire detection. With time, this will prove the efficiency of the automatic detection system.

The output of the automatic detection system will be a tire image and a decision. The tire image corresponds to the identification of areas with biased behavior and a classification of the image features that differ from the reference images. The decision will depend of several factors but the level of confidence about the decision will be crucial to determine about the next step for the tire in the process. Whenever the automatic detection system is able to decide about the quality grade of a tire image (OK or NOK) with high probability, i.e. with a level of confidence higher than a pre-determined value (e.g. higher than 95%), the tire might be sent directly to the grading station (tire NOK) or to the uniformity tests (tire OK). However, one suggests that this decision is only taken by the virtual inspection system model, as mentioned in 6.2.

6.2 Virtual tire inspection system characterization and model

The virtual tire inspection system might be seen as a decision-making tool that implements a collaborative work between the system and the operator that performs the image

inspection and takes decisions. In fact, the user will take several decisions along the time rather than inspecting the tire images. Looking to the virtual inspection as a decision-making process makes all the difference. One is gathering the variables that influence the decision rather than absorbing the tacit knowledge operators have when inspecting the tire. For that reason, it is important to build-up a decision-maker model that translates the influence of each variable in the final result, i.e. in the decision taken by the operator concerning the quality grade of the tire images.
Bezerra *et al.* [156] suggests a mathematical model where functions of influence ($F(t_i)$) characterize the relationships between the elements of personalization and the elements of the decision-making process. Additionally, the authors also establish the relationships between the functions of deterioration ($I(t_i)$) and the instantaneous state in relation to the decision-making process. Both $F(t_i)$ and $I(t_i)$ functions are polynominal functions of one or several variables. The model representation shown in Figure 6.2 evidence the influence of the personalization and the instantaneous state in the decision taken when the decision-maker is facing a situation (in this case, when a tire image is shown in the visualization tool).

The parameters considered in the personalization refer to the distinctive characteristics

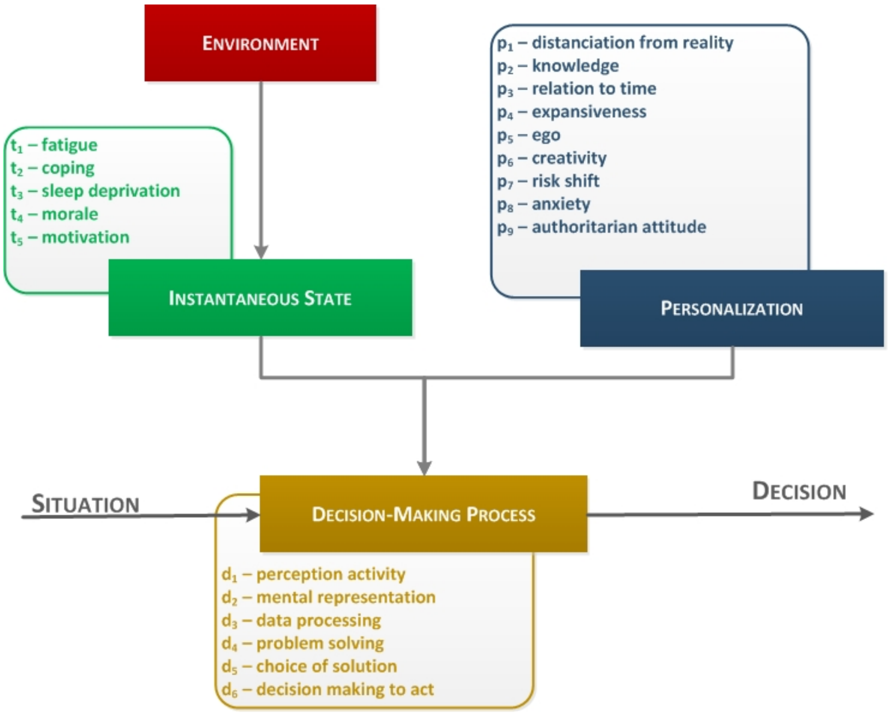


Figure 6.2: Decision-Maker model and its different components

of the individual which can be grouped into nine distinct categories: distanciation from reality, knowledge, relation to time, expansiveness, ego, creativity, risk shift, anxiety, and

authoritarian attitude. The instantaneous state bears upon the consistent features of the situation, i.e. the instant when the decision is taken, which is composed by five categories: fatigue, individual ability to cope with stress at the given time (coping), sleep deprivation, state of morale, and level of motivation. The decision-making process is composed by six consecutive stages: perception activity, mental representation, data processing, problem solving, choice of solution, and decision making to act.
The mathematical model takes for granted that the variables are independent of each other, and each variable in personalization and instantaneous state influences at most three other stages of the decision-making process, thus ensuring a selectivity of variables. Bezerra *et al.* [156] establish a set of equations ((6.1) to (6.6)) to represent the mathematical model of the decision-making process.

$$d_1 = F_{11}(p_1) + I_{11}(t_1) + I_{12}(t_2) \tag{6.1}$$

$$d_2 = F_{22}(p_2) + F_{23}(p_3) + I_{23}(t_3) + I_{24}(t_4) \tag{6.2}$$

$$d_3 = F_{34}(p_4) + F_{35}(p_5) + I_{35}(t_5) \tag{6.3}$$

$$d_4 = F_{46}(p_6) + I_{43}(t_3) + I_{45}(t_5) \tag{6.4}$$

$$d_5 = F_{52}(p_2) + F_{55}(p_5) + F_{57}(p_7) + I_{54}(t_4) + I_{55}(t_5) \tag{6.5}$$

$$d_6 = F_{63}(p_3) + F_{64}(p_4) + F_{68}(p_8) + F_{69}(p_9) + I_{61}(t_1) + I_{62}(t_2) + I_{63}(t_3) \tag{6.6}$$

The decision-maker model can gather the influence of the operator in the virtual inspection performance with respect to the quality of the decisions taken as well as some hints about the confidence level of the results one might expect. The model does not provide any data about the other important aspects of the virtual inspection system like the inspection time or the best strategy that shall be followed in order to get the most suitable performance. In order to answer to that need, one proposes a generic model like the one presented in Figure 6.3. The virtual inspection model is composed by a function block to estimate the inspection time for a certain tire image and a quality strategy function to determine the number of operators and the most suitable individual to inspect a certain image. The inspection time estimation is based on the features of the image provided to the system and the level of experience of the operators. The quality strategy definition function considers the detection ratio and previous decisions of operators for similar tire images, and the level of confidence of the decisions taken by the automatic tire detection model. The number of operators can vary from *zero* (when the level of confidence is considerably high enough to discard virtual inspection) and a maximum number defined by the company as a trade-off between the desired level of quality and production costs. A specific operator might be selected upon the human characteristics that are better aligned with the tire image characteristics and the quality requirements.

The tire image features influence the inspection time in the virtual environment as demonstrated in Chapter 5. In particular, for the inspection time estimation, one will consider the influence of the image length derived from the automatic detection system, and the tire surface in analysis. Each of these variables influence the inspection time in different ways. The determination of the influence of each and its correlation with the other variables is essential to have a better estimation of the inspection time. Another important variable to be taken into account is the operators' experience in the virtual inspection environment. It has been shown that inspection time tends to decrease when experience is higher. The trend of the experience of the operators derive from the personality of each individual and their ability to adapt to the new context (from the decision-maker model).

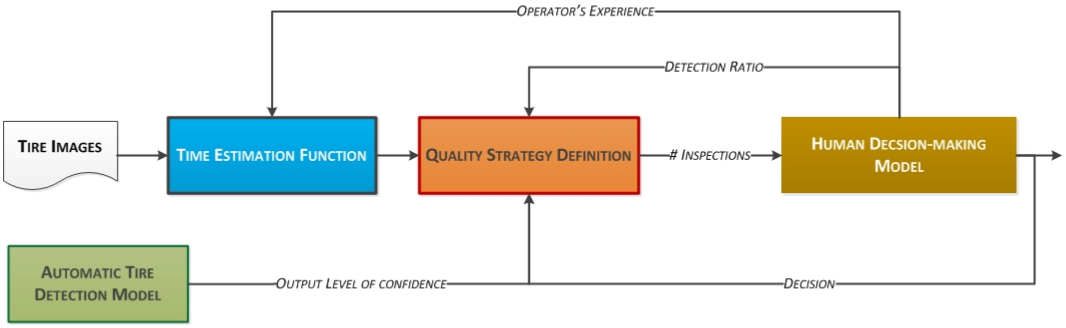


Figure 6.3: Virtual Inspection model: overview of the different elements

The inspection strategy definition has to consider the inspection time estimation for the given tire image. The complexity associated to the definition of the most suitable inspection strategy is inherent to the number of variables involved in this process. It holds the effects of manufacturing-related aspects (costs and quality ratio), quality features (customer evaluation of the article, severity level of escaping a NOK tire, etc.), and characteristics of the new tire inspection solution (level of confidence of the automatic detection system output and the detection reliability of the virtual inspection system). Moreover, it also takes into account the operator's awareness derived from the instantaneous state estimation gathered from the decision-maker model.

When considering all these variables, it is then possible to determine the most suitable number of operators and specific individuals to inspect a certain tire image. The details of the virtual inspection model is presented in Figure 6.4. By applying this model, one can understand the dynamics of the virtual inspection system as well as measuring the main variables in order to assess the performance of the system.

6.3 Proposal for tire inspection system decision model

The interdependencies revealed by the model presented before show the importance of both systems (automatic tire detection system and virtual inspection system) in the global performance of the new tire inspection solution. The model intends to be a living model where small increments of automation are expected to be introduced in order to improve the overall system performance. The level of automation is associated with the level of automatic decisions derived from the automatic detection system. The model evolves in a dynamic way with the knowledge acquired along the time by the different sub-systems and the enhancements verified in the system performance due to technology developments. The proposed model is a baseline for further developments in which one shall expect an accurate determination of the inspection time estimation as well as the influence of each variable in the definition of the inspection strategies. By implementing this model, the company is also able to take decisions about the most suitable level of automation to be used as well as identifying the areas for improvement. In addition, the quality limits can be adjusted according to customer and to article, always depending on Quality department assessment.

The experiments realized so far allowed to validate the tire inspection solution concept. In order to obtain a mathematical model of the decision-making process, additional experiments shall be done to identify to correlation among the different variables. The variables involved in the inspection time estimation and in the inspection strategies determination require an implementation of the system in the production flow, guaranteeing a stable process so the different variables of the system can accurately be measured.

Finally, it is of the most importance to gather and analyze the interaction between the decisions taken in the virtual inspection system and the decisions over the automatic tire detection system. The balance between the two systems is an indicator about the correct relation between the quality thresholds of the automatic detection system and the necessary conditions for the operators to take the right decisions. Whenever a significant difference between the two systems is verified, this could mean that either the the thresholds are not accurately defined (or even a system breakdown) or the operator's behavior is biased.

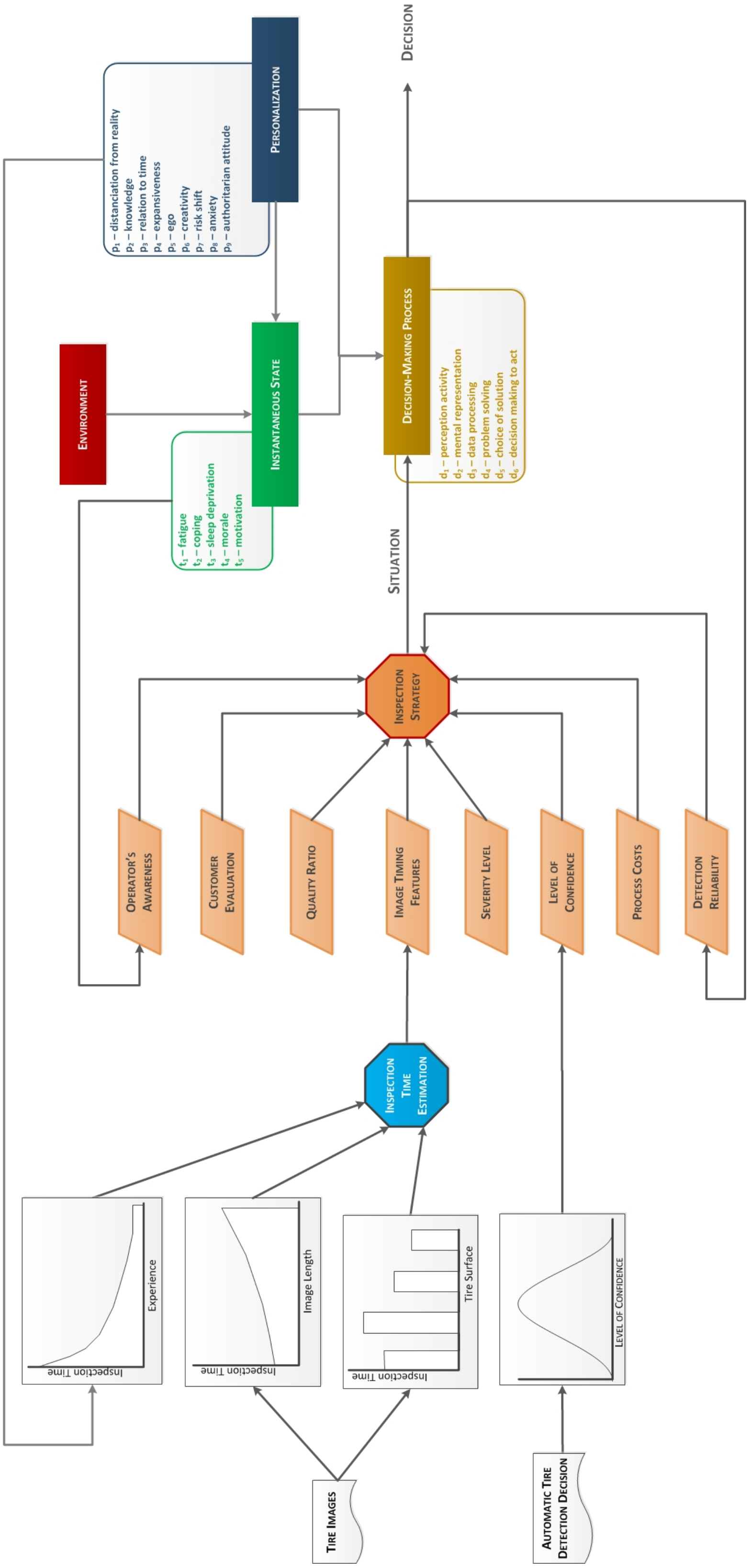


Figure 6.4: Virtual Inspection model: detailed view and interdependencies

Chapter 7

Conclusions

The research approach followed along the entire project has proven to be adequated for the problem in hands. The results obtained and the feedback received along the way showed that the path chosen to accomplish the goals of the project was right. Several attempts to solve the problem did not succeed in the past, but with the proposed solution the company is confident that it can achieve the goals without compromising the quality perception by the customers and aiming to reduce the process costs. The decision to industrialize the solution shows the relevance of the work developed in the AutoClass project, always supported by the scientific work.

The solution might be seen as a platform where further developments can be done in order to have a continuous improvement approach to the inspection process. It also provides the necessary structure to gather the knowledge from the system and, with that, identify the improvement areas. With the recommended solution, the company has the necessary information to take decisions about the solution industrialization as well as the most suitable level of automation it wants for the process. The possibility to introduce increments of automation in an iterative way gives a powerful tool to decide which configuration the system shall have and avoiding the high risks inherent to a drastic change in the process. The solution can accommodate the necessary learning process required to familiarize the operators with the new inspection process approach. A smooth transition from the actual system to the new inspection process is possible with this solution.

The methodology presented in Chapter 4 showed very interesting output with respect to the technology selection and integration once the results obtained for the image acquisition station are very promising. The application of such methodology in other fields is also possible especially on those where the technology selection issue plays an important role, in particular when multi-attribute analysis is required.

The HMI methodology also proved to be suitable once a significant evolution has been observed along the time. The use of people's feedback and the translation to the design of the interface requires an intense interaction with the operators but at the same time reduce drastically the risks of developing something that is not adapted to the end user.

The capability of the user to correctly inspect an object based on the image instead of the "real" object has also proven to be valid even when taking into account the low level of training and the sudden changes faced by the operators. The risks associated to the process changes were minimized by the close interaction with the end users, making them understand the value of their contribution for the process changes where they will keep the central role. Understanding their "working" language as well as their difficulties and expectations for the new system was crucial for the success verified in the results.

The decision model proposed to model the new inspection process has all the necessary features to characterize and to simulate the desired level of automation in which the company would like to work with in order to maximize the system performance. All the relevant variables are considered and the output of the system can be measured so the decision-maker can assess the impact of the system configuration at different levels as well as to determine the actions to overcome the issues of the areas that require some kind of improvement.

7.1 Scientific Contributions

The diversity of subjects presented along this document reveal the level of complexity existent in the research done to reach the project goals. Although the project is mainly technology driven, the incorporation of people in the development process arises additional questions that need to be taken into account.

The courses taken in the first year of the PhD, and in particular the course of Engineering & Manufacturing Systems, provide insightful knowledge that has been useful and applied in the research project. In the scope of the Engineering & Manufacturing Systems course, two papers [85, 172] were published in one of the most important conferences of Engineering Systems, the INCOSE (International Council on Systems Engineering). The papers are focused on the subject of strategic planning in complex systems [85] and in the generation and selection of strategic plans of action [172].

The use of a methodology for the generation and selection of strategic plans of action in an airline company has proven to be suitable and provided good results. The approach followed in those publications inspired the methodology presented in this document for the technology selection, integration and deployment methodology (4.1).

The richness of the research contents can perfectly lead to publications in journals with high impact level. However, due to the Non-Disclosure Agreement (NDA) signed in the scope of the AutoClass project, any publication depends on the company agreement. Once the solution for the inspection process is seen by the company as a strategic option, no publication can compromise the patent release or industrial secrecy. For that reason, anything related to the technology development cannot be published.

The solution developed for the inspection process has a significant potential to be patented. For that reason, the team has suggested to Continental the possibility to issue the patent with respect to the tire inspection system for inspecting visual imperfections that can possibly occur in any surface of the tire, where the system is composed by an image acquisition station, a feature extraction unit, an image classification toolbox, and an assisted human-based inspection station. Since the technologies adopted for the solution are commercially available, the patent focus on the process and the methodology for the inspection process.

Whenever the conditions for publishing are in place, one suggests one publication about the technology selection, integration and deployment methodology, another one about the HMI development methodology, a further publication about the main factors influencing the virtual inspection of object images, and finally a publication about the decision model of semi-automatic systems. Moreover, one believes that the present document can provide insightful knowledge for future developments in the above mentioned subjects, and that can be generally applied in inspection systems, especially on those where the human contribution plays an important role.

7.2 Future Work

The work presented in the document creates a baseline for further developments. The solution adopted for the inspection process is gifted with the propriety of modularity. It serves as a platform for future developments and enhancements one desires to incorporate in the solution. It gives space for the introduction of incremental levels of automation, providing at the same time the necessary support for testing and validating the solutions before releasing them.

However, in order to fully implement the system in the industrial environment, some work shall be done in order to better assess some of the features highlighted along this document. Regarding the HMI, there are still some developments and studies that might be done. One of them is about the determination of the exact influence of each of the identified variables in the system performance. Training was identified as one of them, but the data gathered until cannot fully extract the exact impact of the learning curve in the system performance. Additional experiments must be done, with a larger number of operators to better assess the contribution of the training in the operator's action. Those experiments will also be suitable to understand the individual characterization of the operators carrying out the virtual inspection process.

Additionally, still concerning the HMI, one suggests a study to compare the performance of the operators in the virtual inspection using a mouse (as today) and using a touch screen. The touch screen technology has several advantages but there are still some aspects that requires some attention (e.g. maintenance of the screen). The comparison between these two interface systems might also require some changes in the HMI in order to take full advantage of the interface solution.

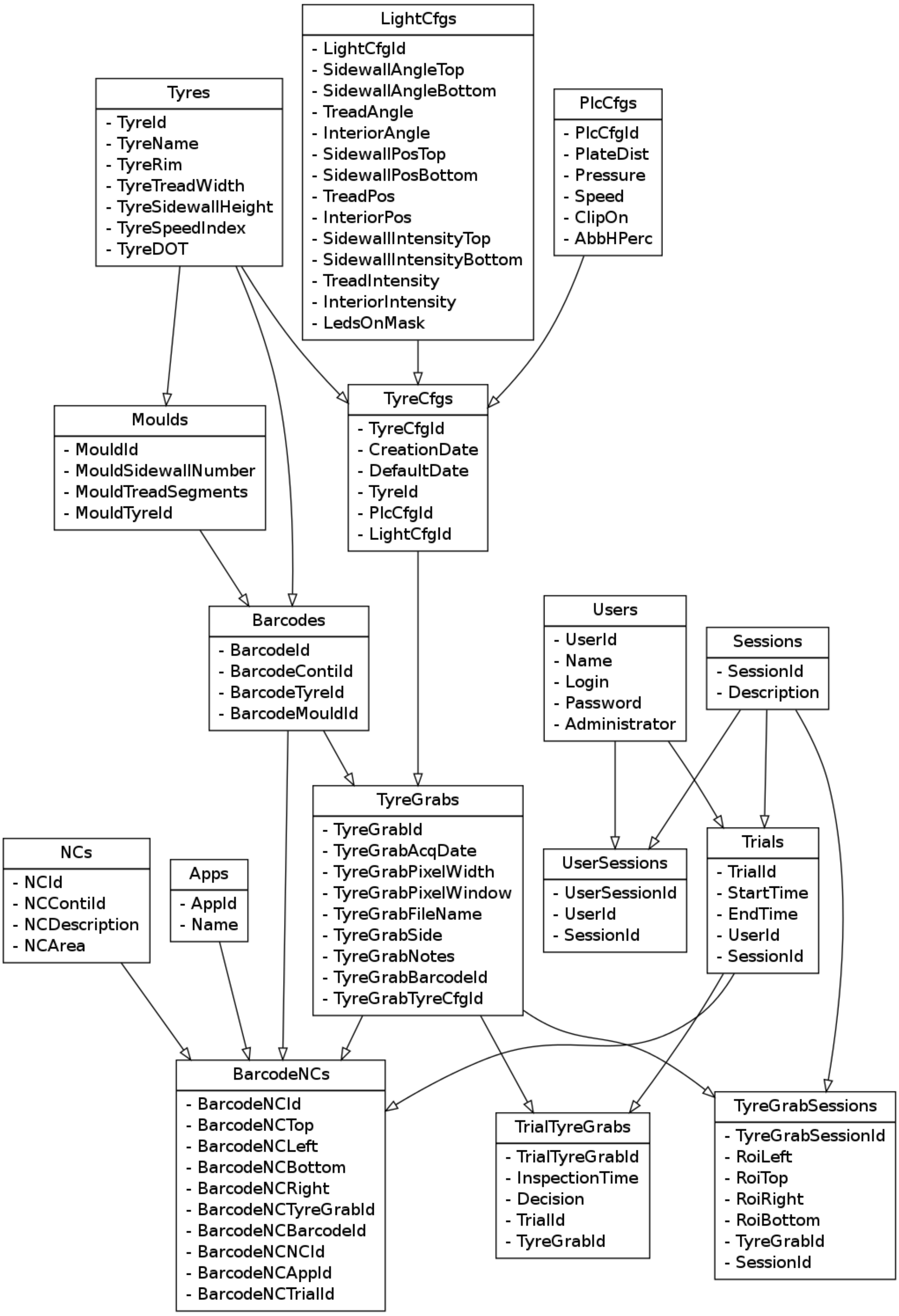
In order to incorporate the image acquisition station in the production line, one must study the interface with the conveying system. There are several solutions available and attention shall be addressed to the system performance concerning the process time. The way the tire is inserted and taken out of the station is crucial to not compromise the overall system performance. One suggests the use of the technology selection methodology to better assess the most suitable solution for the interface with the conveying system.

Another aspect about the acquisition station is the possibility to determine the most adequated configuration of the system to acquire a certain object. Until now, the system loads the recipe for a specific tire from the DB which is configured according to the method presented in 3.1.1. However, whenever a new tire, which has not been acquired in station yet, arrives the system does not know in advance which configuration shall use. A first approach is to select one configuration similar to the one used with another tire with the same dimensions. Nevertheless, a more robust approach might be followed. Characterizing each configuration by the lighting features and shadows/bright characteristics might lead to a system that finds out the most suitable configuration for a certain tire by optimizing the image features gathered in the acquisition station. The configuration mode will increase the acquisition time significantly for those tires, but it will not require any operator or technician to validate the image obtained (as it is mandatory with the first approach). Anyone who is assessing an image will introduce some degree of subjectivity which is not desired. By adopting an automatic process of configuring the image acquisition station, one reaches an uniform output of tire images for the different tires.

The decision model presented in the document is yet a preliminary model where the determination of each variable is important to understand its influence in the inspection time estimation and in the judgment of the most suitable strategy for the virtual inspection. The measurement of each variable requires the implementation of the system so one gathers all the important features and data from the semi-automatic system. Once the system can be adapted through the time, the determination of the variables might change.

Appendix A

Data structure to support FISA


LightCfgs
- LightCfgId
- SidewallAngleTop
- SidewallAngleBottom
- TreadAngle
- InteriorAngle
- SidewallPosTop
- SidewallPosBottom
- TreadPos
- InteriorPos
- SidewallIntensityTop
- SidewallIntensityBottom
- TreadIntensity
- InteriorIntensity
- LedsOnMask
Tyres
- TyreId
- TyreName
- TyreRim
- TyreTreadWidth
- TyreSidewallHeight
- TyreSpeedIndex
- TyreDOT
PlcCfgs
- PlcCfgId
- PlateDist
- Pressure
- Speed
- ClipOn
- AbbHPerc
Moulds
- MouldId
- MouldSidewallNumber
- MouldTreadSegments
- MouldTyreId
TyreCfgs
- TyreCfgId
- CreationDate
- DefaultDate
- TyreId
- PlcCfgId
- LightCfgId
Barcodes
- BarcodeId
- BarcodeContiId
- BarcodeTyreId
- BarcodeMouldId
Users
- UserId
- Name
- Login
- Password
- Administrator
Sessions
- SessionId
- Description
TyreGrabs
- TyreGrabId
- TyreGrabAcqDate
- TyreGrabPixelWidth
- TyreGrabPixelWindow
- TyreGrabFileName
- TyreGrabSide
- TyreGrabNotes
- TyreGrabBarcodeId
- TyreGrabTyreCfgId
NCs
- NCId
- NCContiId
- NCDescription
- NCArea
Apps
- AppId
- Name
UserSessions
- UserSessionId
- UserId
- SessionId
Trials
- TrialId
- StartTime
- EndTime
- UserId
- SessionId
BarcodeNCs
- BarcodeNCId
- BarcodeNCTop
- BarcodeNCLeft
- BarcodeNCBottom
- BarcodeNCRight
- BarcodeNCTyreGrabId
- BarcodeNCBarcodeId
- BarcodeNCNCId
- BarcodeNCAppId
- BarcodeNCTrialId
TrialTyreGrabs
- TrialTyreGrabId
- InspectionTime
- Decision
- TrialId
- TyreGrabId
TyreGrabSessions
- TyreGrabSessionId
- RoiLeft
- RoiTop
- RoiRight
- RoiBottom
- TyreGrabId
- SessionId

Appendix B

Survey used in the first phase of experiments with operators

EXPERIMENTS WITH VIS

Please take a moment to assess the application you have been trying out.
Thank you for giving us the opportunity to get your opinion.

***EVALUATION SCALE*:**

(5) Very Easy (4) Easy (3) Fair (2) Difficult (1) Very Difficult

OVERALL EXPERIENCE	5	4	3	2	1

INTERFACE:

How friendly is the interface?	5	4	3	2	1
How intuitive is to handle the tire?	5	4	3	2	1

What shall be changed or improved?

____

____

IMAGE QUALITY:

Is it possible to clearly observe the tire? YES NO

Why not?

____

____

Is it possible to clearly observe the imperfections? YES NO

Why not?

____

____

How difficult is to inspect the tire virtually?	5	4	3	2	1

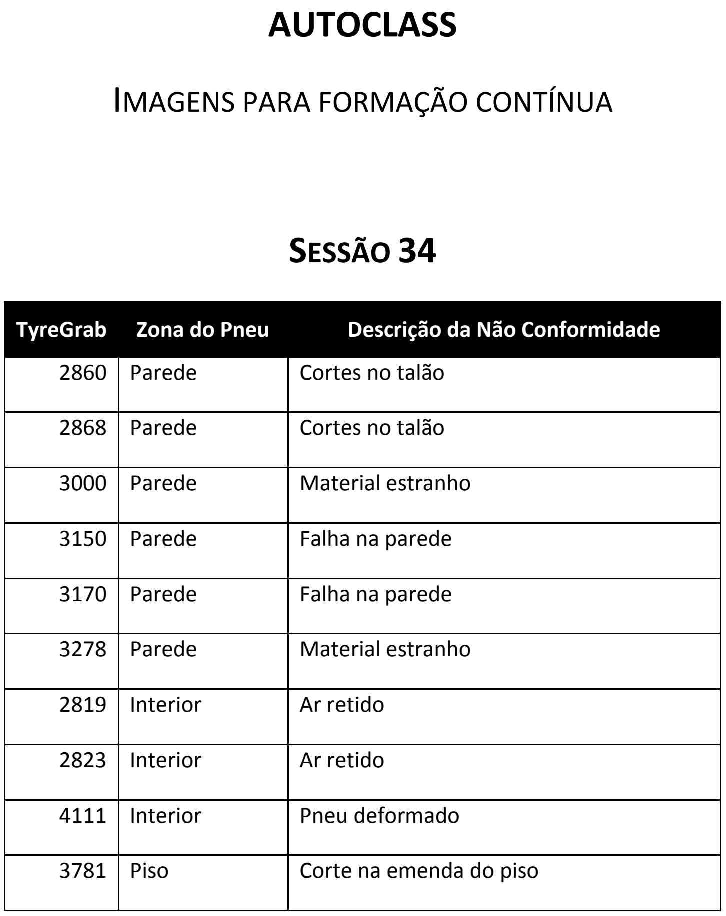
Why was it difficult to inspect?

____

____

Appendix C

Training session sheet example



AUTOCLASS

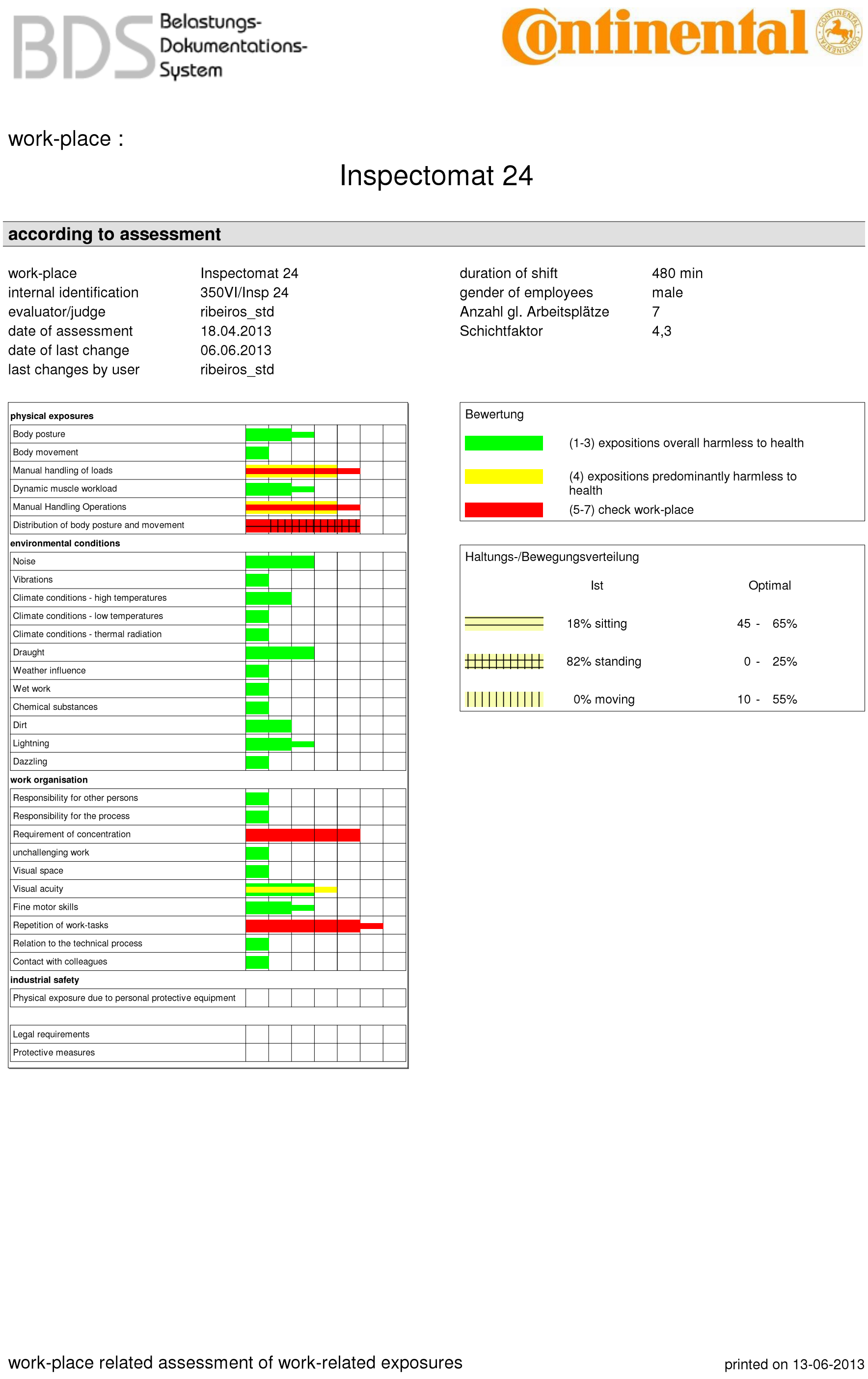
IMAGENS PARA FORMAÇÃO CONTÍNUA

SESSÃO 34

TyreGrab	Zona do Pneu	Descrição da Não Conformidade
2860	Parede	Cortes no talão
2868	Parede	Cortes no talão
3000	Parede	Material estranho
3150	Parede	Falha na parede
3170	Parede	Falha na parede
3278	Parede	Material estranho
2819	Interior	Ar retido
2823	Interior	Ar retido
4111	Interior	Pneu deformado
3781	Piso	Corte na emenda do piso

Appendix D

Ergonomic assessment of the workplace (InspectoMat)



Belastungs-
Dokumentations-
System

work-place :

Inspectomat 24

according to assessment

work-place	Inspectomat 24	duration of shift	480 min
internal identification	350VI/Insp 24	gender of employees	male
evaluator/judge	ribeiros_std	Anzahl gl. Arbeitsplätze	7
date of assessment	18.04.2013	Schichtfaktor	4,3
date of last change	06.06.2013		
last changes by user	ribeiros_std		

physical exposures							
Body posture	🟩	🟩	🟩				
Body movement	🟩						
Manual handling of loads	🟥	🟥	🟥	🟥	🟥		
Dynamic muscle workload	🟩	🟩	🟩				
Manual Handling Operations	🟥	🟥	🟥	🟥	🟥		
Distribution of body posture and movement	🟥	🟥	🟥	🟥	🟥		
environmental conditions							
Noise	🟩	🟩	🟩				
Vibrations	🟩						
Climate conditions - high temperatures	🟩	🟩					
Climate conditions - low temperatures	🟩						
Climate conditions - thermal radiation	🟩						
Draught	🟩	🟩	🟩				
Weather influence	🟩						
Wet work	🟩						
Chemical substances	🟩						
Dirt	🟩	🟩					
Lightning	🟩	🟩	🟩				
Dazzling	🟩						
work organisation							
Responsibility for other persons	🟩						
Responsibility for the process	🟩						
Requirement of concentration	🟥	🟥	🟥	🟥	🟥		
unchallenging work	🟩						
Visual space	🟩						
Visual acuity	🟨	🟨	🟨	🟨			
Fine motor skills	🟩	🟩	🟩				
Repetition of work-tasks	🟥	🟥	🟥	🟥	🟥	🟥	
Relation to the technical process	🟩						
Contact with colleagues	🟩						
industrial safety							
Physical exposure due to personal protective equipment							
Legal requirements							
Protective measures							

Bewertung

🟩	(1-3) expositions overall harmless to health
🟨	(4) expositions predominantly harmless to health
🟥	(5-7) check work-place

Haltungs-/Bewegungsverteilung

Ist	Optimal
18% sitting	45 - 65%
82% standing	0 - 25%
0% moving	10 - 55%

work-place related assessment of work-related exposures

printed on 13-06-2013

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