The use of Augmented Reality in the Lean workplaces at smart factories

Ana Cláudia Ribeiro Pereira

UMinho | 2022

**Universidade do Minho**
Escola de Engenharia

Ana Cláudia Ribeiro Pereira

# The use of Augmented Reality in the Lean workplaces at smart factories

June 2022

**Universidade do Minho**
Escola de Engenharia

Ana Cláudia Ribeiro Pereira

# The use of Augmented Reality in the Lean workplaces at smart factories

Doctoral Thesis in Industrial Engineering and Systems

Work carried out under the supervision of
**Professor Anabela Carvalho Alves**
**Professor Pedro Miguel Ferreira Martins Arezes**

June 2022

## DIREITOS DE AUTOR E CONDIÇÕES DE UTILIZAÇÃO DO TRABALHO POR TERCEIROS

## ACKOWLEDGEMENTS

The present PhD thesis is the reflection of an intense dedication to a project, resulting from the collaboration of several people and entities that worked, directly or indirectly, in its development. Therefore, I would like to express my sincere appreciation to all the people who made this work possible.

First and foremost, I want to express my sincerest gratitude to my supervisors, Professors Anabela Alves and Pedro Arezes, from School of Engineering, Department of Production and Systems, University of Minho, for their constant support, motivation and guidance provided throughout the development of this research work. To Professor Anabela Alves, my deepest appreciation for her unconditional support from the first moment. Without her continuous encouragement and demand, the completion of this project would not have been possible.

I would also like to thank the company selected to develop the case study and to all the people I worked with. Particularly, I want express my gratitude to thank to Francisco Duarte, the mentor of this project, who showed me the way at an early stage and gave me the opportunity to develop this project in an industrial environment. Moreover, a special acknowledgement to Rui Albuquerque, who always supported this project and provided all possible resources throughout the development of this work. Finally, an enormous recognition to the vital role that Ana Pombeiro had in making this project a reality, showing her unconditional support and being available whenever I needed her valuable help.

Furthermore, I would like to express my gratefulness to all from the Department of Production and Systems, for the support and availability shown, in particular to Professor Celina Leão, who has been available numerous times to help me and provide valuable information for the completion of the project.

A very special thanks to my parents, Rosa and Abílio, who I owe everything. Without their unconditional support, nothing would have been possible. I will never be able to thank them enough for all they have done for me and it is to them that I dedicate this thesis.

Finally, I would like to say a word of thanks to all the people who, in a personal, academic or professional way, have contributed, in some way, to the realization of this work, especially to Miguel for the support and motivation during this research work.

This work has been supported by the Doctoral scholarship SFRH/BD/139533/2018 funded by FCT, the Portuguese national funding agency for science, research and technology.

## STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledge the Code of Ethical Conduct of the University of Minho.

## Abstract

### The use of Augmented Reality in the Lean workplaces at smart factories

In the last years, the global industrial landscape has deeply changed due to disruptive technological advancements enabled by the so-called Industry 4.0, a new paradigm that focuses on the transformation of conventional manufacturing systems into smart factories. Augmented Reality (AR) is one of the disruptive technologies that are emerging within this context and intends to combine the physical world with virtual information, augmenting and enhancing people's capabilities and senses.

This project intended to improve the working conditions within logistic workplaces, identifying which type of AR best suits these processes, evaluating the tasks and defining which human capabilities and senses should be augmented. In a context of Lean Thinking that brings a human-centric approach, the main aim was to reduce the human effort during tasks performance, mitigating the risks within workplaces and improving ergonomic conditions. Moreover, Lean Thinking enhanced the potential for creating waste-free and more efficient workplaces, while studying the potential of Human Augmentation (HA).

Operators and the enhancement of their working conditions were the main motivation of this work. Therefore, this work was focused on the creation of a symbiosis between Industry 4.0 and Industry 5.0 paradigms, combining the implementation of a disruptive technology and the transition to human-centric, sustainable and resilient systems. For this purpose, this project aimed to develop a methodology – RAES-Log – that allows the analysis and definition of AR implementation requirements within logistic workplaces in order to mitigate the existing risks and study the potential for the enhancement of working conditions through the implementation of AR technology.

Furthermore, a study about the potential of working conditions' enhancement through the implementation of AR has been carried out in order to analyse the current situation regarding Musculoskeletal Disorders (MSD) and perceived exertion during tasks execution. Then, the workers' opinion and acceptance about the proposed AR solutions that resulted from the implementation of RAES-LOG methodology at a case study were collected and analysed. The global worker's opinion was positive for every proposed AR solution and the majority of workers showed curiosity and optimism about these technologies, believing that these could be good solutions to mitigate risks within their workplaces. As a result of this implementation, lower prevalence of MSD, lost time days and lower injury severity can be expected, as well as, a greater operator motivation and involvement in continuous improvement processes.

**Keywords:** Human Augmentation, Industry 4.0, Industry 5.0, Lean Thinking, Human Factors

## RESUMO

**O uso da Realidade Aumentada em postos de trabalho Lean nas fábricas inteligentes**

Nos últimos anos, o cenário industrial global mudou profundamente devido aos disruptivos avanços tecnológicos potenciados pela chamada Indústria 4.0, um novo paradigma focado na transformação de sistemas de produção convencionais em fábricas inteligentes. A Realidade Aumentada (RA) é uma das tecnologias que surgiram nesse contexto, combinando o ambiente físico com informações virtuais, aumentando e melhorando suas capacidades e sentidos das pessoas.

Este projeto visou a melhoria das condições de trabalho nas áreas logísticas, identificando o tipo de soluções de RA que melhor se adequam a estes processos, avaliando as tarefas e definindo quais as capacidades e sentidos a aumentar. Num contexto de *Lean Thinking*, que traz uma abordagem centrada no ser humano, o principal objetivo consistiu na redução do esforço durante a execução das tarefas, mitigando os riscos nos locais de trabalho e melhorando as condições ergonómicas. Além disso, o *Lean Thinking* aumentou o potencial de criação de locais de trabalho mais eficientes e sem desperdícios, estudando o potencial de aumento humano.

Os operadores e a melhoria das suas condições de trabalho foram a principal motivação deste trabalho. Desta forma, este projeto centrou-se na criação de uma simbiose entre os paradigmas da Indústria 4.0 e da Indústria 5.0, aliando a implementação de uma tecnologia disruptiva com a transição para sistemas centrados no humano, sustentáveis e resilientes. Para o efeito, este projeto teve como objetivo o desenvolvimento de uma metodologia – RAES-Log – que permitisse a análise e definição de requisitos de implementação da RA nas áreas logísticas, de forma a mitigar os riscos existentes e estudar o potencial de melhoria através da implementação desta tecnologia.

Adiconalmente, foi realizado um estudo sobre o potencial de melhoria das condições de trabalho através da implementação da RA, analisando a situação atual em relação às lesões musculoesqueléticas e percepção de esforço durante a execução das tarefas. De seguida, a opinião e aceitação dos trabalhadores sobre as soluções de RA resultantes da implementação da metodologia RAES-LOG num estudo de caso foram recolhidas e analisadas. Na globalidade, as respostas foram positivas em relação a todas as soluções de RA propostas, sendo que a maioria dos trabalhadores acredita que poderiam ser boas soluções para mitigar riscos nos seus locais de trabalho. Como consequência desta implementação poder-se-á esperar menor prevalência e gravidade de lesões musculoesqueléticas e menor absentismo, bem como uma maior motivação e envolvência dos operadores nos processos de melhoria contínua.

**Palavras-chave:** Aumento Humano, Indústria 4.0, Indústria 5.0, *Lean Thinking*, Fatores Humanos

## TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

## LIST OF EQUATIONS

## List of abbreviations

AAR – Augmented Audio Reality

AGV – Automated Guided Vehicles

AHP – Analytic Hierarchy Process

AR – Augmented Reality

CEN – European Committee for Standardization *(Comité Européen de Normalisation)*

CLI – Composite Lifting Index

CPPS – Cyber-Physical Production Systems

CPS – Cyber-Physical Systems

EAWS – Ergonomic Assessment Worksheet

EU – European Union

ESD – Electrostatic Discharge

FILI – Frequency Independent Lifting Index

FIRWL – Frequency Independent Recommended Weight Limit

GNP – Gross National Product

HA – Human Augmentation

HAL-TLV – Threshold Limit Value for Hand Activity Level

HARM – Hand Arm Risk-assessment Method

H-CPS – Human Cyber-Physical Systems

HF – Human Factors

HHD – Hand-Held Displays

HMD – Head-Mounted Displays

HMI – Human-Machine Interface

IC – Integrated Circuits

IIoT – Industrial Internet of Things

IoT – Internet of Things

ISO – International Organization for Standardization

IT – Information Technology

JSI – Job Strain Index

KIM – Key Indicator Method

KPI – Key Performance Indicators

LI – Lifting Index

LM-MMH – Liberty Mutual Manual Materials Handling

MMH – Manual Materials Handling

MSD – Musculoskeletal Disorder

NACE – Statistical Classification of Economic Activities in the European Community

NIOSH – National Institute for Occupational Safety and Health

NMQ – Nordic Musculoskeletal Questionnaire

OAWS – Ovako Working-posture Analysis System

OCRA – Occupational Repetitive Actions

OSH – Occupational Safety and Health

PCB – Printed Circuit Board

PDA – Personal Digital Assistant

PoUP – Point of User Provider

RAES-Log – Risks Assessment for Ergonomics and Safety in Logistics

REBA – Rapid Entire Body Assessment

ROI – Return On Investment

RULA – Rapid Upper-Limb Assessment

RWL – Recommended Weight Limit

SAR – Spatial Augmented Reality

SD – Standard Deviation

SMD – Surface-Mount Device

STLI – Single Task Lifting Index

STRWL – Single Task Recommended Weight Limit

TO – Transport Order

VR – Virtual Reality

WWD – Wrist-Worn Device

# 1 INTRODUCTION

This chapter will introduce the context and motivation of this research project, depicturing its main objectives. Then, the overview of the research methodology framework will be presented and, finally, the outline of the thesis is described.

## 1.1 Context and motivation

The global industrial landscape has deeply changed in the last years due to the rising advancements in technology and manufacturing processes. The successive technological innovations have led to the emergence of new concepts that are being widely discussed by academics and organisations. Recently, an increased attention has been turned toward the so-called Industry 4.0, or the fourth industrial revolution, which became an increasingly important topic (Kagermann et al., 2013a; Zhou et al., 2016).

Industry 4.0 is being compared with the previous three industrial revolutions that occurred in the last centuries (Schmidt et al., 2015). After steam power, electricity and the advent of computers, the emerging fourth industrial revolution will bring together the digital and physical worlds through the Cyber-Physical Systems (CPS) technology mainly enhanced by the Internet of Things (IoT) and Services (IoS), which are considered the main Industry 4.0 technology enablers (Kagermann et al., 2013a; Monostori et al., 2016; Tunzelmann, 2003).

The concept of Industry 4.0 can be described as a complex technological system that embraces a set of disruptive industrial developments, being highly focused on the creation of smart products and processes, using smart machines and transforming conventional manufacturing systems into smart factories (Weyer et al., 2015). This new industrial paradigm holds a huge potential and will bring new opportunities to organizations that are moving toward Industry 4.0, having further impacts in industry, markets, economy, products, business models and completely changing the current workplace and the work environment (Kagermann et al., 2013b).

AR is one of the disruptive technologies that are also emerging with Industry 4.0 and intends to combine the physical world with computer-generated texts and images or animations, providing an intuitive interaction experience to the users. This technology provides new opportunities and can be defined as a real-time direct or indirect view of an enhanced or augmented real world environment, where virtual and physical objects interact in real-time, with the final aim at improving the work performance and efficiency in manufacturing environment (Furht, 2011; Sääski et al., 2008).

Moving toward Industry 4.0 paradigm and implementing emerging disruptive technologies as AR will enable new type of interactions between humans and machines, transforming the current industrial workforce and workplace. Furthermore, the new Human-Machine Interface (HMI) paradigm will lead to deep impacts in worker tasks and demands in work environment, which will be characterized by the cooperation between smart machines and humans (Gorecky et al., 2014; Romero, Bernus, et al., 2016).

To mitigate these impacts, there are several aspects to consider for AR implementation. The AR tools must be developed with functionalities that allow a user-friendly collaboration between human and technology, in order to enhance their experience and improve their performance and awareness in a non-intrusive way. Thus, it will be possible to meet the industrial requirements, allowing people to be more efficient and effective in their tasks (Michalos et al., 2016).

At the same time, it is important that humans develop such tasks without overburden or stress or, even, accidents due to workplace unevenness that are considered, normally, symptoms of wastes or *muda*, in Japanese (Liker, 2004). Wastes are all activities that do not add value from the client's point of view (Ohno, 1988), may it be a client, anyone requiring a product inside the company (the next worker in the production line/process) or the external client (the one that buys the product). This is the first principle of Lean Thinking: Value that derives from Lean Production (Womack, 1996).

Lean Production is an organizational approach that resulted from the Toyota Production System (TPS) (Ohno, 1988), which main goal is "doing more with less", where less means less human effort, less stocks, less resources, less space, less product development time. Additionally, it tries to enable a greater production flexibility, while meeting quality standards and deadlines. After decades, enhancing Lean Production solutions represents a huge potential for current industrial landscape and Lean Automation, which consists of automation integration into Lean Production, brings several opportunities for the smart factories context (Kolberg & Zühlke, 2015).

Lean Automation has been discussed largely by some authors concerning the improvement of the production system performance, mainly in the manual assembly tasks of the assembly lines and support to it with main purpose of reducing manual activities (Malik & Bilberg, 2017, 2019; Stadnicka & Antonelli, 2019).

Nevertheless, less attention has been paid to logistic activities in warehouses or supermarkets, in particularly, in the loading and unloading of parts in shelves. This continues being a highly manual activity in many companies, which increases the ergonomics risks and contributes to the development of MSD (Afonso et al., 2021; Sun et al., 2019).

Logistics plays a crucial role in supply chain management, ensuring the delivery of products in the right time, in a safe and effective way. However, even with the emerging of the important new concept of Logistic 4.0, which consists in the specific application of Industry 4.0 technologies to logistic activities, the main discussion is usually about the efficiency, better tracking and response to the customer (Bigliardi et al., 2021). Less importance has been given to Human Factors (HF) in logistics and operators overload, overburden, stress and safety in logistics field and how industry 4.0 technologies or AR, in particular, can overcome these issues (Cimini et al., 2019).

In order to explore these opportunities, this thesis project intended to evaluate how Industry 4.0 technologies are changing the HMI and workplaces at smart factories, particularly in logistics activities, through the implementation of AR in Lean industrial environment. The main focus is the improvement of HF, ergonomic conditions and mitigation of Occupational Safety and Health (OSH) risks, studying the potential of HA in logistics activities. HA relies on the use of technologies such as AR to enhance human senses, augmenting their capabilities and cognition.

In sum, humans are allowed to perceive the real world in an enhanced way, since they are provided with relevant information in order to improve their perception, well-being and performance and allowing new HMI solutions (Kymäläinen et al., 2016). An augmented human, known as Operator 4.0, has extended capabilities regarding physical, sensing and cognitive abilities (Romero, Bernus, et al., 2016). However, it is also important to find out how understanding of the tasks and performance, as well as operation times and human errors were influenced by waste-free workplaces supported by Lean Thinking.

## 1.2 Objectives

The use of emerging cutting-edge technologies, such as AR, will lead to the transformation of traditional factories into smart factories. However, the the potentials and the impacts of this technology must be evaluated to understand the benefits of its use in industrial environments. The general purpose of this project consisted in providing relevant understanding about how Industry 4.0 technologies, in particular of AR, are changing the HMI.

Consequently, this project intended to assess which type of AR best suits each industrial process in logistics area. For this purpose, the processes were analysed and the most important human capabilities and senses to perform the required tasks were identified.

Therefore, the application of AR in order to augment these capabilities and senses were studied. HA techniques using AR will not only allow the increasing of task performance and productivity, it will also enhance the ergonomics conditions and eliminate the risks within logistic workplaces, improving the HMI in industrial environment, which is the focus of this work.

Moreover, physical logistics processes have been selected for the analysis of the case study, since the literature always focuses more on production processes, generally leaving out the logistics processes. This fact is even more visible when it comes to the analysis of ergonomic factors and risks within workplaces. These factors are often overlooked in logistics areas, which makes the importance of analysing these processes from an ergonomic and safety point of view increasingly important.

Attending to Lean Thinking, the potential AR implementation was studied to enhance the creation of waste-free workplaces with a strong focus on HMI, allowing the workers to be more efficient and effective in their tasks without stress and overburden. The logistic operator was the main focus of this study and the aim was to reduce the human effort during tasks performance, mitigating the risks and improving ergonomic conditions in the workplace. Fundamentally, the main aim is creating a healthy workplace, where there is a continual improvement process to protect and promote health, safety and well-being of all workers (Burton & WHO, 2010).

The expected outcomes of this project regard to the use of HA techniques by using AR technologies to enhance HMI in order to augment human's physical, sensorial and cognitive capabilities (Pereira et al., 2019).

Furthermore, it was intended to study the potential of creating a symbiosis between human and technology, assessing how AR is changing workforce, workplaces and, consequently, HMI. Accordingly, it intended to assess which type of AR is more suitable for some of the analysed logistic processes and, therefore, which human sense or capability should be augmented in order to improve task performance, productivity and efficiency at those workplaces.

For this purpose, each logistic process was analysed with a strong focus on HF, ergonomics, HMI, and safety, in order to identify which type of AR best suits logistic processes, evaluating the tasks and which human capabilities and senses should be augmented, in order to:

- Enhance human capabilities and senses;
- Increase productivity and efficiency;
- Eliminate non-value added activities;
- Eliminate human errors;
- Enhance ergonomic conditions and improve HMI;
- Eliminate or mitigate OSH risks;

- Reduce human effort during tasks;
- Reduce logistics activities times;
- Give people more time to learn, think and innovate.

In this context, HA focused on the enhancement of HF and HMI, eliminating workplace's wastes, non-value added activities and risk factors. Furthermore, the operator's efforts during task performance were expected to be reduced, promoting well-being within the organizations and ensuring equality for all workers, regardless their capabilities or disabilities, promoting a safe and secure working environment.

The accomplishment of "The Use of Augmented Reality in Lean Workplaces at Smart Factories" project intended to address the following main specific objectives:

- Understand how AR technology is changing the HMI and the work environment;
- Define implementation requirements of AR technology in lean industrial environment;
- Define strategies to mitigate the OSH risks through HA techniques;
- Propose AR implementation methodologies in workplaces, considering relevant factors such as requirements, lean principles and HMI impacts;
- Study the potential of AR implementation at case study to address Industry 4.0 principles;
- Enhance workers' experience using AR technology, creating an enhanced HMI and augmented work environment to improve working conditions;
- Improve tasks performance and workers' efficiency, decreasing human errors and effort, through AR implementation in lean workplaces.

Furthermore, the accomplishment of this project addressed the following objectives, that can be categorized into three, of the 17 United Nations Sustainable Development Goals (UN, 2019):

- Ensure healthy lives and promote well-being for all at all ages (Goal 3): This project focus on HF and in the improvement of workplaces, through the elimination of risks and the reduction of operator's effort during task performance, promoting well-being within the organizations;
- Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all (Goal 8): The implementation of AR in workplaces represents a technological innovation that focuses on high value-added operations and aims to eliminate non-value added activities. Furthermore, this technology will allow the increasing of productivity and efficiency. Moreover, HA in workplace will promote equality for all workers, regardless their capabilities or disabilities, promoting safe and secure working environments, since this project aims to improve HMI and enhance human capabilities;

- Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation (Goal 9): AR technology allows the upgrade of the technological capabilities of industrial sectors, enhancing industrialization and economic development and improving organization's performance and competitiveness. Also, technologies may reduce work time, giving people more time to learn, think and innovate.

## 1.3 Research questions and research methodology framework

In order to accomplish the objectives of this project outlined in the previous section, a fundamental and general research question has raised, addressing the full scope of this project: Research Question 1 (RQ 1) – *How can AR enhance human capabilities and senses in lean workplaces?*

This general research question addresses the main objectives of the project and allows a better understanding about the relationship between industry 4.0 technologies, namely AR, Lean and HF, which is the main focus of this work. Consequently, this main research question was divided into two, being this work motivated by those questions which are the main focus of this research:

- Research Question 1.1 (RQ 1.1) – *How can AR enhance human capabilities and senses in order to mitigate risks?*
- Research Question 1.2 (RQ 1.2) – *How can AR enhance human capabilities and senses in order to improve ergonomic conditions?*

The relationship between the first research question (RQ 1) and the two subsequent research questions, as well as the fields on which each one is focused is depicted in Figure 1.

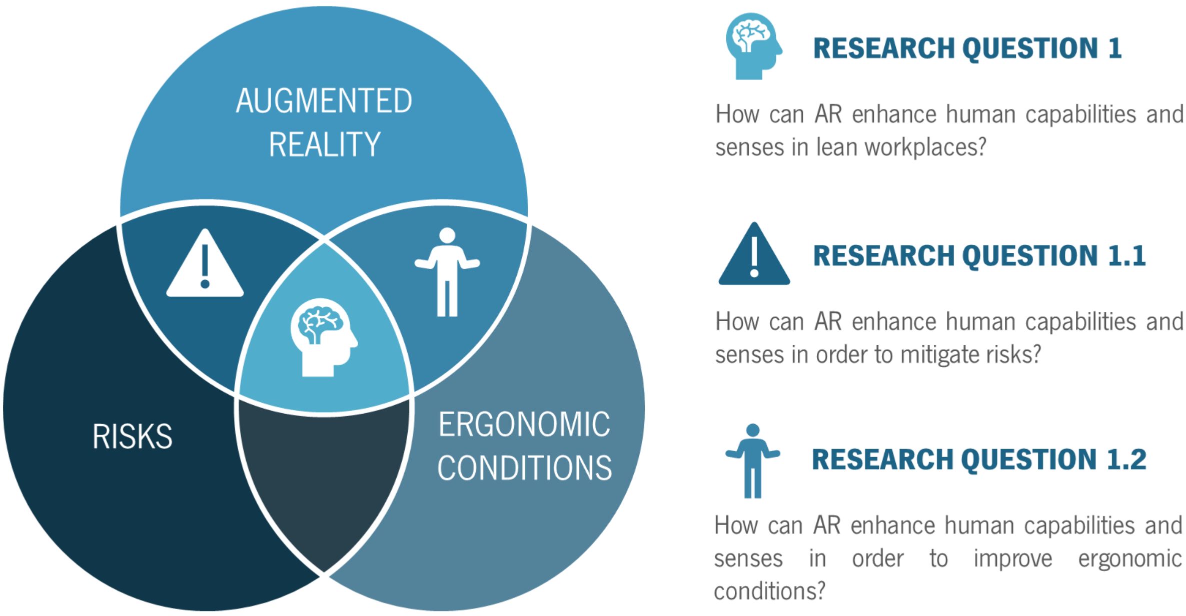

Figure 1. Relationship between first research question and the two subsequent research questions

The research questions RQ 1.1 and RQ 1.2 are very similar and intend to evaluate which human capabilities and senses should be augmented using AR in order to enhance HMI and HF, while improving performance and efficiency in workplaces. RQ 1.1 regards to the mitigation of risks in HMI context, while RQ 1.2 addresses the enhancement of ergonomic conditions. For this purpose, industrial processes, namely logistics processes, will be mapped and analysed, being the main aim the decreasing of human effort, improving work environment regarding HF and OSH risks.

The definition of the capabilities and senses to augment leads to the second research question (RQ 2), whose objective is the accurate definition of the AR solutions that best suit logistic processes in order to augment the capabilities and senses identified in RQ 1.1 and RQ 1.2, as well as the establishment of use cases of each technology: Research Question 2 (RQ 2) – *Which AR solutions are more suitable for logistic processes?*

Moreover, both main research questions (RQ 1 and RQ 2) and subsequent questions (RQ 1.1 and RQ 1.2) to be addressed during the deployment of this research project, as well as their core that relies on Lean Thinking principles, are represented in Figure 2.


Figure 2. Core and relationship between research questions

In order to achieve the above-mentioned research questions, a research methodology framework was designed that consisted in the accomplishment of four main phases, namely: (1) literature review; (2) case study analysis; (3) methodology definition; and (4) analysis and discussion. These phases of research methodology framework are detailed in Figure 3.

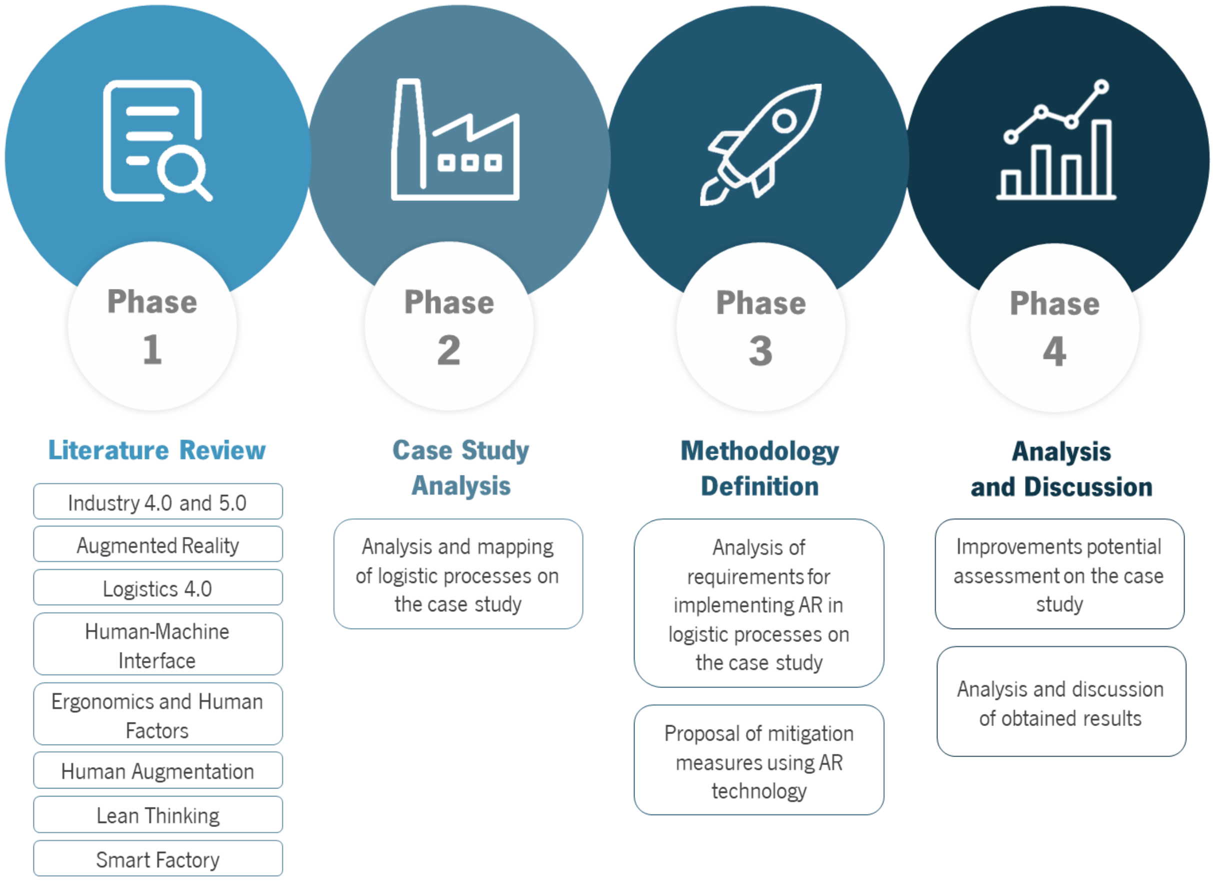


Figure 3. Research methodology framework

This research began with a literature review embracing several topics, which allowed the collection of relevant information about studies previously developed in the project area, being crucial for the characterization of project scope and objectives, as well as the research question definition. This phase consisted in a critical analysis on the works in the literature that are related to the research area, such as relevant scientific papers presented in conferences or published in national or international journals, books, newspapers, dissertations and theses. Therefore, the literature review, which is detailed in chapter 2, emphasized the following topics: Industry 4.0 and 5.0; Logistics 4.0; AR; HMI; Ergonomics and HF; HA; Lean thinking and Smart factory.

The second phase, described in chapter 4, regards to the analysis of industrial processes and consists in the mapping of all the industrial processes under study on the case study plant. This project focuses on the logistic processes that occur in incoming area, raw materials warehouse and production supermarkets and shipping. This analysis was carried out through meetings organization with the Logistics Section Head, Team Leaders, the ergonomist responsible for such areas and relevant employees for the processes' analysis. This phase comprised process observation and data collection, as well as, interviews to operators and other employees involved in the studied processes. The process mapping intends to analyse the operations and tasks that are performed by operators, intending to identify the main risk to which operators are exposed and which human capabilities and senses should be augmented using AR, in order to mitigate or even fully eliminate them.

The methodology definition constitutes the third phase, being twofold and presented in chapter 5. This phase is focused on the analysis of requirements for implementing AR in logistic processes and the proposal of mitigation measures using AR. For this purpose, work-related occurrences in the case study have been analysed during the last few years, in order to understand what the most critical logistic areas and processes are, as well as the main consequences of occurrences. Afterwards, it was possible to evaluate the OSH risks, identifying the existing hazards and categorising the risk factors. This analysis focused on the identification of HF and ergonomic issues in order to understand how HA can benefit operators and enhance their well-being, as well as, what are the human senses and capabilities that should be augmented in order to reduce effort during tasks performance and mitigate OSH risks. Moreover, the most critical processes regarding the prevalence of occurrences that result in MSD or the processes that accounted the highest scores in ergonomic risks during OSH risk evaluation were further analysed using a suitable ergonomic assessment method in order to quantify the risk, analyse the improvement potential and propose mitigation measures using AR technology to reduce human effort and the risk of develop work-related MSD.

Thus, the proposal of mitigation measures using AR technology, augmenting human senses and operator's capabilities, will allow the decreasing of human effort, mitigating the OSH risks and improving work environment and ergonomic conditions. For this purpose, a comprehensive analysis was conducted that allowed the definition of which type of AR that was more suitable for each process and the senses and capabilities that, when augmented, have the potential to mitigate the identified OSH risks. These activities were supported by the literature review performed on the previous phase, that was crucial for the collection relevant data about this emerging technology and every type of AR, implementations and uses in industrial environments, particularly in logistics, and the best practices that were being implemented by the companies that are moving toward the I4.0 paradigm.

Despite the project being developed in the logistics area, AR can be implemented in nearly all kind of industrial sectors. For this reason, the developed methodology would be suitable for logistics processes in every industry and not only for the organization of the research. This way, it was crucial the proposed methodologies took into account the several aspects, such as:

- Best adopted practices;
- Required steps to implement the methodologies;

- Specificity of the process in which it will be implemented;
- Human capabilities and senses that will be augmented in each process;
- AR solutions that are more suitable to logistic processes;
- AR technology's design principles;
- Lean Thinking principles;
- Tools to be used.

The fourth and last phase of the research methodology, described in chapter 6, comprises the improvement potential assessment at case study. With the implementation of new technologies in industrial environments, namely AR, some concerns within the Ergonomics and HF domains arose, in particular related to the HMI. During this phase, attention was paid to the relationship between the human and technology and understanding how the use of AR can benefit logistic workers regarding safety and ergonomic issues. This was one of the most important focus of this project and the improvement's potential assessment in case study has allowed the assessment of AR potential implementation impacts in workplaces regarding the mitigation of risks and enhancement of ergonomics conditions during logistics tasks performance.

Furthermore, this last phase culminates with the analysis of obtained results, whose goal was to highlight the main findings and the project relevance for the topic under study. At this phase, the collected data was organized, summarized and evaluated through descriptive statistics, giving rise to the main results and conclusions about the impact of AR technology in logistics processes regarding to HF and HMI, OSH risks, ergonomics and work environment.

Moreover, during this project, several research tools were undertaken to answer the research questions, that are presented and detailed in chapter 3, as well as, the research philosophy, approaches and methods used. Additionally, lean principles have been applied during the deployment of this project in order to enhance the potential for creating lean and healthy workplaces, decreasing wastes and allowing the workers to be more efficient and effective in their tasks.

## 1.4 Outline of the thesis

This thesis is divided into seven main chapters. The first chapter gives a brief introduction, describing the motivation of this project and presenting the main objectives. Also, in the first chapter, a brief overview of the research questions and the research methodology framework is given, as well as, the structure of the thesis is outlined. Furthermore, the second chapter regards to literature review, where relevant information about studies previously developed in the project area are presented. In turn, the detailed research methodology is described in the third chapter, while the case study and the logistics processes at case study are presented in the fourth chapter. Moreover, the analysis of requirements for implementing AR technology and the developed methodology is proposed in chapter 5 and the analysis and discussion of proposed mitigation measures are presented in chapter 6. Finally, the conclusions are drawn in the last and seventh chapter of this thesis, followed by references and appendices.

# 2 LITERATURE REVIEW

This literature review first approaches Lean Thinking, once this methodology supports the project and solutions to be developed. Furthermore, the new industrial paradigm which is called Industry 4.0 is presented, as well as, its background, the future manufacturing vision, along with the main technologies enabled by the fourth industrial revolution and its main implications. Thereafter, the relationship between Lean Thinking and Industry 4.0 is analysed, along with a future manufacturing vison addressing Industry 5.0 concept, followed by a section approaching the HF and ergonomics.

Furthermore, the AR technology and its use in industrial environments is analysed, as well as the implications of these technologies in HMI and the presentation of new emergent concepts such as HA. Finally, a critical review analysis is presented.

## 2.1 Lean Thinking

Lean production is an organizational management methodology that enables companies to face the worldwide economy and the extremely competitive variable markets. This term was popularised by the internationally known book "The machine that changed the world" (Womack et al., 1991) and had its roots in the Toyota Production System (TPS), which was conceived in a demanding period for the Japanese economy (Monden, 1983; Ohno, 1988).

This organizational approach tries to increase productivity and to reduce costs by eliminating wastes (Ohno, 1988). Ohno (1988) has considered wastes the activities that do not add value to the products in a client point of view. A client can be external (the one that buys the finished product) or anyone that is requiring a product inside the company (the next worker in the production line/process). Ohno (1988) classified the wastes in seven categories: (1) overproduction; (2) over processing; (3) transportation; (4) defects; (5) motion; (6) inventory; and (7) waiting. Later on, Liker (2004) identified an extra waste, i.e. untapped human potential.

Nevertheless, already in 1977, Sugimori et al. (1977) defined TPS as a respect-for-human system in a first published English paper because workers were allowed to apply their full potential and actively participate in improving their own workshops.

TPS main goal is "doing more with less", where less means less human effort, less stocks, less resources, less space, less product development time. For this reason, it was called Lean Production (Krafcik, 1988; Womack et al., 1991) . In other words, TPS was designed in a way that fewer and fewer resources would be required, in order to deliver the right products at the right time and at the shortest possible deadline, through the elimination of all types of wastes. Additionally, it tries to enable a greater production flexibility, while meeting quality standards and deadlines.

A successful implementation of Lean principles goes beyond process improvement, since any change in work practices or workstations has deep effects on workers and their performance, affecting their well-being, safety and security (Alves et al., 2019). Hence, it can be said that human factors and ergonomics have impact on company's business strategy and competitiveness (Dul & Neumann, 2009).

According to Brito et al. (2018), ergonomics and human factors should be integrated into the lean process from the beginning, which unfortunately does not occur in many companies that fail to realise the potential of the integration and implementation of ergonomic principles at the same time as lean practices. Thus, most of the industrial projects implementing lean principles do not always address the ergonomics factors (Maia et al., 2012), being just focused on the gains of productivity and process improvement, instead of taking advantage of this field of study to advance organizational effectiveness, business performance and costs (Alves et al., 2019; Nunes, 2015).

Therefore, combining lean and ergonomic design concepts will reduce errors, improve productivity and simultaneously improving the working conditions while reducing risk factors that can lead to the development of injuries or MSD, as so, Lean impacts ergonomics (Arezes et al., 2015; Nunes, 2015).

In the HMI context, it is crucial to ensure that people develop their tasks without wastes and symptoms of wastes (*muda*, in Japanese). Beyond *muda*, there are the *mura* and *muri* that are considered the symptoms of *muda*. For instance, within the ergonomic context, *mura* are the consequences of wastes that result in workplaces unevenness or irregularities, such as applying a force that increases the risk of strains and injuries that causes a higher fatigue, which leads to reduced workplace and productivity. *Muri* is the overburden or stress caused by repetitive tasks or weights lifting or, even, accidents that could occur in the workplace due to other symptom of waste, such as the unevenness or irregularity, i.e. *mura*. All together these three Japanese words are called 3M (Liker, 2004). Ergonomic design focuses on the creation of efficient and appropriate body postures, reducing the amount of strength required to perform a task, avoiding repetitive postures and motions throughout the work shift (Alves et al., 2019).

To systematically eliminate wastes, Womack and Jones (1996) have designed the Lean principles in order to guide a company in value creation and wastes elimination, as shown in Figure 4. The first Lean principle is specifying value, taking into account costumer's needs. Thus, value is assumed as the features intended by the costumer. Anything that does not generate value for customer should be eliminated. The second principle regards to the identification of the value stream, comprising the mapping of all the activities required from concept to launch in order to provide a specific product. This principle includes a comprehensive analysis throughout the entire production system in order to identify value-added activities and eliminate those that do not generate value for the costumer, that are considered wastes. Flow, the third Lean principle, consists in creating a continuous flow of materials throughout the entire value stream without waiting, stoppages, scrap, stock gathering or backflows. The fourth principle is the pull production, which means producing only what is pulled by customer, in a cascading production system in which the upstream supplier does not produces anything until downstream customer requests something. When organised to flow, pull production allows the elimination of excess production, avoiding inventories and unnecessary costs. Finally, the fifth principle regards to pursuit of Perfection, which implies searching for continuous improvement (Kaizen) and means the complete waste elimination along the value stream (Womack et al., 1991).

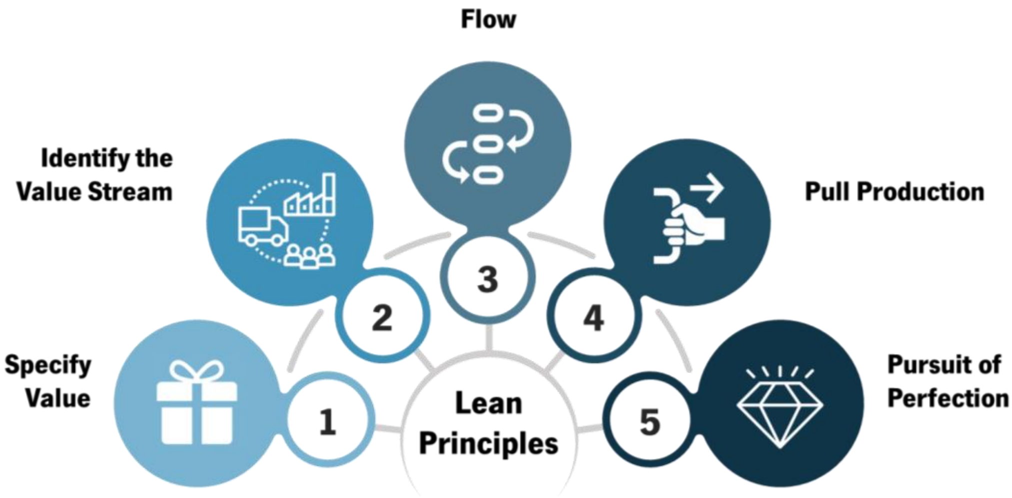


Figure 4. Lean principles

These principles happen cyclically and the last one allows the continuous improvement, known as kaizen, which is made by creative people committed with Lean and questioning the status-quo and thus becoming thinkers, through the people heads, heart and hands (3H) because only people have the capability to think, promoting companies' agility (Alves et al., 2012; Spear, 2004).

Workers are the core of every production system and their understanding of lean principles and safety awareness are essential to ensure companies competitiveness and effective process design and principles implementation. In what regards to worker safety in lean production environment, it is crucial to have well informed, empowered and active operators, with relevant knowledge, skills and opportunities to act within the workplaces in order to eliminate or mitigate hazards, as well as risks regarding ergonomic conditions and physical safety. Hence, basic lean, ergonomics and safety principles should be included in the training plans in order to provide knowledge that allows workers to recognize risk factors and apply these concepts, in order to increase productivity and quality, enhance workers satisfactions and reduce errors and lost work days (Brito et al., 2019).

Nevertheless, the most sceptical have not been convinced by the good results of Lean companies all over the world (Cowger, 2016). Nonetheless, with so many studies reporting benefits and supporting that Lean implementation is a key enabler to move manufacturing operations abroad and remaining competitive, it suggests that it seems a question of time for a greater adoption of Lean (Amaro et al., 2019; Sanidas & Shin, 2017; Whitefoot & Donofrio, 2015). The literature on lean is wide, being highly focused on theory and application of lean, providing relevant guidance for Lean implementation (Browning & de Treville, 2021; Cusumano et al., 2021; Hopp & Spearman, 2021).

Additionally, Lean is interdisciplinary, multidisciplinary (Alves et al., 2016; Flumerfelt et al., 2015; Sinha & Matharu, 2019), suitable for complex socio-technical system, influencing its complexity and attributes (Soliman et al., 2018) and being a transversal and global methodology. It embraces many other concepts, fostering the establishment of synergies with other areas, such as logistics (Kaspar & Schneider, 2015), Lean Automation (Kolberg & Zühlke, 2015) and ergonomics (Arezes et al., 2015), as shown in Figure 5.


Figure 5. Synergies and concepts embraced by Lean
(Adapted from: Alves et al. (2016))

Lean Logistics, which is the application of lean to supply chain and warehouse management (Flumerfelt et al., 2015), is one of the main focus of this project. This concept consists in the implementation of lean thinking principles and methods in order to improve the efficiency of logistic processes, eliminating wastes and creating value-added logistic activities throughout the value chain (Fan & Deng, 2016).

Furthermore, Lean Automation regards to the synergies between industry 4.0 and lean. This term is referred as the integration of Industry 4.0 technologies and automation into Lean Production (Kolberg & Zühlke, 2015).

Moreover, the combination of lean, safety and ergonomic aspects within a workstation is understood as Lean Ergonomics (Brito et al., 2020). It is possible to combine these Lean concepts simultaneously in order to increase logistics processes performance, enhancing working conditions in terms of ergonomics and safety, reducing the risk of MSD (Vicente et al., 2016).

Thus, Lean Thinking is a philosophy that has become increasingly important for the companies' competitiveness, being transversal and interdisciplinary, embracing areas from industry and services in any area and helping organisations to continuously improve in order to face the current and future challenges.

## 2.2 Industry 4.0

The term "Industry 4.0" is often referred to as the fourth industrial revolution and embraces a set of technological advances that are having a high impact in the current industrial landscape. In this section, the background of Industry 4.0 phenomenon is analysed, as well as the future manufacturing vision enabled by this new manufacturing paradigm. Additionally, the key features about this concept and the key technologies enablers are presented in order to better understand the main expected impacts of Industry 4.0.

### 2.2.1 Background of Industry 4.0

In the last few years, several growing advancements in manufacturing processes and technology have allowed the emergence of many new global concepts. The term "Industry 4.0" has become an increasingly important topic in the last few years due to technological advancements and disruptive developments in the global industrial sector. This concept appeared firstly in an article published in November 2011 by the German government that resulted from an initiative regarding high-tech strategy for 2020 (Zhou et al., 2016). The concept draws on earlier concepts and perspectives that evolved over the years (European Commission, 2010; Kagermann, 2015)

As a result of successive innovations and disruptive developments, the industrial landscape has changed drastically in the last few years, mostly regarding digital technology and manufacturing. Similar to the first three industrial revolutions that occurred in the last centuries as a result from disruptive technological advancements, Industry 4.0 can be referred as the fourth industrial revolution (Schmidt et al., 2015). The increasing productivity is the core of every industrial revolution. The previous three industrial revolutions had a strong impact in industrial processes, allowing productivity and efficiency increase through the use of disruptive technological developments that have represented disruptive changes in manufacturing (Schuh et al., 2013).

The First Industrial Revolution took hold in England in the middle of the 18th century and was triggered by the invention of the steam engine, which allowed the use of steam and waterpower to mechanize the production. During the second half of 19th century, the rise of mass production and the replacement of steam by chemical and electrical energy were the key drivers of the Second Industrial Revolution that came up in Europe and USA. Furthermore, in order to meet the growing demand, several technologies in industry and mechanization have been developed, such as the assembly line with automatic operations, allowing the increasing of productivity. The invention of the Integrated Circuit (IC) was the technological advancement that has started the Third Industrial Revolution that consisted in the use of electronics and Information Technology (IT) in order to achieve further automation in production. This revolution has emerged in the last years of 20th century in many industrialized countries around the world (Acemoglu, 2002; Tunzelmann, 2003). Finally, the emerging fourth industrial revolution can be generally described as a complex technological system that embraces digital manufacturing, network communication, computer and automation technologies, as well as many other relevant areas (Zhou et al., 2016).

### 2.2.2 Key technologies for Industry 4.0

Industry 4.0 has been widely discussed and researched, having a great influence in the industrial sector, since it introduces relevant advancements that are related with smart and future factories. This emerging Industry 4.0 concept is an umbrella term for a new industrial paradigm that embraces a set of future industrial developments regarding CPS, IoT, IoS, Robotics, Big Data, Cloud Manufacturing and AR (Figure 6), that will influence both products and processes, allowing efficiency and productivity improvements among companies that will adopt such technologies (Schmidt et al., 2015).

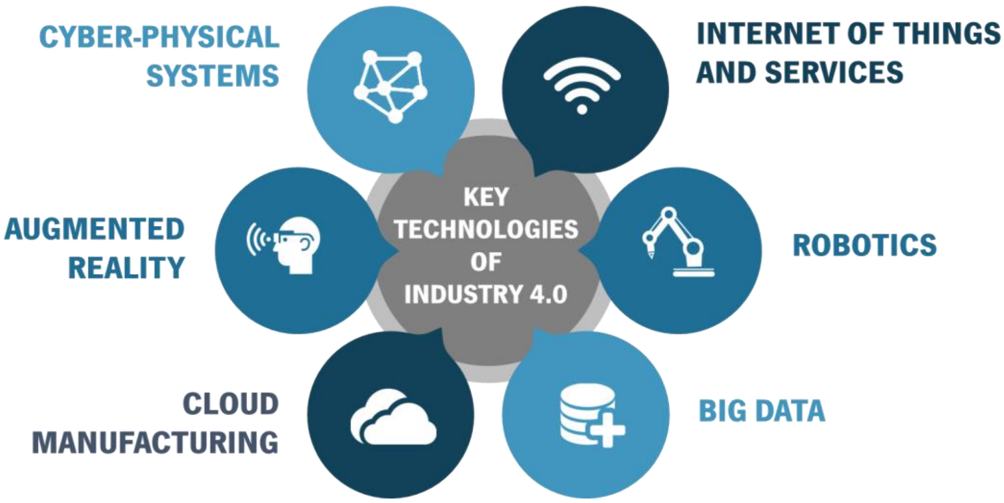


Figure 6. Key technologies of Industry 4.0

The so-called fourth industrial revolution is being shaped fundamentally by connectivity, integration and production digitization, fostering new opportunities for integrating all elements in a value-adding system (Neugebauer et al., 2016) while embracing digital manufacturing technology, network communication technology, computer technology and automation technology (Zhou et al., 2016). Disruptive technologies that are arising with Industry 4.0 are eliminating the boundaries between the digital and physical world, fully integrating humans, machines, materials, products, production systems and processes (Erol et al., 2016)

This emerging industrial revolution is being predominantly shaped by the technical integration of CPS into manufacturing processes and the use of the IoT and IoS in industrial processes, which are considered the main drivers of this industrial paradigm (Kagermann et al., 2013a). CPS consist in the interaction between the physical and the virtual environment, integrating, controlling and coordinating processes and operations and, simultaneously, providing and using data accessing and processing (Monostori et al., 2016).

CPS, which are frequently used to define Industry 4.0, represent one of the most significant advances regarding computer science and information technologies development. These systems consist in the interaction between the physical and the virtual environment, integrating, controlling and coordinating processes and operations and, simultaneously, providing and using data accessing and processing (Monostori et al., 2016). Generally, CPS can be defined as innovative technologies that enable the management of interconnected systems through the integration of their physical and computational environments (Lee et al., 2015).

The integration of these systems with production, logistics and services will led to an industrial transformation using Cyber-Physical Production Systems (CPPS), which can be defined as CPS when specifically applied to production. These will play an important role, since these systems consist in the connection across all levels of supply chain between autonomous and cooperative elements, such as Smart Machines, and sub-systems, including Smart Factories (Francalanza et al., 2017).

Alternatively, the IoT, frequently pointed out as one of the main drivers of Industry 4.0, is an emerging term based on the connection between physical things and the Internet that can be defined as the Internet connection between everyday physical objects in the shop floor, people, systems and IT systems. This allows the creation of a smart manufacturing environment often referred as smart factory (Shariatzadeh et al., 2016), making it possible to expand the Internet into a next level: smart objects (Kopetz, 2011). Smart object is the basis of a IoT vision, since not only able to collect information and interact with their environment, but also to be interconnected with other objects, exchanging data and triggering actions through the Internet (Borgia, 2014).

Furthermore, IoS pursuits a similar approach of IoT, but it is applied to services instead of physical entities. This concept is described as a new business model that will deeply change the way services are provided, allowing a higher value creation that results from the relationship between every stakeholder within the value chain, such as the organisation, customers, intermediaries, aggregators and suppliers (Cardoso et al., 2008; Schmidt et al., 2015).

The application of IoT in industry environments and value chains and its proliferation is often associated to Industrial Internet of Things (IIoT) concept, which implies the use of disruptive technology such as sensors, actuators, control systems, machine-to-machine, data analytics, and security mechanisms to improve modern industrial systems (Mourtzis et al., 2016). Therefore, it has a great impact in several fields, such as, automation, industrial manufacturing, logistics, business processes, process management and transportation (Atzori et al., 2010; Miorandi et al., 2012). The further development and proliferation of IoT techniques will allow things to become smarter, more reliable and more autonomous, enabling the provision of added-value products and services (Kyriazis & Varvarigou, 2013).

According to Hermann et al (2016), Industry 4.0 concept can be understood as a collaborative term for technologies and concepts that embraces the whole organizations' value chain. This author, whose theory emphasizes the smart factory vision and the integration between its elements along the value chain through the use of key technology enablers, has identified four key aspects of Industry 4.0:

1. CPS;
2. IoT;
3. IoS;
4. Smart Factory.

In industry 4.0 framework, smart factories are organized by a modular structure, whose processes are controlled and monitored by CPS, that make decentralized decisions. On the other hand, IoT technology enables the cooperation between every CPS in the smart factory and operators in real-time, while IoS provides internal and cross organizational services over the whole value chain.

### 2.2.3 Implications and impacts of Industry 4.0

Innovation and technological developments play an important role in every organization. However, the digital transformation advancements and the rising interconnectivity will bring new challenges to organizations, since Industry 4.0 will significantly change the products and manufacturing systems regarding design, processes, operations and services (Pereira & Romero, 2017).

Industry 4.0 concept has become an increasingly important topic, being discussed and researched by academics and companies in recent years. However, despite the increasing interest about Industry 4.0 topic, it is still a non-consensual concept and the misunderstanding about this topic starts with what involves Industry 4.0 and its meaning and vision. Therefore, companies need to take actions to prepare this transformation, defining the most suitable manufacturing model and planning the target roadmaps in order to address this new industrial paradigm's challenges (Almada-Lobo, 2016).

In order to achieve better process efficiency and competitiveness, companies that are moving towards Industry 4.0 need to be aware of the main implications and challenges that will be faced, as well as, the opportunities for innovation. This new industrial paradigm will lead to potential deep changes in several domains that go beyond the industrial sector. This new paradigm holds an enormous potential for organizations that can be can be categorized into six main areas (Pereira & Romero, 2017), as shown in Figure 7: (1) Industry; (2) Products and services; (3) Business models and market; (4) Economy; (5) Work environment; and (6) Skills development.

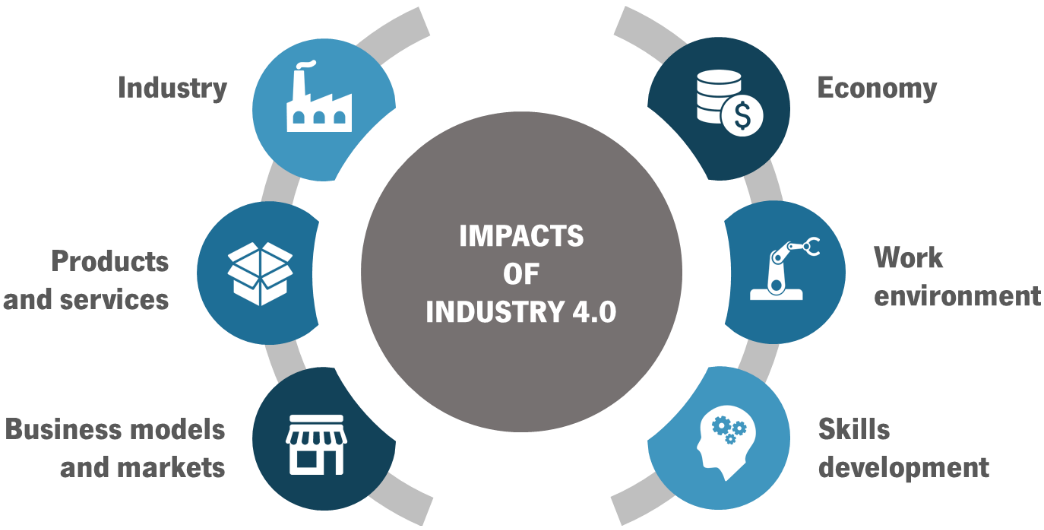

Figure 7. Impacts of Industry 4.0

Briefly, Industry 4.0 holds a huge potential of opportunities for many areas, having deep impacts within the whole value chain, improving production and engineering processes, enhancing the quality of products and services, optimizing the relationship between customers and organizations, bringing new business models and economic benefits, changing the education requirements, creating new jobs, transforming the current work environment and workplaces and bringing new ways of operating (Foidl & Felderer, 2016; Pereira & Romero, 2017).

Following the human-centric approach of Industry 5.0 concept and having the focus on workers, it is crucial to consider that some skills will inevitably become obsolete with the increased automation and digitalisation. As such, it is important to create new jobs and foster education, re-skilling and up-skilling in order to meet the new demands regarding qualifications, as qualified human capital is the most essential resource to enable the digital transition in industries (European Commission, 2021).

### 2.2.4 Future manufacturing vision and Industry 5.0

The future of production as predicted by Industry 4.0 consists in pervasive integration, where every manufacturing element autonomously exchange information, trigger actions and control themselves independently (Weyer et al., 2015).

The term "smart" is becoming central within Industry 4.0 framework, though it is not easy to find an accurate definition. However, a possible definition of this concept that meets several authors' vision can be associated with independent and autonomous devices that are able to communicate in real-time and cooperate in a smart environment with other smart devices, making decisions and performing actions that are based on real-time updates (Radziwon et al., 2014; Raji, 1994). Industry 4.0 is a new manufacturing paradigm that is highly focused on the creation of smart products and processes, through the use of smart machines and the transformation of conventional manufacturing systems into smart factories (Weyer et al., 2015).

Due to these disruptive technological advancements, the industrial landscape has been changing over the last years. Beyond the emphasis on traditional manufacturing transformation, smart factories and intelligent machines, Industry 4.0 concept embraces a set of technological developments that influence both products and processes, allowing the creation of smart products through the integration between digital and physical world (Schmidt et al., 2015). Similar to the industrial landscape, also the market requirements are changing rapidly, demanding for smarter products that are characterized by increased functionalities and more complexity, based on interaction of several technologies (Persson, 2016).

Furthermore, Posada et al. (2015) outlined the key aspects addressed by Industry 4.0: (1) the products mass customization enabled by the use of IT; (2) the automatic and flexible adaptation of production systems for changing requirements; (3) the tracking and self-awareness of parts and products and their capability to communicate within their environment; (4) the improved HMI, the coexistence with robots and the emergence of new ways of interaction and operation; (5) the communication within the smart factory and the production optimization enabled by IoT; and (6) the emergence of new services and business models, influencing the whole value chain, as shown in Figure 8.

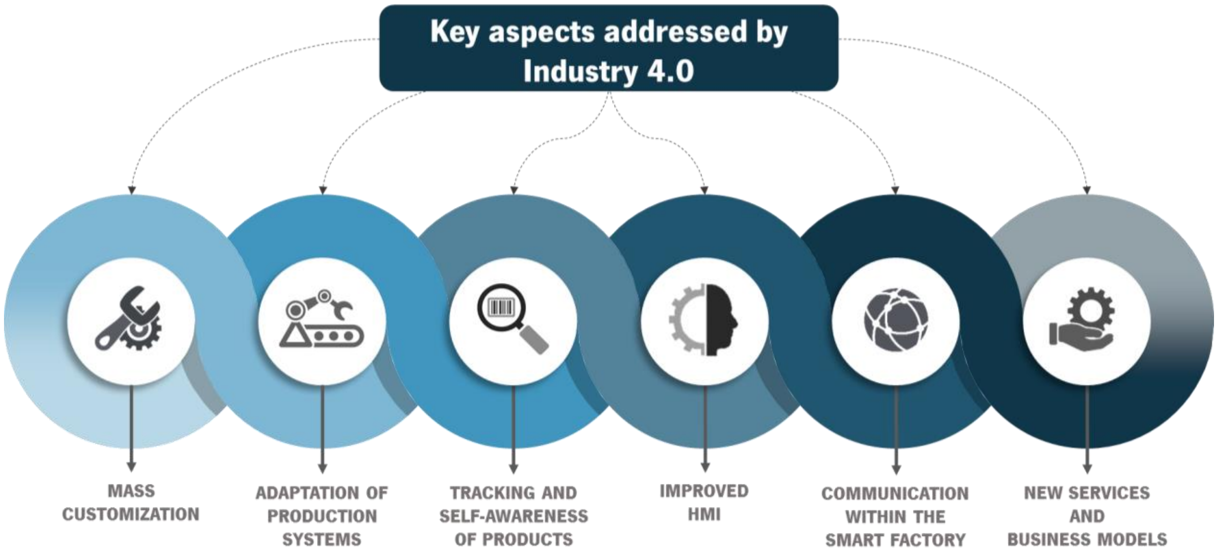

Figure 8. Key aspects addressed by Industry 4.0
(Adapted from: Posada et al. (2015))

After a decade has passed since discussion of Industry 4.0 first appeared, yet visionaries are already forecasting the next revolution – Industry 5.0. Over these years, Industry 4.0 has focused less on social principles and more in digitalisation and use of disruptive technologies for increasing efficiency and flexibility. Thus, Industry 5.0 focus on the importance of a human-centric industry and its service to humanity (European Commission, 2021).

Therefore, the concept of Industry 5.0 and Society 5.0 are related, since both of them are focused on a shift of society, economy and industry towards a new paradigm aimed at creating a people-centric society (Deguchi et al., 2020; European Commission, 2021).

The Society 5.0 term was presented in 2016 by Keidanren (2016), an important Japanese business federation, and its aim is fostering economic development while solving societal and environmental problems, promoting the quality of life and creating a society that attends the different needs of people, regardless of region, age, sex, language or disabilities (Fukuyama, 2018).

For this purpose, the merge between real world and cyber space is crucial in order to gather and generate data that will be useful to create solutions to face the challenges, enhancing the safety, security, and comfort conditions of people (Shiroishi et al., 2018).

Thus, Industry 5.0 complements and extends Industry 4.0 paradigm. It emphasises several aspects for the place of industry in the future society, such as environmental, social, and fundamental rights. Industry 5.0 is not a continuation or an alternative to the existing Industry 4.0, but yes, a strategy that has resulted from a forward-looking exercise to help framing how industry and emerging societal trends and needs can co-exist. Thus, Industry 5.0 complements the existing Industry 4.0 paradigm, driving the transition to human-centric, sustainable and resilient systems, as shown in Figure 9 (European Commission, 2021).


Figure 9. Approach of Industry 5.0
(Adapted from: European Commission (2021))

The human-centric approach focuses on human needs and interests, taking advantage of emergent technology implementation to meet human interests. Thus, the starting point is the human and workers and not the potential of the rapidly evolving technology.

Furthermore, Industry 5.0 is focused on the development of sustainable systems, adopting circular processes and reducing energy consumption in order to respect planetary boundaries. Moreover, resilience refers to the development of systems endowed with a high degree of robustness, flexible processes and adaptable production capacity to meet rapid changes of the market needs (European Commission, 2021).

The future manufacturing vision can be seen as a new approach that will bring together the digital and physical worlds. Researchers and companies hold different points of view about this concept and visions, but there is a consensus about the main aspects that address the future manufacturing vision (Qin et al., 2016), as shown in Figure 10: (1) Smart Factory; (2) Smart Products; (3) Business Models; and (4) Customers.

On the one hand, smart factories are characterised by an intelligent environment along the entire value chain that allows the performance of flexible and adaptive processes which are suitable for dynamically and rapidly meeting market requirements with high complexity. These are also able to manage complexity and increase manufacturing efficiency (Radziwon et al., 2014) and establishing an integrative real-time intercommunication within a network between every manufacturing resource, such as human resources, machines and objects, such as smart products (Kagermann et al., 2013b; Qin et al., 2016).

On the other hand, smart products are integrated with the whole value chain as an active part of the systems, monitoring their own production stages through data storage, being able to request the required resources and control the production processes autonomously (Nunes et al., 2017).

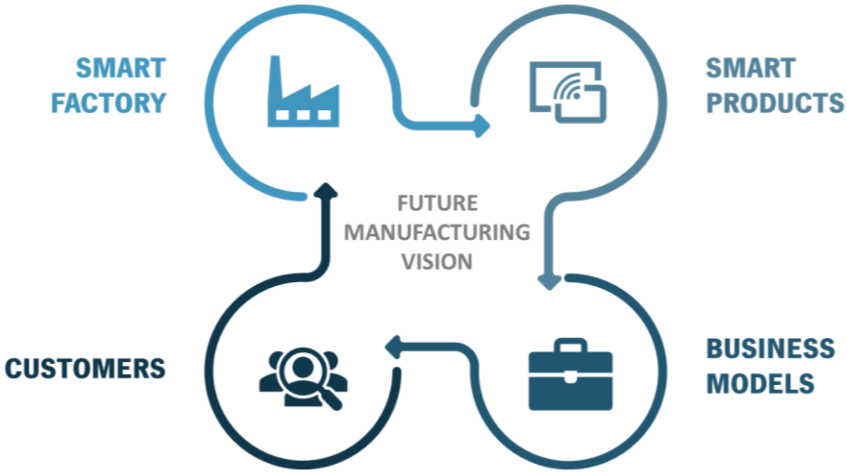


Figure 10. Future manufacturing vision
(Adapted from: Qin et al. (2016))

Furthermore, smart products, as final products, should be self-aware about the parameters within they should be used, providing information about their status and interacting with their physical environment without any human intervention during their whole lifecycle (Kagermann et al., 2013a; Schmidt et al., 2015). In this way, it is possible to manage them in real-time through the whole value chain, optimizing the smart factory regarding to logistics, production, maintenance and business management processes (Kagermann et al., 2013a).

These products are aware about their functionalities, features and able to track themselves, having the capability to interact with their environment and components and with their users during the whole lifecycle (Mühlhäuser, 2008), being characterized by a high degree of autonomy, able to be autonomously operated, self-coordinated and self-diagnosed (Porter & Heppelmann, 2015).

Additionally, business models are being highly influenced by Industry 4.0, since this new manufacturing paradigm implies a new way of communication along supply chains. Business modelling is changing in the last few years due to new industrial and market requirements and new business models are emerging, allowing the creation of collaborative environments (Glova et al., 2014). There are many opportunities for optimizing value creation processes and integration through the value chain, in order to achieve self-organization capability and real-time integration and communication (Qin et al., 2016).

Lastly, the customers are a key factor in every business model and Industry 4.0 brings a set of advantages for them, improving communication along the value chain and enhancing the customer's experience. The high level of integration and the autonomous exchange of information will allow real-time requirements change. Additionally, smart products will provide relevant information to their users about their status and utilization parameters (Qin et al., 2016).

Briefly, smart factories are connected to a value chain in order to fulfil market requirements and consist in the integration between machines and materials through standardized interfaces. Smart materials and smart products are tracked along their whole lifecycle time, allowing a high degree of customization. Industry 4.0 is bringing the emergence of new business models that better meet customers' changing requirements, through the real-time communication capability along the whole supply chain (Erol et al., 2016).

## 2.3 Lean Thinking, Industry 4.0 and Logistics 4.0

In the past few years, the relationship between I4.0 technologies and lean practices has been studied, as well as the potential of integrating these domains and the synergies related with this relationship. The integration between the two domains has been firstly referred as Lean Automation by Kolberg and Zühlke (2015). After decades, enhancing Lean Production solutions represents a huge potential for current industrial landscape and Lean Automation, which consists in the automation integration into Lean Production, brings several opportunities for the smart factories' context (Kolberg & Zühlke, 2015).

According to the systematic literature review presented on the paper published by the proponent of this thesis (Pereira, Dinis-Carvalho, et al., 2019), every emerging technology can provide potential benefits when integrated with Lean Thinking principles. However, it is important to evaluate how effective each technology is in a particular context. Many mistakes have been made over the years with several emerging technologies, creating many problems in many companies.

In order to take the most of this symbiosis, new technologies, lean principles and concepts must be very well grasped. Table 1 presents a summary of which I4.0 technologies impact and support which lean practices.

The most common benefits taken to lean from the technologies enabled by the fourth industrial revolution referred in this literature are related to data collection, ease of communication between different productive actors, information processing capabilities, and data display. These technologies, if aligned with lean principles and concepts can, indeed, reduce non-value adding activities in organizations, as well as, improving workers satisfaction (Pereira, Dinis-Carvalho, et al., 2019).

Furthermore, it was concluded that AR technology can contribute to the development of VSM, fostering continuous improvement and wastes elimination, as well as problem-solving and decision support, enhancing the improvement of human factors and facilitating the communication and information sharing (Pereira, Dinis-Carvalho, et al., 2019).

Table 1. Lean tools supported by Industry 4.0 technologies
(Pereira, Dinis-Carvalho, et al., 2019)

| **Lean Practices** | **Industry 4.0 Technologies** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | **Other Referred Technologies** | | | |
| | **Cyber-Physical Systems** | **Internet of Things** | **Big Data** | **Cloud Manufacturing** | **Augmented Reality** | **Robotics** | **3D Printing** | **Simulation** | **Video-based and 3D Models** | **Optimization Algorithms** |
| Value Stream Mapping | | | ● | | ● | | | ● | | |
| Standard work | ● | | ● | ● | | ● | | | ● | ● |
| Continuous improvement and wastes elimination | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● |
| Andon | ● | | | | | | | | | |
| Heijunka and production planning | ● | ● | | | | | | ● | | ● |
| Pull production | ● | | | | | | ● | | | |
| Jidoka / Autonomation | ● | | | | | ● | | | | |
| Kanban | ● | | | | | | | ● | | |
| Just-in-Time | ● | ● | | | | | ● | ● | | |
| Supermarket | ● | | | | | | | | | |
| Milk run | | | | | | | | | | ● |
| Problem-solving and decision support | ● | ● | ● | ● | ● | | | | | ● |
| Key Performance Indicators | ● | | ● | | | | | ● | ● | |
| Empowerment and involvement of workers | | | ● | | | | | | | |
| Improved human factors | | | | | ● | | ● | | | |
| Six Sigma | ● | ● | ● | | | | | | | |
| Total Productive Maintenance | ● | | | ● | | | | | | |
| Communication and Information sharing | ● | ● | ● | ● | ● | ● | | ● | ● | |
| Decreased operation and waiting times | ● | | ● | ● | | ● | ● | | | |
| Decreased stocks and inventory management | ● | | ● | ● | | | ● | ● | | |
| Increased flexibility | ● | | ● | | | ● | | ● | | ● |

Moreover, Bittencourt et al. (2021) considered that Industry 4.0 technologies must be triggered by Lean Thinking. This means that such technologies should only be acquired after a careful cost-benefit analysis resultant from a problem identify that could not be solved in another way. This is important as such technologies demands a high investment and skills, many times, not affordable by the companies.

With the advent of disruptive technologies enabled by Industry 4.0, new approaches are need in order to foster successful digital transformations. Romero et al. (2019) has proposed an approach where organisation's processes and culture are aligned to ensure successful Industry 4.0 technologies adoptions, based on Lean Think principles, defining five management pillars towards digital transformation:

1. Strategic management;
2. Processes re-engineering management;
3. Technology management;
4. Change management;
5. Risk management.

The synergies between Lean Production and Industry 4.0, known as Lean Automation, have been widely discussed recently, pointing out some benefits, such as the performance improvement, elimination of manual tasks and assembly tasks support (Malik & Bilberg, 2017, 2019; Stadnicka & Antonelli, 2019).

Although, little attention has been paid to logistics area, unlike production and assembly areas, the application of Industry 4.0 technologies to logistic activities has been discussed by some authors, which gave rise to the new concept of Logistics 4.0 (Bigliardi et al., 2021).

The key logistics activities, such as transport, inventory management, material handling, supply chain structure and information flow are affected by Logistics 4.0, that comprises an environment characterised by the following features: (1) Real-time big data analytics; (2) On-site, on-demand and rapid manufacturing, which reduces the inventory. (3) autonomous robots and vehicles with tracking and decision-making systems; (4) Real-time exchange of information; and (5) Smart products and cloud-supported network (Strandhagen et al., 2017).

Logistics is essential in every industrial sector and its importance is growing due to the increasing relevance of emerging markets and globalization of supply chains (Cirulis & Ginters, 2013). Nevertheless, it is important to highlight that transport, stocks and motion are part of the main processes of logistics but these are also three of the most common wastes identified in the companies (Liker, 2004), which reinforce the need to reduce or eliminate them by having an effectiveness logistic process.

Moreover, Logistics 4.0 allows a network where all processes can communicate with each other in real-time, as well as with humans in order to enhance their analytical potentialities throughout the supply chain, improving their performance and decision-making process (Barreto et al., 2017).

Hence, the use of disruptive technologies, namely AR, holds a great potential to improve logistic processes and solve problems related with human error caused by stressful situations and warehouse worker routines. Therefore, the successful implementation of this cutting-edge technology can simplify the decision-making process, based on computer generated visualizations and 3D model projections that provide instruction to workers in a three-dimensional space, while making the tasks more humane (Cirulis

& Ginters, 2013), releasing and enhancing the untapped and uniquely human capabilities by taking full advantage of new digital knowledge and machine potentials (Porter & Heppelmann, 2017).

## 2.4 Ergonomics and Human Factors

Ergonomics or HF are defined by the Council of the International Ergonomics Association (2015) as the *"scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance"*.

Moreover, according to a report published by the World Health Organization, a healthy workplace is *"one in which workers and managers collaborate to use a continual improvement process to protect and promote the health, safety and well-being of all workers and the sustainability of the workplace"* (Burton & WHO, 2010).

The same report mentions that a healthy workplace regards to: *"(1) health and safety concerns in the physical work environment; (2) health, safety and well-being concerns in the psychosocial work environment including organization of work and workplace culture; (3) personal health resources in the workplace; and (4) ways of participating in the community to improve the health of workers, their families and other members of the community"*.

The ability of humans to work are directly related with their well-being and health. According to Maslow (2013), people are motivated to achieve certain needs that are categorised hierarchically. The most basic need is for physical survival and, once it is fulfilled, the humans are motivated to achieve the next one, that concerns to safety needs.

Therefore, the next level concerns to love and belongingness needs, followed by esteem needs and, finally, the highest level that refers to self-actualization needs. A safe and healthy workplace addresses the second level of Maslow's (2013) hierarchy of needs, referring to worker's well-being and need of safety against accidents or injuries.

Hancock et al. (2005) stated that hedonomics is the branch of science that refers to the promotion of pleasurable interaction between humans and technology. Its main aim is to augment and expand ergonomic tools for improving the design of HMI. These authors presented a similar hierarchy that derives from Maslow's, however, emphasizing the enhancement of ergonomics and hedonomics (Figure 11).

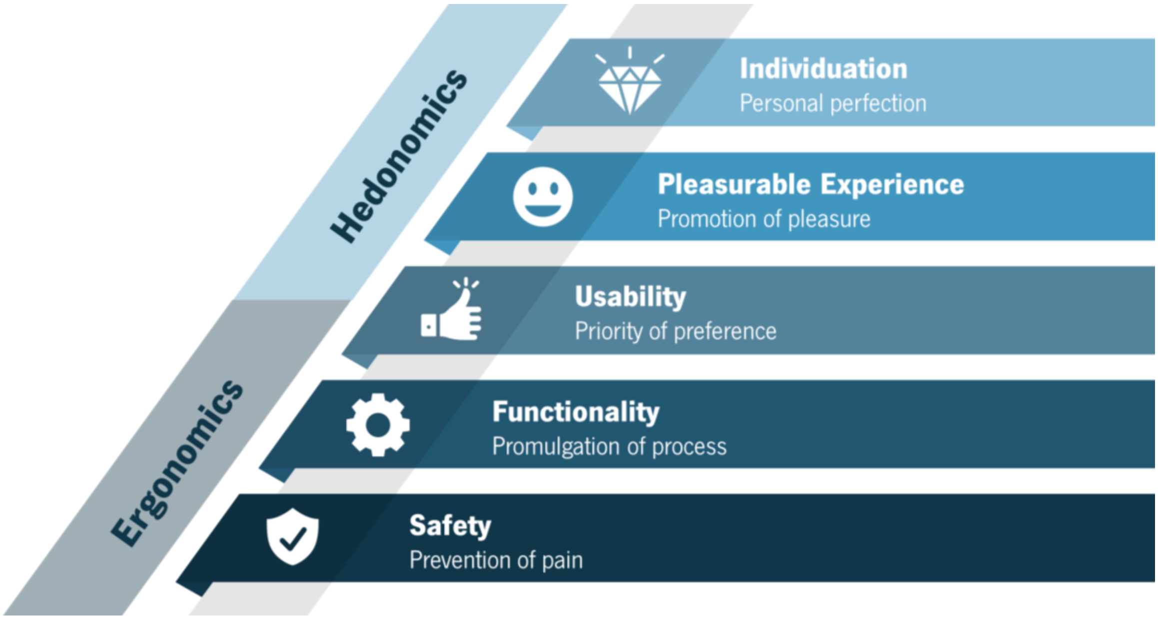


Figure 11. Hierarchy of ergonomics and hedonomics
(Adapted from: Hancock et al. (2005))

The ergonomic needs address safety, functionality and usability, while hedonomic needs concern to usability as well, pleasurable experience and individuation. Safety needs is the foundation of this hierarchy and the basis of ergonomics, regarding to prevention of pain, creating safe workplaces and mitigating risks in order to avoid injuries. Once the safe operating conditions are ensured, the next needs level requires a functional system that allows the users to perform and accomplish their tasks (Hancock et al., 2005).

Moreover, the next level, usability, promotes and improves tasks performance, allowing the user to finish them in an effective and efficient way, fostering the user satisfaction. Once safety, functionality and usability are achieved, the systems need to be redesigned in order to fulfil psychosocial and sociological needs, namely, belongingness, achievement, completion and independence. For this purpose, systems design must incorporate concepts like motivation, quality of life, well-being, enjoyment and pleasure. The final goal can be achieved through the individuation, which consists in the customization of systems in order to meet individual needs, permitting each worker to adapt himself to the system and achieve goals on an individual level, based on their traits, past experiences and cognitive appraisals (Hancock et al., 2005).

Additionally, a workplace and workers motivation are highly affected by social relationships and its surroundings. Elton Mayo (2004) defended that workers are not only concerned about money, but could be better motivated if their social needs are met. For this purpose, managers should have more focus on workers, their well-being, their opinion and concerns and promoting enjoyable interactions between workers and teamwork, as well as a two-way communication with managers.

Moreover, according to Hancock and Diaz (2002), that have approached the problem of ergonomics amongst rapid technological development, nowadays, the technology is the most powerful shaping force on the planet and its individual impact is most evident at the HMI. Therefore, ergonomics can mediate these synergies between operators and technology, enhancing the work environment and the design of HMI.

### 2.4.1 Musculoskeletal Disorders and work-related health problems

Unfavourable work environment and conditions, as well as the exposure of workers to risk factors, can lead to the emergence of physical disabilities. When a disability affects the worker's physical ability to perform the tasks as usual, preventing them from lifting weights or moving, it is said that the worker is suffering from a work-related MSD (Berlin & Adams, 2017).

Work-related MSD that result from repetitive tasks and high demanding working conditions continue to represent one of the biggest problems in industrialized countries and one of the main biggest concerns of companies (Nunes & Bush, 2012), having a huge impact on labour world and highly affecting the health and well-being of the work force, increasing the number of sickness absences and reducing productivity on organisations (Nunes, 2009).

According to Centers for Disease Control and Prevention, MSD are *"injuries or disorders of the muscles, nerves, tendons, joints, cartilage, and spinal discs. Work-related MSD are conditions in which the work environment and performance of work contribute significantly to the condition and/or the condition is made worse or persists longer due to work conditions"* (CDC, 2020). Symptoms of MSD include pain in one or more areas of the body. The main cause of MSD are the accumulated minor injuries that are a result from repeated long-term work-related load (NRC, 2001).

Logistics activities in warehouses and supermarkets, where the ergonomic conditions are, most of times, not suitable for workers and the manual tasks, such as loading and unloading, represent a high risk of developing MSD (Sun et al., 2019). Manual Material Handling (MMH) is one of the most difficult and physically demanding tasks due to repetitive movements, awkward postures of limbs or forceful exertion (Rajesh et al., 2013). This type of tasks highly increases the rate of MSD on workers due to manual lifting or lowering loads, carrying, pushing or pulling of heavy materials (Ayoub & Mital, 2020; Mital et al., 2017). However, the safest way to avoid injuries resulting from lifting and handling loads is to eliminate the need to carry them (Costa & Arezes, 2005).

When the worker capabilities are exceeded in order to fulfil job strength requirements, the risk of developing an MSD is increased. Thus, the emergence of MSD is often associated with high costs, such as absenteeism, loss of productivity, increased healthcare, disability and compensation costs due to physical disabilities. The cost a company incurs when an employee takes a sick leave can reach huge proportions. It includes the loss of performance and productivity of the company, the cost of a worker to replace the one that left, worker's sick leave compensation, rehabilitation costs, as well as the costs of recruitment and training of new workers. Furthermore, there are high costs associated to losses of productivity and quality, since the new worker has not reached the previous employee's level of competences, skills and speed during tasks performance (Berlin & Adams, 2017).

The application of ergonomic methods principles to avoid the emergence of MSD can increase the performance and productivity and, most important, can help operators to be more comfortable and secure, enhancing their well-being (Ansari & Sheikh, 2014).

Therefore, MSD are a huge concern not only because their negative impacts on worker's health, but also due to their economic impact on companies and social costs to the government. It is not easy to estimate the economic impact of MSD, however, there are some estimative that may be useful to assess the general cost of a MSD that can diverge, depending on the job, type of injury and part of the body injured. Hansen and Jensen (1993) and Toomingas (1998) estimated that between 20 and 25% of all expenditure for medical care, sick leave and sickness pensions in the Nordic countries is due to work-related MSD.

Moreover, certain studies have estimated that upper limbs MSD could represent between 0.5% and 2% of the Gross National Product (GNP) of countries (Toomingas, 1998). Furthermore, in Germany, during 2016 MSD accounted for EUR 17.2 billion in loss of production costs and EUR 30.4 billion in loss of Gross Value Added (GVA). These values represent 0.5% and 1% of Germany's GDP, respectively (EU-OSHA, 2019).

The extent of the losses associated with MSDs is highly dependent on the severity of the health problem, the nature, the patient and the health care service received. However, there are other conditions to take into account, such as psychosocial factors, workplace characteristics, and compensations (Piedrahita, 2006). MSD are the most frequent occupational disease affecting workers throughout the world (Leigh et al., 1999).

In European countries, the incidence of MSD represented 60% of all work-related health problems reported by workers in 2018, which registered an increase of 6% when compared to 2007 data, as shown in Figure 12.

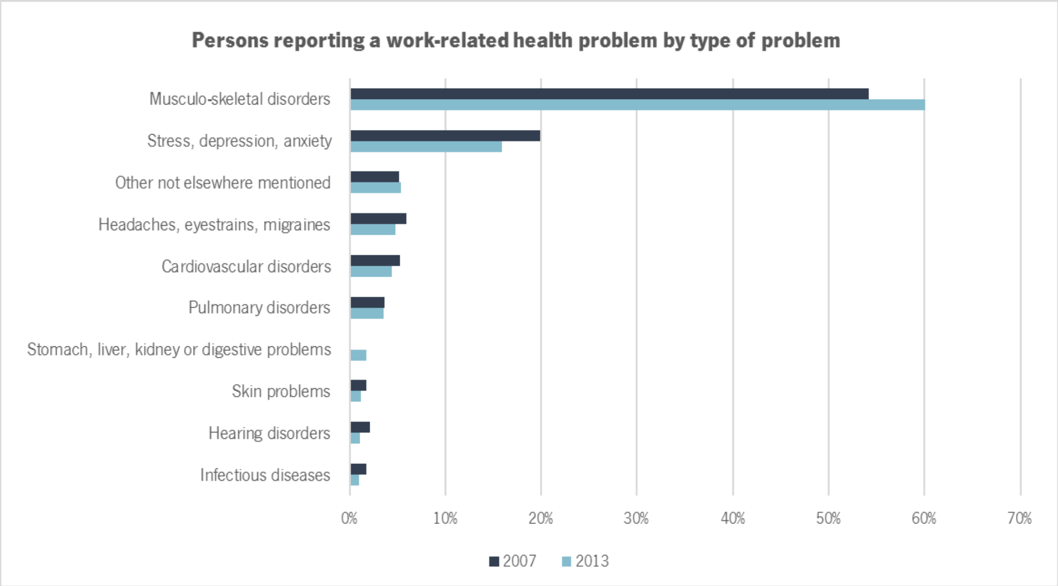

Figure 12. Persons reporting a work-related health problem by type of problem, EU-28 countries, 2007 and 2013 (Adapted from: Eurostat (2019f))

Stress depression and anxiety is another concern regarding to work-related health problems, representing 16% of all reported problems within this context. Thus, MSD and stress, depression or anxiety accounted for over three-quarters of work-related illness incidence (Eurostat, 2019f).

Consequently, the safety and well-being of workers is not limited to their physical health in the workplace. Mental health and well-being have to be considered while designing workplaces. While there are new risks associated with technology, such as the risk of burnout, the same technologies could be used to support workers in better controlling and managing the risks and impact of the new working environment, creating new opportunities for alerting workers about critical health conditions, both physical and mental, supporting them in adopting healthy behaviours in the workplace (European Commission, 2021).

Psychosocial risk factors, such as stress, anxiety and mental well-being play an important role on the development of MSD and further progress. For this reason, it is crucial to take into account these factors when assessing and preventing MSD risks, as well as when treating their symptoms. Early interventions are essential to minimise disability and restore worker's health and well-being, preventing long-term work absence (EU-OSHA, 2019).

The Figure 13 shows the share of fatal and non-fatal accidents at work in the EU-27 countries during 2018, categorised by economic activity, according to NACE (Statistical Classification of Economic Activities in the European Community) system. According to Eurostat (2013), on the one hand, a fatal accident leads to the death of a victim within one year after the accident. On the other hand, a non-fatal accident implies, at least, four days' absence from work.

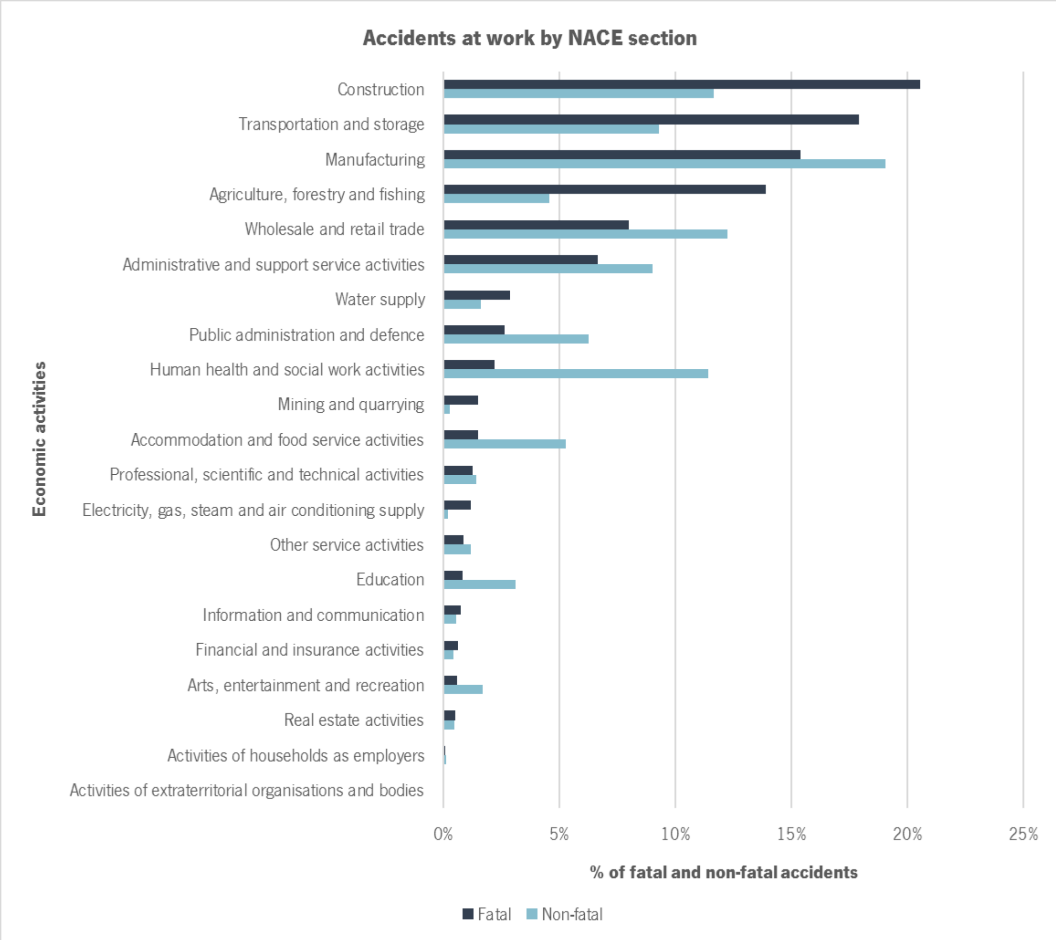


Figure 13. Fatal and non-fatal accidents at work by NACE section, EU-28 countries, 2018
(Adapted from: Eurostat (2019d, 2019e))

During 2018, a total of 3.486 fatal and 3.299.956 non-fatal work accidents occurred within European Union (EU) countries. The incidence of work-related accidents is highly related to the economic activity. In 2018, within EU-28 countries, the construction, transportation and storage, manufacturing, and agriculture, forestry and fishing sectors together accounted for around two thirds (67.8%) of all fatal accidents at work and more than a half (52.3%) of all non-fatal accidents. The second highest share of all fatal accidents at work in the EU-28 countries during 2018 took place within transportation and storage sector (17.9%), which comprises logistic activities. Regarding non-fatal accidents, transportation and storage sector scored a total share of 9.3% (Eurostat, 2019d, 2019e).

The NACE activity that concerns to logistic activities – transportation and storage – scored a total of 625 fatal and 306560 non-fatal accidents during 2018 within EU-28 countries. Regarding to the part of body injured due to non-fatal accidents, the highest incidence was in lower and upper extremities injuries, followed by lesions of back, scoring 75% of the total injuries due to non-fatal accidents. Concerning fatal injuries, the highest incidence was in whole body, not specified parts of body and head, as shown in Figure 14 (Eurostat, 2019b).

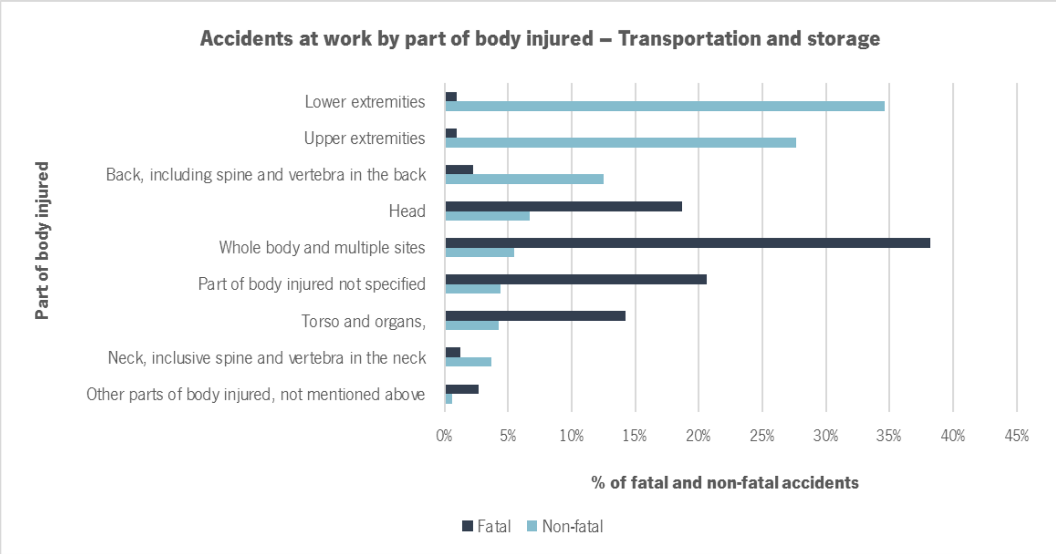


Figure 14. Accidents at work by part of body injured – Transportation and storage NACE section, EU-28 countries, 2018 (Adapted from: Eurostat (2019b))

Regarding the types of injuries that occur during work accidents in the activities of transportation and storage, 73% of the deaths related to fatal accidents are due to multiple injuries, concussions and internal injuries as well as unspecified injuries. Instead, 83% of the total non-fatal accidents result in dislocations, sprains and strains, concussions and internal injuries, wounds and superficial injuries and bone fractures, as shown in Figure 15 (Eurostat, 2019c).

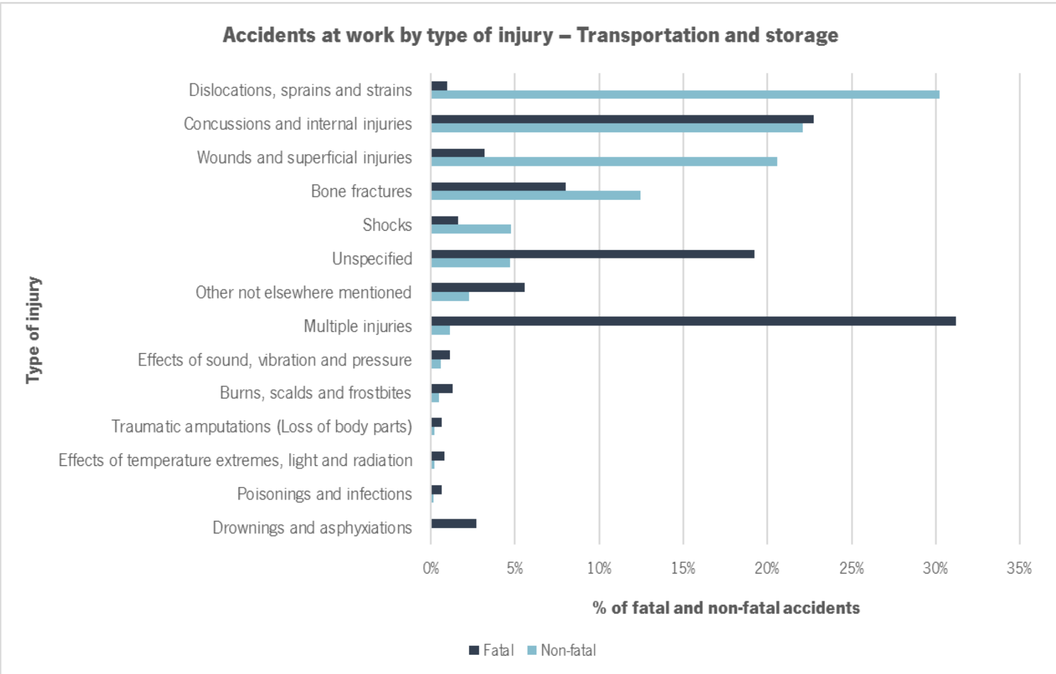


Figure 15. Accidents at work by type of injury – Transportation and storage NACE section, EU-28 countries, 2018 (Adapted from: Eurostat (2019c))

As mentioned before, a non-fatal accident implies at least four days' absence from work, which has a huge impact on absence and a high proportion of days lost. According to Eurostat (2019a), within EU-28 countries in 2018, more than 40% of the 306560 non-fatal accidents that occurred in transportation and storage activities have resulted in an absence from work longer than 20 days (Figure 16).

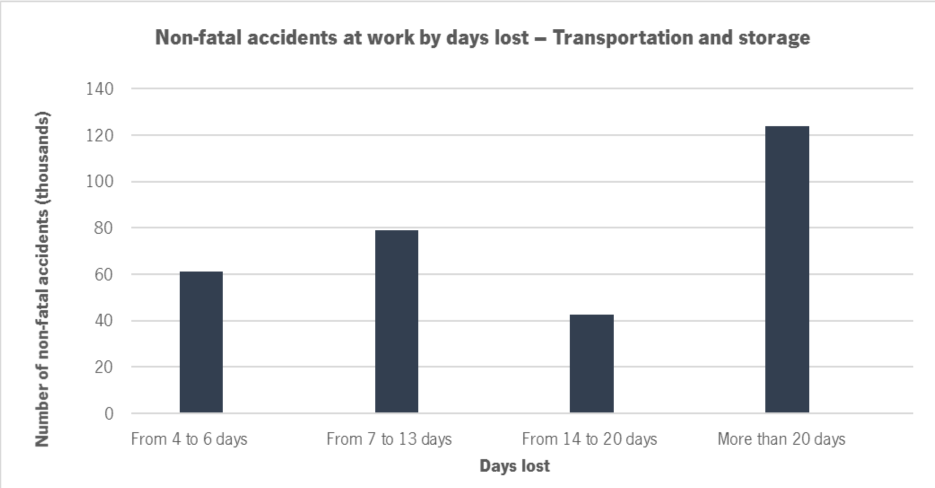


Figure 16. Non-fatal accidents at work by days lost – Transport and storage NACE section, EU-28 countries, 2018 (Adapted from: Eurostat (2019a))

A substantial proportion of health problems are attributed to unfavourable working conditions, which implies the need for prevention of risks in the workplaces. The lack of knowledge about the occurrence and prevalence of work-related health problems can make their prevention difficult in the workplaces. For this reason, it is crucial to have a sense of the dimension of the problem, in order to quantify the risks and mitigate them.

### 2.4.2 Occupational Safety and Health risks assessment

Hazard and risk are two important concepts related to OSH risk evaluation and assessment. On the one hand, hazards can be a source, situation or action that has the potential to cause a harm. On the other hand, risk is understood as probability of the combination of a hazardous event and the severity of injury or ill health that can result from this exposure (BSI, 2008).

Risk assessment traditionally involves the quantification of the risk of an incident, usually based on two aspects: (1) the likelihood of a risk, or frequency; and (2) the impact or consequence of the risk occurring, or severity (Nunes, 2013). Bearing the above-mentioned aspects in mind, the risk level of an activity represents the amount of injury that is expected to occur as a result of a potential work-related occurrence, being estimated by multiplying the severity and the frequency of an occurrence (Azadeh-Fard et al., 2015).

Furthermore, in this context, risk evaluation intends to quantify the value for each risk, calculating the amount of injury that is expected to occur as a result of a potential occurrence associated with an activity. Thus, the quantitative risk evaluation requires the calculation of the two components of the risk: the probability that the risk will occur, and the severity of the potential consequences (Nunes, 2013).

Hence, the frequency of exposure to hazardous conditions regards to the probability of a hazard occurring and originating a damage, while the severity refers to the potential for harm associated with the hazard or risk factor, considering the possible consequences, the exposure to risk factors, as well as the fraction of workers that are at risk. Therefore, the severity of each risk factor refers to who might be harmed, describing the highest level of damage possible when an accident or incident occurs from a particular hazard (Nunes, 2013).

The risk assessment matrix allows the quantification and categorization of different risk levels. Typically, in a risk assessment matrix, the ordinates axis represents the scale of frequency and abscissas axis refers to the scale of severity of an occurrence. There are several matrices already developed with different frequency and severity levels, such as the one proposed in British Standard 8800 with four levels of frequency, or likelihood, and three levels of severity (BSI, 2004).

Conversely, the matrix developed by Australian standard AS/NZS 4360: 2004 is a 5x5 matrix with four risk levels (Risk Management - AS/NZS 4360-2004, 2004), while a 3x3 matrix with three levels of risk has been recommended by the European Agency for Occupational Safety and Health (EU-OSHA, 2007).

Moreover, an alternative 6x4 risk assessment matrix has been proposed by the U.S. Military Standard MILSTD-882c (Defense, 1993). However, organisations should adjust the design and levels of the matrix in order to suit their needs (BSI, 2004).

Based on the risk values obtained during the risk evaluation phase, each identified risk should be ranked according to their risk level (Nunes, 2013), defining a risk acceptability criteria in order to define whether a risk is acceptable or not (Rodrigues et al., 2015), followed by the risk control phase, that consists in the definition and implementation of safety measures in order to control risks, including design, planning and implementing of safety control measures, as well as training and workers information (Nunes, 2013).

### 2.4.3 Quantitative ergonomic risk assessment methods

The successful introduction of new technologies and its combination with Lean Thinking leads to deep changes on workstations, demanding a human-centred approach. High strain jobs represent risks of MSD and injuries development and psychological overload, which can result in company losses. Hence, the use of suitable ergonomic risk assessment methods represents a major contribution for designing lean systems and workstations, allowing the enhancement of ergonomic and safety conditions (Nunes & Machado, 2007).

Furthermore, the effective inclusion of ergonomics on processes design has been proven costs related to disabilities, injuries, extra or overtime hours, medical care and compensations due to occurrence (Brito et al., 2019).

Therefore, in order to carry out a quantitative ergonomic evaluation, there are two assessment levels to consider among the available methods (IMD, 2014; Schaub et al., 2013):

First-level screening tools: Risk evaluation tools that require a quick screening checklist. The aim of these tools is to quickly map several areas to identify potential risks;

Second-level analysis tools: Risk evaluation tools that approach a detailed analysis for a specific risk area. They are usually applied where a possible risk has been previously detected by a first-level tool.

Table 2 summarises the different risk areas, correlating them with some of the most relevant first and second levels analysis tools that cover the ergonomic risk analysis for each section.

Table 2. Compatibility between 1st and 2nd levels ergonomic risk assessment methods
(Adapted from: IMD (2014) and Berlin and Adams ((2017))

<table>
<tr><th rowspan="2">Risk Areas</th><th colspan="3">Methods</th></tr>
<tr><th>Detailed analysis<br>(2nd level)</th><th colspan="2">Screening analysis<br>(1st level)</th></tr>
<tr><td>Body Postures</td><td>OWAS – Ovako Working-posture Analysis System<br>REBA – Rapid Entire Body Assessment<br>HARM – Hand Arm Risk-assessment Method</td><td rowspan="3">Automotive Assembly Worksheet (AAWS)</td><td rowspan="4">Ergonomic Assessment Worksheet (EAWS)</td></tr>
<tr><td>Action Forces</td><td>Snook and Ciriello<br>LM-MMH – Liberty Mutual Manual Materials Handling</td></tr>
<tr><td>Manual Materials Handling</td><td>NIOSH – National Institute for Occupational Safety and Health<br>KIM-MHO – Key Indicator Method for Manual Handling Operations</td></tr>
<tr><td>Upper Limbs</td><td>OCRA – Occupational Repetitive Actions<br>JSI – Job Strain Index<br>HAL-TLV – Threshold Limit Value for Hand Activity Level<br>RULA – Rapid Upper-Limb Assessment</td><td></td></tr>
</table>

Analysing the main methods used for ergonomic analysis, it is possible to highlight the major characteristics of each one, as well as their limitations in order to determine which method is most suitable to assess the risk associated to each task.

The methods that concern detailed analysis, as well as screening analysis will be presented in the next sections. Special attention is given to National Institute for Occupational Safety and Health (NIOSH) and Ergonomic Assessment Worksheet (EAWS), methods that will be used in the context of this project.

#### 2.4.3.1 Detailed analysis

The detailed analyses are supported by secondary level tools, that provide a comprehensive and exhaustive assessment of a specific risk area.

Regarding body posture-based methods, the most relevant ergonomic tools that are used to assess risk within body postures area are OWAS, REBA and HARM. In what concerns to action forces assessment, which refers to the analysis of extreme joint angles and action forces on the finger-hand-arm-shoulder system and vibrations (Fritzsche, 2010), Snook and Ciriello (1991), later revised and originating the LM-MMH method, is the most relevant method for ergonomic risk assessment.

On the other hand, manual materials handling is defined by International Standard Organization (2003) as *"any activity requiring the use of human force to lift, lower, carry or otherwise move or restrain an object"* and the most relevant ergonomic tools to assess this kind of activities are NIOSH equation and KIM-MHO. Otherwise, there are several relevant ergonomic tools that can be applied in order to assess the risk associated to upper limbs during tasks performance, such as OCRA, JSI, HAL-TLV and RULA methods.

Therefore, Table 3 summarises the different detailed analysis methods considering the risk area, the body part under study and its purpose.

Table 3. Description of detailed analysis methods

| **Risk Areas** | **Detailed analysis methods** | **Body part** | **Purpose (Reference)** |
|---|---|---|---|
| Body Postures | OWAS | Whole-body | Posture analysis and screening over time (Karhu et al., 1981) |
| | REBA | Whole-body | Whole-body posture analysis and screening (Hignett & McAtamney, 2000) |
| | HARM | Arm, neck and shoulders | Analysis and screening of hand and arm postures during repetitive tasks. (Douwes & Kraker, 2009) |
| Action Forces | Snook and Ciriello / LM-MMH | Upper limbs | Identification of the maximum acceptable limits of loads and forces for any percentile for lifting, lowering, carrying, pushing or pulling, without risks for MSD (Snook & Ciriello, 1991). LM-MMH method consists in a revision of Snook and Ciriello tables (Potvin et al., 2021). |
| Manual Materials Handling | NIOSH | Whole-body | Identification of the lifting load that is acceptable for workers (Waters et al., 1993). |
| | KIM-MHO | Upper limbs | Identification of the risk level associated with manual material handling tasks. This method considers different cases for assessment: Lifting-Holding-Carrying and Pulling-Pushing (Klussmann et al., 2010). |
| Upper Limbs | OCRA | Upper limbs | Assessment of upper limbs exposure to biomechanical overload. Tasks characterization according to frequency and effort required (Occhipinti, 1998). |
| | JSI | Upper limbs | Risk assessment for upper extremities disorders with special focus on repetitive tasks (Moore & Vos, 2004) |
| | HAL-TLV | Hands | Assessment of hand activity considering two risk factors: normalized peak force and repetition (ACGIH, 1995) |
| | RULA | Upper limbs | Upper-body and limbs assessment. Identification of postures and efforts that lead to muscle pain and injuries in upper limbs (McAtamney & Corlett, 1993). |

NIOSH equation is a hole-body workload assessment tool and can be used to assess asymmetrical lifting and lowering tasks with both hands, including their impact on the back. This method will be used in the context of this project, which is the reason why it is being given special focus.

Hence, the revised NIOSH lifting equation considers three criteria, namely, biomechanical (force), physiological (energy expenditure) and psychophysical (maximum acceptable weight to 75% of female and 99% of male workers) – in order to determine a Recommended Weight Limit (RWL) for a specific manual lifting task. This value represents the load that nearly all healthy workers could lift over a substantial period of time (Waters et al., 1993).

To determine the heaviest load a healthy worker could lift without developing low back pain, it is crucial to calculate six critical measurements, as shown in Figure 17 (Waters et al., 1993):

1. Horizontal Location (H): distance of hands on the load from mid-point of the line joining the inner ankle bones to a point projected on the floor directly below the mid-point of the hand grasps;
2. Vertical Location (V): starting vertical height of the hands from the ground to the mid-point between hand grasps;
3. Vertical Travel Distance (D): Vertical travel distance of the lift or the difference between the V at the origin and the corresponding V at the destination of the lift;
4. Lifting Frequency (F): time between lifts or frequency of lifting;
5. Asymmetric Angle (A): angle of the load in relation to the body or the angle between the movement and the neutral body position;
6. Coupling Type (C): Quality of the grasp or handhold (good, fair, or poor).

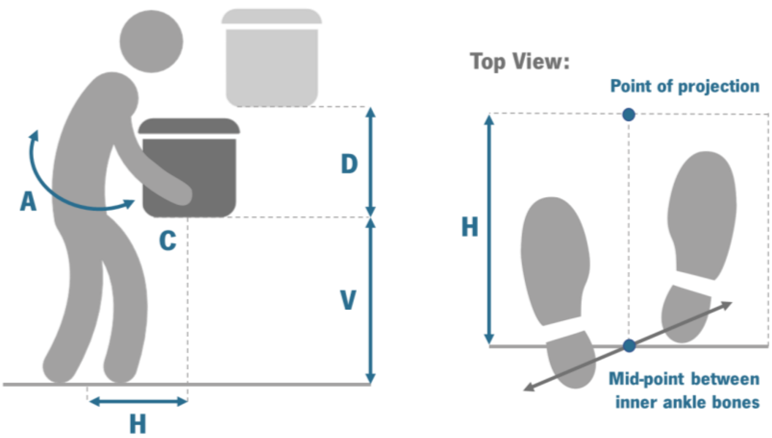


Figure 17. Measurements for NIOSH equation
(Adapted from: Waters et al.(1993))

The NIOSH Lifting Equation (Equation 1) uses a load constant (LC) of 51 lb or 23 kg (Waters et al., 2007), which represents the RWL under ideal conditions. Moreover, the equation uses several task variables expressed as coefficients or multipliers (In the equation, M = multiplier) that are used to calculate the RWL for a specific lifting task.

$$RWL = LC \times HM \times VM \times DM \times FM \times AM \times CM$$

Equation 1. RWL calculation
(Waters et al., 1993)

Where the multipliers considered for the calculation are the following (Waters et al., 1993):

1. Load constant (LC) = 23 kg
2. Horizontal Multiplier factor (HM) = 25/H
3. Vertical Multiplier factor (VM) = 1- 0.003×|V-75|
4. Distance Multiplier factor (DM) = 0,82+(4,5/D)
5. Frequency Multiplier factor (FM) = depends on the frequency of lifts (Table 4)
6. Asymmetric Multiplier factor (AM) = 1-(0,0032×A)
7. Coupling Multiplier (CM) = depends on the quality of the handle:
   - For V < 75 cm: C = 1 for Good; C = 0.95 For Fair; C = 0.90 For Poor;
   - For V > 75 cm: C = 1 For Good and Fair; C = 0.90 for Poor.

Table 4. FM calculation table
(Waters et al., 1993)

| Frequency Lifts/min | Work duration | | | | | |
|---|---|---|---|---|---|---|
| | ≤ 1 hour | | > 1 but ≤ 2 hours | | > 2 but ≤ 8 hours | |
| | V < 30 in | V ≥ 30 in | V < 30 in | V ≥ 30 in | V < 30 in | V ≥ 30 in |
| ≤ 0.2 | 1.00 | 1.00 | 0.95 | 0.95 | 0.85 | 0.85 |
| 0.5 | 0.97 | 0.97 | 0.92 | 0.92 | 0.81 | 0.81 |
| 1 | 0.94 | 0.94 | 0.88 | 0.88 | 0.75 | 0.75 |
| 2 | 0.91 | 0.91 | 0.84 | 0.84 | 0.65 | 0.65 |
| 3 | 0.88 | 0.88 | 0.79 | 0.79 | 0.55 | 0.55 |
| 4 | 0.84 | 0.84 | 0.72 | 0.72 | 0.45 | 0.45 |
| 5 | 0.80 | 0.80 | 0.60 | 0.60 | 0.35 | 0.35 |
| 6 | 0.75 | 0.75 | 0.50 | 0.50 | 0.27 | 0.27 |
| 7 | 0.70 | 0.70 | 0.42 | 0.42 | 0.22 | 0.22 |
| 8 | 0.60 | 0.60 | 0.35 | 0.35 | 0.18 | 0.18 |
| 9 | 0.52 | 0.52 | 0.30 | 0.30 | 0.00 | 0.15 |
| 10 | 0.45 | 0.45 | 0.26 | 0.26 | 0.00 | 0.13 |
| 11 | 0.41 | 0.41 | 0.00 | 0.23 | 0.00 | 0.00 |
| 12 | 0.37 | 0.37 | 0.00 | 0.21 | 0.00 | 0.00 |
| 13 | 0.00 | 0.34 | 0.00 | 0.00 | 0.00 | 0.00 |
| 14 | 0.00 | 0.31 | 0.00 | 0.00 | 0.00 | 0.00 |
| 15 | 0.00 | 0.28 | 0.00 | 0.00 | 0.00 | 0.00 |
| > 15 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

For lifting tasks that require a significant control at the destination, the RWL must be calculated at both the origin and the destination of the lift, in order to identify the most stressful location of the lift. Therefore, the most stressful location refers to the lowest calculated RWL, which should be used to calculate the Lifting Index (LI) in order to estimate the level of physical stress and MSD risk associated with the manual lifting tasks, given by the relationship of the average loaded weight and the RWL, as represented in Equation 2.

Therefore, LI represents the estimated relative magnitude of physical stress for a task or job. The greater the LI, the smaller the fraction of workers that are able to safely perform a given task without risks (Waters et al., 1993, 2007).

$$LI = \frac{Loadedweight}{RWL}$$

Equation 2. LI calculation

RWL and LI can also be used to identify potentially hazardous lifting jobs and prioritise ergonomic redesign of workstations based on the level of risk associated to tasks performed. From a NIOSH perspective, tasks with a LI higher than 1.0 represent an increased risk for workers and the goal is designing workstations and lifting jobs to achieve a LI lower than 1.0 (Waters et al., 1993).

Many of the lifting jobs comprise multiple lifting activities and could be analysed as either a single or a multi-task job. On the one hand, the single-task assessment consists in the determination of RWL and LI for a lifting task. On the other hand, the multi-task approach is more complex than the single-task and requires the calculation of several variables, such as, the Frequency-Independent Recommended Weight Limit (FIRWL), the Single-Task Recommended Weight Limit (STRWL), the Frequency-Independent Lifting Index (FILI) and the Single-Task Lifting Index (STLI) for each task. The final step consists in the calculation of Composite Lifting Index (CLI) for the overall job. The multi-task assessment must follow the steps (Waters et al., 1993):

1. Compute the FIRWL for each task, which represents the compressive force and muscle strength demands for a single repetitive task. Its calculation uses the respective multiplier factors for each task, setting the FM to a value of 1.0, regardless of the frequency of the lifts;
2. Compute the STRWL for each task, multiplying its FIRLW by its appropriate FM. This variable is the RWL for a single-task assessment, reflecting the overall demand for a single task and not reflecting the overall demands when the other tasks are considered;
3. Compute the FILI for each task, by dividing the maximum load weight for that task by the respective FIRWL, which represents the maximum biomechanical loads to which the body will be exposed, regardless of the frequency of the lifts. A FILI higher than 1.0 represents a risk and ergonomic changes may be needed;
4. Compute the STLI for each task. By dividing the average load for each by the respective STRWL. This variable is the LI for a single-task assessment and can be used to identify individual tasks with excessive physical demands and a STLI higher than 1.0 represents a risk and ergonomic changes may be needed. If the FILI exceeds STLI for any task, the risk may be related with the maximum weight and further evaluation is necessary;

5. Compute the CLI for the overall job, which represents the collective demands of the job, combining every task. The first step is ordering the tasks from the greatest STLI to the smallest STLI, putting the more difficult tasks first. Hence, the assessment of multi-task is completed with the determination of the CLI, which is calculated according to the Equation 3.

$$CLI = STLI_1 + \sum \Delta LI$$

Where:

$$\sum \Delta LI = \left( FILI_2 \times \left( \frac{1}{FM_{1,2}} - \frac{1}{FM_1} \right) \right) + \left( FILI_3 \times \left( \frac{1}{FM_{1,2,3}} - \frac{1}{FM_{1,2}} \right) \right) + $$
$$+ \left( FILI_4 \times \left( \frac{1}{FM_{1,2,3,4}} - \frac{1}{FM_{1,2,3}} \right) \right) + \cdots + \left( FILI_n \times \left( \frac{1}{FM_{1,2,3,4,\dots,n}} - \frac{1}{FM_{1,2,3,\dots,n-1}} \right) \right)$$

Equation 3. Calculation of Composite Lifting Index

Note that the numbers in the subscripts refer to the STLI ranking order and FM values are determined from Frequency Multiplier factor calculation table (Table 4), based on the sum of the tasks listed in the subscripts.

#### 2.4.3.2 Screening analysis

The screening analyses are supported by first- level tools that provide a quick evaluation, covering several risk areas, which are particularly useful for a fast identification of potential risks for workers.

The EAWS method, also known as European Assembly Worksheet (Schaub et al., 2013), is a quick screening tool developed by the International MTM Directorate (2014). The method is originally an extension of the Automotive Assembly Worksheet (AAWS), being oriented for physical workload that aims to reduce the demand of fatigue that can result from a manual cycling task.

This is an innovative approach to improve the ergonomic design of a workplace and assess the risk associated to physical workload regarding whole-body and upper limbs, being a comprehensive tool that aims to reduce the demand of fatigue that can result from a manual cycling task (Fondazione Ergo-MTM Italia, 2021).

While AAWS used to cover three risk areas (body postures, action forces and manual materials handling), the analysis of the upper limbs was enclosed, giving rise to EAWS method, which is a system that covers all risk areas, combining all aspects of manual load handling, such as posture, strength, weight and repetition. According to Schaub et al. (2013; 2012a; 2012b), this method comprises four sections for the evaluation of ergonomic working conditions (Table 5).

Table 5. Categories and sections of EAWS
(Fondazione Ergo-MTM Italia, 2021)

| **Analysis** | **Category** | **Section** |
|---|---|---|
| Whole-body | Body postures | Standing |
| | | Sitting |
| | | Kneeling or crouching |
| | | Lying or climbing |
| | Action forces | |
| | Manual materials handling | Repositioning |
| | | Holding |
| | | Carrying |
| | | Pushing and pulling (distance < = 5 meters) |
| | | Pushing and pulling (distance > 5 meters) |
| | Additional workloads | |
| Upper limbs | Duration | |
| | Force | |
| | Posture | |
| | Additional factors | |

The first three sections regard to the assessment of risk associated to whole-body, being divided into: body postures and movements with low additional physical efforts; action forces of the whole body or hand-finger system; and manual materials handling. On the other hand, the last section evaluates the repetitive loads of the upper limbs.

Hence, EAWS covers four risk areas: body postures, action forces, manual materials handling and upper limbs (with focus on high frequency tasks). This approach is aligned with several international standards, such as European Committee for Standardization (CEN) and International Organization for Standardization (ISO) and supports its users in the assessment of physical strain, conducing risk analysis and the assessment of improvement measures regarding ergonomics, providing detailed results that can be categorised into aforementioned different four sections (Berlin & Adams, 2017).

Following a traffic light scheme, the rating system of this method, based on a cumulative point scale, it is categorized into three different categories – green, yellow and red – based on the risk associated to the task performance. This ergonomic tool is mainly used for the assessment of risk due to biomechanical overload, providing an overall risk evaluation, which considers every biomechanical risk to which an operator may be exposed during a task performance (Fondazione Ergo-MTM Italia, 2021).

The EAWS method was created from the automotive industry, where defined cycle times are used and a task consists in standardized movements. This tool is used to analyse short cyclic tasks and considers that these cycles are repeated over a shift duration. As a first-level screening tool, EAWS provides a quick evaluation of the task, though not providing the accuracy and complexity of a secondary level analysis tool. However, it is very useful for the identification of potential risks associated to a cyclic task (Schaub et al., 2013) Though it is a screening tool, it can exceed the detail of several secondary tools (OWAS, RULA, JSI or HAL-TV) in some sections (IMD, 2014).

## 2.5 Augmented Reality

The origins of Augmented Reality (AR) are dated back to the 1960s, when a Harvard professor and computer scientist – Ivan Sutherland – created the first wearable device that enhanced user's experience and their perception of the world through the use of computer-generated graphics (Sutherland, 1968). A few years later, Myron Kruger created the "Videoplace", a laboratory dedicated to artificial reality where the computer perceived the participant's actions and responded in real-time using visual and auditory displays (Krueger & Wilson, 1985).

However, the term "Augmented Reality" was coined by Tom Caudell from Boeing in the early 1990s, when AR finally transitioned from laboratorial to industrial environment (Caudell & Mizell, 1992). On the other hand, the term "Industrial Augmented Reality" has been presented by Fite-Georgel to describe the use of AR technology to support industrial processes (Fite-Georgel, 2011).

AR is one of the disruptive technologies that are emerging with Industry 4.0 and intends to combine the physical word with computer generated texts and images or animations, providing an intuitive interaction experience to the users. AR can be defined as a real-time direct or indirect view of an enhanced or augmented real world environment, combining real and virtual objects that interact in real-time, which allow the improvement of work performance and efficiency in manufacturing environment (Furht, 2011; Sääski et al., 2008). In other words, AR is used to supplement and enhance the physical environment, overlaying digital computer-generated information such as images, sound, video and graphics (Falcioni, 2016).

Nevertheless, AR applications should include every human sense (R. Azuma et al., 2001) and features as touch and haptic sensations can be used in order to enhance the perception of real environment (Kipper & Rampolla, 2012). Its aim is allowing the organizations to bring processes and visualization together (Falcioni, 2016), which simplifies the user's experience by bringing virtual information and enhancing their perception and interaction with real world, augmenting the sense of reality in real-time (Furht, 2011).

This technology is often related with Virtual Reality (VR), since these are two closely related areas. However, AR and VR are different concepts. VR is a technology that completely immerses their users in a computer-generated environment that consists in a 360-degree views of a virtual and simulated world.

Lastly, Mixed Reality (MR) is the intersection of both AR and VR technologies, intending to merge physical and virtual worlds and generating new environments where virtual and physical objects interact in real-time (Falcioni, 2016).

AR can be seen as a variation of VR, since their technologies and systems components are very similar. However, it is important to distinguish between these two concepts, since the main goal of VR is to totally immerse the users in a simulated environment, preventing the real-world viewing. On the other hand, AR aims to augment computer generated graphics and information, over real objects, merging the physical and virtual worlds through virtual information overlaid on the user's perception of physical world (Kipper & Rampolla, 2012; Lu et al., 1999).

This information is added three dimensionally, in order to create a visual space and assist human behaviour and movements (Tachi, 2013). While VR is represented in a computer-generated environment, AR has a strong focus on the physical environment and on the physical products, augmenting the reality through the attachment of relevant information and the enhancement what users see in real world (Friedrich et al., 2002).

Industrial and manufacturing context involves complex tasks and operations that require high time consumption and expensive training methodologies. AR and VR technologies have been widely used in industrial domains, supporting the training methods and making them more efficient than the traditional approaches. These technologies bring new opportunities to reduce costs and increase efficiency regarding training for complex tasks, providing a user experience that combines virtual and real images in real-time, without changing the real environment (Mourtzis et al., 2017; Suárez-Warden et al., 2015).

AR technology holds a set of opportunities for manufacturing field, since it can provide to operators the access to information that could not be gathered with their ordinary senses. Furthermore, this information is provided in the correct context and when it is needed (Syberfeldt et al., 2016). In the last years, the way of providing information to operators has been changing (Pereira, Abreu, et al., 2016).

The emerging technological developments have allowed the transition from traditional paper-based instructions to the application of 3D visualization techniques in order to increase productivity, cost savings and control regarding error traceability. Furthermore, the use of advanced visualization technologies allows real-time changes in provided information and processes available to be seen by workers, avoiding wastes caused by delays and errors (Weber, 2014).

There are many studies about the effectiveness of this technology to provide relevant information to operators (Wang et al., 2016). The integration of disruptive visualization techniques can provide a higher level of quality, reduced times, more precise task performance, and cost effectiveness (Ropp et al., 2013).

However, the development of these tools requires high complexity, since it is crucial to ensure that the correct virtual information is shown at the correct moment, demanding a high degree of integration. This is needed in order to certify the information retrieval and interpretation, ensuring an accurate element's identification and allowing the achievement of tasks and operations (Hou et al., 2013; Syberfeldt et al., 2016).

There are a lot of potential applications for these disruptive visualization technologies, for instance, military training, entertainment, maintenance and repair, manufacturing, technical training, medical domain, product development, gaming, sports and tourism (Azuma et al., 2001; Furht, 2011; Lu et al., 1999; Michalos et al., 2016; Yuan et al., 2008).

These advanced techniques enabled by Industry 4.0 are being introduced in industrial environments as collaborative tools that can facilitate the sharing of knowledge and enhance the real world with computer generated representations of the products (Verlinden & Horváth, 2009).

AR technology can be implemented in industrial context to enhance assembly tasks performance, supporting the operators to efficiently perform the assembly tasks. This technology provides an useful visual guidance that enhances the operator's reality perception and increases the human sensory capacity through the overlaying of virtual contents on the real environment (Mura et al., 2016; Syberfeldt et al., 2015).

According to Fraga-Lamas et al. (2018), there are several aspects that are essential to successfully implement AR in industrial environment:

- Provide value-added services;
- Avoid functional discontinuities or gaps in the operating modes that can affect the functionality;
- Reduce cognitive discontinuities between old and new work practices;
- Reduce physical side-effects caused by the devices on users in the short and long term;
- Avoid unpredicted effects of the devices on users unfamiliar with the technology;
- Take into consideration the user perception regarding ergonomic and aesthetic issues;
- Make user interaction as user-friendly as possible.

Furthermore, this technology can be used as a tool that promotes the communication between every stakeholder (Chatzimichali et al., 2011), allowing the economic development and improvement of organization's performance, competitiveness and flexibility.

### 2.5.1 Elements of Augmented Reality

In order to bring combine physical environment and virtual elements, it is important to take into account that an AR system involves a set of essential technologies and elements, such as (Fraga-Lamas et al., 2018):

1. A device to capture images, such as a charge-coupled device, stereo camera or depth-sensing camera;
2. A display to merge the virtual information with the acquired images by the capture device;
3. A processing unit to generate the virtual information;
4. Activating elements that trigger the representation of virtual information, such as images, GPS positions, QR codes or sensor values retrieved from accelerometers, gyroscopes, compasses, altimeters or thermal sensors, gesture tracking, spatial tracking, barometer, hygrometer, pressure and light sensors or Infrareds (Syberfeldt et al., 2017).

Another important factor to consider regarding virtual environments is the space and the perception of it from the user's point of view. It is crucial to provide accurate special information such as distance and size. In Augmented Reality based environments, the space can be categorized into two measured distances (Lin et al., 2019; Pereira, Lee, et al., 2016):

- Egocentric distance, which is the distance between an observer and the object. Usually, the depth toward the object is estimated by the user. Using egocentric view, the AR elements are directly displayed to the subject from a first-person perspective;
- Exocentric distance is the distance between two objects. Using exocentric view, the AR elements are available inside a map that shows a view from an object.

In particular, a recent study compared the egocentric and exocentric distances tested in a simulated AR interface for a forklift operator in a warehouse, performing stock picking and movement tasks (Pereira, Lee, et al., 2016). In this study, the users have navigated through the warehouse significantly faster using the egocentric condition and have felt that the information provided on egocentric view has been more useful and improved their performance.

### 2.5.2 Types of Augmented Reality

There are many applications of AR in industrial environment. Display technologies can be classified into two different types: Video-mixed display and optical see-through displays. The video-mixed technology allows the combination of virtual and real images previously acquired, representing them on a display. Alternatively, the optical see-through technology regards to the representation of virtual information which is superimposed on the user's field and environment using projection-based systems (Fraga-Lamas et al., 2018). Hence, AR can be described as a system that has three different characteristics (Azuma, 1997):

1. Combination of real and virtual environments;
2. Real-time interaction;
3. Use of 3D objects.

However, AR technology holds a huge potential to augment all human senses and capabilities, being not limited to sight sense. AR can be applied to all senses, augmenting smell, touch or hearing. This technology can be used to enhance or substitute any missing sense of its users, through sensory substitution (Azuma et al., 2001; Azuma, 1997).

AR has traditionally been primarily visual, enhancing the sight sense. However, human perceptual capabilities are frequently shared by every sense, thus auditory and tactile senses are often enhanced as well within this context.

On one hand, visual perception consists in the identification of an object presence and its intrinsic properties, such as, brightness or colour, size, or shape, as well as its extrinsic properties, for instance, position, orientation or motion (Livingston, 2005).

On the other hand, auditory perceptual capabilities consist in the recognition of objects via hearing, supported by systems with alert mechanisms to attract users' attention or make them aware of dangerous situations, which is very useful in industrial context in order to mitigate risks through the use of Augmented Audio Reality (AAR). Similar systems use visual signs, such as blinking, or even tactile to trigger some action or give some clue to the user. Haptic devices are based on tactical tasks and allow the application of virtual forces in AR systems in order to identify objects and their properties through kinaesthetic senses (Livingston, 2005).

Also, AR can be used to enhance physical capabilities in order to reduce physical workload and improve ergonomic conditions and mitigate risks through the use of systems such as exoskeletons (Romero, Stahre, et al., 2016).

The hardware used by AR technology can be divided between several categories: Head-Mounted Displays (HMD); Hand-Held Displays (HHD), Wrist-Worn Displays (WWD) and Spatial Augmented Reality (SAR). Furthermore, there is a third type of display technology that can be considered as well, which is retinal projection. However, its use is very rare in industrial applications (Fraga-Lamas et al., 2018). The Figure 18 show the different types of AR, categorized into six different applications.

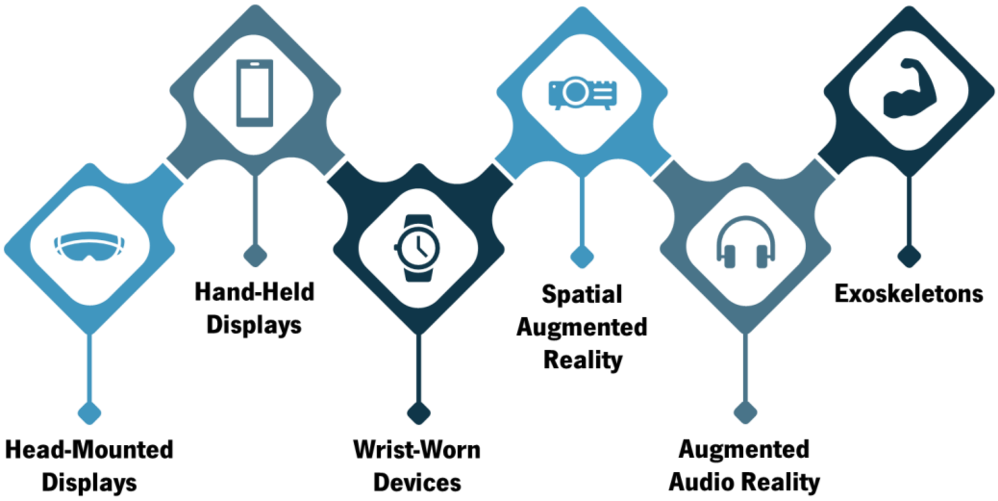


Figure 18. Types of AR

In sum, AR can be used to augment human senses, cognitive abilities and physical capabilities. Each type of AR will be described in the next sections.

#### 2.5.2.1 Head-Mounted Displays

One of the most usual applications of AR technology in industrial environment regards to the use of wearable devices based on HMD, whose example is represented in Figure 19. These devices hold a particular interest to industrial applications, since their use provides a set of hand-free solutions, allowing an effective communication between their users and the physical world (Stoltz et al., 2017). Wearing HMD, users are able to see the whole environment in which they are immersed, since these displays are included in wearables devices such as smart glasses or smart helmets (Fraga-Lamas et al., 2018).

Figure 19. Example of HMD: HoloLens 2
(Reproduced from: Microsoft (2020))

Furthermore, one of the biggest advantages of HMD regards to the eye-level displays that facilitate the perception of AR environment, enhancing. However, a prolonged usage of these devices can lead to discomfort associated to headaches, dizziness and nausea (Nee et al., 2012).

There are several aspects to take into account when implementing HMD on industrial environment. Syberfeldt et al. (2017) have developed an evaluation methodology for AR smart glasses, in order to identify which are the best products available in the market according to different characteristics. Furthermore, these authors have pointed out several key characteristics of these devices, however can be extended to any HMD, that require further attention in order to ensure a successful implementation of AR glasses at smart factories (Syberfeldt et al., 2017) and are presented in Table 6.

Table 6. Key characteristics of HMD

| **Key characteristics of HMD** | **Description** |
|---|---|
| Extending the field of view | The HMD field of view should be as wide as possible in order to enhance user experience and improve the perception of the environment. The natural human field of view is about 180 degrees horizontally, however, devices that have half of this width would represent a huge advancement, since this width is not possible nowadays. |
| Making the devices wearable | It is supposed to wear the HMD throughout the entire day of work, which means they should be comfortable and as light as possible. Nowadays, most of these devices weight too much and cannot be worn for extended periods. Heavy HMD will cause a lot of physical strain and affect the operator and his performance negatively. Furthermore, many models have a cable that disturbs the operators. Conversely, in case of using wireless HMD, it is crucial to ensure that battery last the whole working day. Lastly, one of the biggest issues regards to the use of AR glasses or other HMD while wearing ordinary eyeglasses. |
| Developing guidelines for user interface design | Designing user interface for these devices requires a whole new approach regarding the level of provided information. It is crucial to enhance real world without blocking it with excess of information and overlapped objects. For this reason, it is important to define guidelines to meet during the design phase in order to avoid harming the user experience. |
| Enabling benchmark evaluation | In addition to the previous topic regarding the guidelines during design of user interface, also the establishment of a method for benchmark evaluation is important, in order to identify the best products and design. |
| Improving voice-based interaction in noisy environments | Voice-based interaction is highly recommended in order to free operator's hands, as they are required to perform tasks. However, it is still a challenge to implement voice-based interaction when working in environments with the presence of noise. |

#### 2.5.2.2 Hand-Held Displays

Mobile HHD, such as smartphones or tablets (Figure 20) provide real-time interaction into one single device that overlays real environment by graphical augmentations (Bimber & Raskar, 2005). The ubiquity and advanced features of mobile devices provide a good opportunity to implement AR in industrial environments for tasks automation and mitigation of information availability deficit for workers (Tesfay et al., 2013).

These devices have many applications being more socially accepted when compared with HMD. Due to their easy transportation, these devices are widely used in industry, capturing the real environment through the device camera and providing superimposed real-time information on the display (Bottani & Vignali, 2019).

Figure 20. Example of HMD: AR Tablet in manufacturing environment
(Reproduced from: StickyLock (2019))

Moreover, the major inconvenience of HHD configuration is that it does not allow hands-free operations (Rekimoto, 1997).

#### 2.5.2.3 Wrist-Worn Devices

The use of both smart watches and AR has grown in the last few years, providing and enhanced user experience and supporting the use of hands-free AR technology, giving a more natural way to experience AR (Thomas & Holmquist, 2020). The use of WWD can provide a real-time tracking and monitoring of various states (Yeo et al., 2019). This enables a quick access and is more suitable than other wearables in many cases and allowing the users to complete tasks in less than four seconds, which is called micro interactions, such as, audio, gesture, graphics, tactile, and vibratory wrist-worn interfaces (Al-Eidan et al., 2018).

Al-Eidan et al. (2018) have found several critical challenges regarding the use of WWD (Figure 21), as well as some possible solutions to overcome these issues, namely:

1. Weight: The solution is the removal of battery, using energy harvesting technology;
2. Battery Life: could be overcome using hardware that uses energy harvesting technology and a software with reduced power consumption;
3. Lack of Standards: the definition of standard would allow the development of devices that meet the requirements;
4. Safety: the use of data collection in order to design systems with high resistance to impact, heat, cold and water;

5. User Acceptance: customization is the key to foster this property, allowing a personalized interface and adaptivity to different settings based on user requirements;
6. Design: devices must be designed to be comfortable and do not disturb the users' daily activities
7. Data: It is important to displaying ambient feedback, as well as, ensure the reliability of data.

Figure 21. Example of WWD: Proglove Mark 2
(Reproduced from: Etiden (2020))

These mobile scanning devices and wearable devices are usually equipped with barcode and QR code scanning technology and commonly used for order-picking process, which holds a huge potential regarding the decreasing of operation times and improvement of accuracy and comfort during tasks performance (Thomas et al., 2018).

Moreover, a WWD can also feature a laser barcode scanner encapsulated in a ring worn on a finger. The ring barcode scanners allow a hands-free operation, being often used in warehouse for receiving and picking goods (Starner, 2002). This solution is faster and more accurate, when compared with HHD (Baumann, 2012), as well as more comfortable to wear regarding ergonomic factors, which is crucial to ensure their acceptance by of workers (Stein et al., 1998).

#### 2.5.2.4 Spatial Augmented Reality

On the other hand, SAR has been introduced by Bimber and Raskar (2005) as a solution to merge physical and virtual worlds. Using spatial displays such as video-projectors, optical elements, holograms or RFID, the virtual information is superimposed directly onto physical environment without requiring the user to wear or carry a display (Carmigniani et al., 2011; Fraga-Lamas et al., 2018).

The application of projectors in AR applications can be categorized into two groups, according to the installation of the projector, namely, fixed installation and portable installation (Nee et al., 2012).

Despite of wearable and HHD holding huge potential to industrial applications, the above-mentioned types of AR hold some limitations that can be overcome through the use of a projector-based AR system. Unlike the spatial displays, that are not associated with a single user, solutions like HMD and HHD are not group-oriented and do not facilitate social interactions. Projector-based AR or SAR (Figure 22) can overcome this social gap, easing collaborative tasks and creating a space-efficient and seamless visual displays that are able to merge augmented physical objects and real environment in a shared workplace (Siriborvornratanakul, 2018).


Figure 22. Example of SAR: Projected work instructions on F-35 aircraft assembly line
(Reproduced from: Aerospace Manufacturing & Design (2015))

#### 2.5.2.5 Augmented Audio Reality

The concept of AAR, is characterized by an extended real sound environment, where virtual and real sounds are mixed, allowing augmentation of hearing sense, in order to perceive virtual sounds as an extension to the natural ones, creating a hybrid augmented environment (Härmä et al., 2004), as shown in Figure 23. Therefore, an AR-enabled audio interface allows a hands-free manipulation of packages, fastening the operation times and decrease the overall strain on the user's limbs (Starner, 2002).

Figure 23. Example of AAR system: Vocollect
(Reproduced from: ILS (2017))

#### 2.5.2.6 Exoskeletons

AR technology allows humans to become stronger and safer in manufacturing environment. Exoskeletons are wearable robots directly controlled by their users that hold a great potential in human physical capabilities augmentation regarding to strength, endurance, durability and speed (Wong & Mir-Nasiri, 2012). This technology consists in a robotic extension of human body, helping in overcoming disabilities or enhance physical performance and capabilities in workplaces, supporting existing human limbs and replacing the lost ones (S.-W. Leigh et al., 2018).

Therefore, the creation of super-strong humans in industrial environment is allowed by the use of wearable, lightweight, flexible and mobile exoskeletons that are enable by a biomechanical system powered by motors, pneumatics, levers or hydraulics that provide a cooperative human-robotic system (Sylla et al., 2014).

The super-strength operators have their physical capabilities augmented by exoskeletons, allowing them to safely lift and move heavy materials, enhancing their physical capabilities, their endurance, allowing them to stay longer in an unfavorable position or applying an additional strength. Exoskeletons, as represented in Figure 24, offer additional protection, support and strength, allowing the improvement of ergonomic conditions, reducing the risk of injuries, accidents and MSD related to heavy work, while fostering quality of work and productivity. Furthermore, the decreasing of physical workload allows operators to relocate their energy to sensorial and cognitive capabilities (Romero, Stahre, et al., 2016).


Figure 24. Example of exoskeleton: MATE-XT
(Reproduced from: Comau (2020))

Moreover, an additional advantage is supporting people with disabilities or elder operators to perform critical tasks without risks (Romero, Stahre, et al., 2016). The world's population is aging rapidly, particularly in developed countries, which means that productivity will be affected by worker's heath conditions, being increasingly important to manage the current aging workforce efficiently. Therefore, exoskeleton is a potential solution to improve ergonomic conditions within workplaces and reduce the physical loads during working tasks (Fondazione Ergo-MTM Italia, 2020).

### 2.5.3 Applications of AR in industrial environment

AR technology holds the potential to augment every human sense, providing virtual information to workers and extending, for instance, their sight or hearing functions. However, the possibilities regarding the application of this technology in industrial environment is not limited to sensory augmentation. It is also possible to augment humans regarding their intellectual or cognitive capabilities (Tachi, 2013), as well as enhance their physical capabilities using exoskeletons in order to improve ergonomic conditions (Pereira et al., 2019), allowing new forms of human actions (Kymäläinen et al., 2016).

In this section, relevant AR applications in industrial environment to augment human capabilities, specially within logistics area, will be summarized, being categorized taking into account the purpose of each AR solution: (1) improved performance and efficiency; (2) enhanced cognitive capabilities; and (3) reduced inequalities within workplaces.

#### 2.5.3.1 Improved performance and efficiency

Superimposing computer generated information into real world in order to provide relevant information that is not available within real world, such as work instructions, directions or safety instructions is one of the most relevant potentials of AR technology within a human-centred environment (Tachi, 2013).

This emerging technology has allowed the transition from traditional paper-based instructions to the application of 3D visualization techniques over the last years, which holds a huge potential regarding the elimination of wastes caused by delays and human errors (Khoshnevis & Lindberg, 2015; Weber, 2014). Additionally, it decreases the training and operation times and the enhances the working conditions, quality, productivity and efficiency (Ropp et al., 2013; X. Wang et al., 2016).

A recent review of the literature on this topic (Wang et al., 2020) summarizes 36 cases of AR technology application in in-house logistics that are using superimposed virtual information in order to provide information to workers and enhance their sight sense, mostly using HMD and HHD. Based on this study, order picking is undoubtedly the logistic process where most AR applications can be found. The main developed functionalities, regarding the enhancement of sight senses and virtual superimposed information, are usually related with the integration of different functions together in order to achieve error-free and optimised processes, such as the real-time object recognition, navigation and calculation of the fastest routes and barcode reading.

Order picking (Figure 25) is one of the most relevant logistic tasks, usually characterised by a high incidence of human errors. The successful implementation of AR technology allows the elimination of such errors, since the logistic workers are provided with additional information for faster object location, using work instructions in three-dimensional space instead of paper-based text or images, which drastically decreases the operation's time (Cirulis & Ginters, 2013).

Figure 25. Operator using a HMD to support order picking process
(Reproduced from: Marsh McLennan (2021))

Regarding picking operations, several authors have proposed virtual picking systems based on HMD or HHD hardware that supports workers, reducing the human factor to the minimum and, consequently, decreasing the rate of human-related errors and wastes. These systems usually consist on recognising the racks where the objects to be picked are located, highlighting them and even scanning the products after providing a warehouse overview to support the navigation and calculating the fastest route in order to reduce motion wastes (Bräuer & Mazarakis, 2018; Elbert & Sarnow, 2019; Fang et al., 2019; Ilanković et al., 2020; Mueck et al., 2005; Reif & Günthner, 2009; Reif & Walch, 2008). Moreover, an AR system that is developed to visually support the order-picking process using a HMD is often called by Pick-by-Vision system (Reif & Günthner, 2009; Schwerdtfeger et al., 2011).

However, the application of AR within logistic processes goes far beyond picking operations and there is a number of studies that have proposed potential use cases based on AR solutions for other key logistic operations, such as incoming, warehousing and shipping, as well as other tasks regarding inventory control and warehouse planning and management (Stoltz et al., 2017; Wang et al., 2020)..

Therefore, Woltering et al. (2020) have developed a model for analysing economic efficiency regarding the implementation of AR technology within packing processes in order to improve productivity, throughput time, quality and quantity of packing material used. Furthermore, Bräuer & Mazarakis (2020) have developed a tool that is integrated with the company's ERP and uses smart glasses, offering the possibility to visualize the turnover rate of products in a warehouse and optimizing their location, which can hold benefits for warehouse management activities and be used to measure and monitor other Key Performance Indicators (KPI).

Thus, the benefits of AR solutions in every logistic operation are similar to the observed improvement potential in order picking, i.e., decreased error rates, wastes elimination and faster execution of operations, as shown in Table 7 (Stoltz et al., 2017; Wang et al., 2020).

Table 7. Potential use cases of AR in logistic for process improvement
(Adapted from: Stoltz et al. (2017) and Wang et al. (2020))

| **Process** | **Potential uses of AR** |
|---|---|
| Incoming | Indicate the unloading dock to incoming truck driver |
| | Scan product information |
| | Automated inspection: check received goods, quality, quantity and delivery notes |
| | Display unloading information: step-by-step instructions on how to most efficiently unload a container according to the size, dimension, and weight |
| | Highlight where to put the items and show how to arrange them in the waiting zone |
| Warehousing | Inform an operator about a new allocated task |
| | Display the storage location of incoming items |
| | Display picture and details of the item to be stored |
| | Indicate best route to storage location |
| | Indicate picker's current status as well as next step of the process |
| | Check locations requiring replenishment while storing |
| | Book the goods in warehouse management system |
| Picking | Inform an operator about a new task allocated to him |
| | Display picture and details of the item to be picked |
| | Display the storage location of the item to be picked |
| | Display picking route |
| | Highlight the physical location with the item required |
| | Inform about errors and disruptions |
| | Scan the item's barcode and QR codes to assign to picking cart or to see more information |
| | Highlight where to put each item on the picking cart for sorting while picking |
| | Give information to prevent congestion in aisles |
| | Monitor picker's condition and performance |
| Shipping | Show what type of cardboard to use |
| | Show the best way to place picked items in a package |
| | Indicate the right location/pallet for the shipment |
| | Show where to place each order on a pallet/in a truck according to type of orders, destination, fragility |
| | Indicate appropriate loading area |
| | Check and count products or orders to be loaded on a truck |
| Inventory control | Show stacking/packing information |
| | Capture the number of available objects in the warehouse |
| Warehouse planning and management | Visualize warehouse in full-scale before even beginning construction |
| | Monitor and record processes metrics: acquisition of process data and KPIs |
| | Display current workload in real time |

Incoming area is the first station of in-house logistics and AR solution hold a set of potentials to optimize the tasks execution and minimize the burden of operators through the automatic scanning and inspections, as well as the provision of relevant information and guidelines to avoid errors. AR could be useful during warehousing operations, supporting workers during the identification, transporting and storing process of the articles, creating shorter throughput times and achieving higher quality (Stoltz et al., 2017; W. Wang et al., 2020).

The order-picking is one of the most relevant logistic processes and a huge potential of AR application is meant to implement in this area. During the process of picking, the operator can acquire all the information about the environment from the warehouse. The AR device collects information about the user-related work orders and shows them directly to the operator, proving support during navigation, picking, scanning as tasks allocation. Furthermore, depending on the requirement of customers and the product's characteristics, items are differently packed and sent within shipping area and AR can support workers during this process (Stoltz et al., 2017; W. Wang et al., 2020).

Barcode scanning is one of the most relevant potentials of AR implementation within every logistic area and process optimisation. However, despite of the fact that HMDs and smart glasses offer the possibility to perform all tasks with free hands, it is important to consider that, regarding the scanning of barcodes and QR codes, commercial scanners and smartphone cameras provide a faster and more reliable solution than the available AR technology (Stoltz et al., 2017).

Furthermore, Vom Stein & Günthner (2016) have found that many articles during picking process are too small or are stored at a ground-level shelf, which leads to difficulties during scanning of barcodes or QR codes with smart glasses or a HMD camera, since the workers would have to bend until the camera is able to scan the products. Thus, the usage of an external scanner is more ergonomic and faster. Nevertheless, a barcode scanning app in smart glasses has been implemented, despite of the above-mentioned ergonomic limitations, as well as issues related with lighting conditions and battery capacity.

Mobile scanning devices and wearable devices equipped with barcode and QR code scanning technology are commonly used for order- picking, offering a strong and cost-effective solution to a faster and accurate process (Thomas et al., 2018). According to Baumann (2012), WWD with ring bar code scanners can reduce the operation times and the amount of equipment needed to perform these tasks, freeing the workers hands and speeding package scanning and inventory control, when compared with HHD. Furthermore, when it comes to AR wearable devices, it's important to consider the ergonomic conditions and understand if it is comfortable and safe for workers that will use it during the working day (Stein et al., 1998) and this kind of wearable devices can decrease the overall strain on the user's body (Starner, 2002).

Regarding logistic management, planning and control procedures, AR can support tasks regarding inventory control, as well as provide warehouse planning and management tools in order to plan or design a new warehouse. Furthermore, it is possible to use AR solutions to monitor and record processes metrics, such as KPI or displaying current workload in real-time for monitoring employees (Stoltz et al., 2017; Wang et al., 2020).

The AR-based superimposed information can be transmitted to the employee with help of acoustic, optical or haptic signals and there are some use cases regarding the implementation of AAR, specially within picking operations, where the order is transmitted from the warehouse's computer to an employee's wearable device. Furthermore, each item and its location are spoken to the employee through a pair of headphones, which enables a hands-free operation that allows the employee to relieve the physical workload and manipulate the packages with both hands (Starner, 2002).

AR systems can include speech commands and allow people to hear and talk with distant peers. Furthermore, AAR goes beyond human-to-human communications and workers can provide instructions or request information from machines or robots, while triggering actions. Another functionality regards to blocking unnecessary background noise on a busy manufacturing environment, in order to clearly hear or recognize speech (Eriksson, 2018).

#### 2.5.3.2 Enhanced cognitive capabilities

The introduction of new methods and transferring the required knowledge to workers is usually an intensive and time-consuming process that can jeopardize the productivity and efficiency of logistics processes. However, the use of AR during training phase can lead to well-trained logistics workers that are able to meet the requirements of flexible logistics systems, allowing them to face challenging and complex tasks and ensuring high efficiency and shortening their learning curve (Reif & Günthner, 2009).

Therefore, AR has the potential to enhance workers cognitive capabilities, providing them the instructions for handling goods and operation instructions that are conveyed via glasses or HMD and displayed in the form of checklists, texts, pictures or videos. The provision of such instruction within workplaces can assist the learning phase and support the training of new employees, displaying individual work process step by step and providing personalised instructions depending on the difficulties (Stoltz et al., 2017; W. Wang et al., 2020). Additionally, according to Eriksson (2018), providing step-by-step visual instructions can increase the operators' efficiency up to 40% and reduce the training cost by ten times less.

Moreover, AR can also help to overcome several competency inequalities, displaying, recognizing and translating texts in every language in real time, making the existing information accessible to every employee, regardless their skills and knowledge (Stoltz et al., 2017; W. Wang et al., 2020).

Thus, AR visualizations can support new employees during the learning phase, irrespective of their native language. This is an advantage that allows the trainees to be more autonomous and perform a wide variety of tasks, increasing the flexibility in job rotation (Murauer et al., 2018). Additionally, it is known that the job rotation is one of the most widespread strategies to relieve physical fatigue, reduce the stress due to repetitive tasks, improve ergonomic conditions and increase the productivity in workplaces (Digiesi et al., 2018).

Furthermore, the ability of undertake high demanding metal tasks and processes that require cognitive capabilities such as decision-making, perception, memory, reasoning and responsiveness can be enhanced through AR approaches (Carroll, 2009). This allows the creation of new interactions between workers, machines and products due to the existing available information about them that is superimposed over the real world (Romero, Stahre, et al., 2016).

In addition to the provision of relevant information to correctly perform their tasks, such as work instructions, workers can be provided with safety information and instructions in order to avoid risks within workplaces, improve their safety conditions and increase their risk awareness, as shown in Table 8. The implementation of AR in the area of safety can be achieved by showing warning and safety instructions to operators through acoustic, optical or haptic signals, enhancing a set of human senses to increase their risk awareness. These messages can be object-related, e.g., the risk of breakage of individual articles or hazardous agents, or process-related safety instructions and guidelines (Wang et al., 2020).

Table 8. Potential use cases of AR for increasing risk awareness in logistics
(Adapted from: Wang et al. (2020))

| **Use case of AR** | **Description** |
| --- | --- |
| Display object-related warning and safety information | Warning or safety instruction is transmitted to the employee with help of acoustic, optical or haptic signals to the object |
| Display process-related warning and safety information | The employee is provided with general or process-related warning or safety instruction by acoustic, optical or haptic signals |
| Automated examination of hazardous goods | Camera-based examination when handling dangerous goods (e.g., warning if the distance between two containers of dangerous goods is too short) |
| Dynamic navigation instructions. | Employee can choose the best route to the target location with the aid of displayed maps of warehouse and real-time traffic information in order to avoid accidents or congestion. |

Additionally, AR solutions can be safer for a human operator and enhance their ergonomic conditions during tasks performance, as the user has both hands free and those devices are wireless. Furthermore, AR systems are able to provide feedback and information for safety purposes or even warn the operators regrading an immediate hazardous situation or danger in real-time (Stoltz et al., 2017).

#### 2.5.3.3 Reduced inequalities within workplaces

AR technology solutions can foster the quality of life, specially to people with special needs or disabilities and elderly people, promoting the inclusion and sustainability of the workforce, while reducing the inequalities within workplaces (Kymäläinen et al., 2016).

Vom Stein & Günthner (2016) have studied the use of pick-by-vision systems to advance the inclusion of people with hearing disabilities, concluding that AR holds a set of benefits to assist these workers during order-picking process, providing relevant information to perform such tasks through the usage of smart glasses or HMD. These solutions promote the inclusion of workers with disabilities, as well as the elimination of communication barriers between coworkers.

Furthermore, regarding to physical conditions and limitations, the application of AR in order to enhance physical capabilities, through the usage of exoskeletons allows the creation of improved working conditions, allowing operators to perform their tasks longer and lift heavier weights, while reducing the physical workload, injuries, accidents and OSH risk factors (Romero, Stahre, et al., 2016).

## 2.6 Human Factors and Augmented Reality

This section relates HF with AR, starting with a presentation of HMI and showing how it can benefit from AR, as well as the challenges to be faced regarding these synergies. Moreover, related concepts, such as HA, operator 4.0 and augmented operator are further analysed.

### 2.6.1 Human-Machine Interface

Industrial revolutions and technological development brought widespread use of tools and machines to workplaces, increasing the complexity of work systems. While in the past, design of workplaces and ergonomics has driven by technical requirements, in the recent years, the operator gained more attention during the design of work systems and ergonomics should drive the technology (Karwowski & Zhang, 2021).

Ergonomics and HF comprise several domains, such as, physical, cognitive, perceptual and psychosocial aspects of human work (Grosse et al., 2015). These aspects comprise and highly influence the behaviour and decision-making capabilities of workers, which affects significantly the performance of tasks, particularly in logistics area. Although the technological advancements are gradually replacing humans in some multiple activities an changing the HMI, human work remains essential. However, with the emergence of new technologies within the workplaces, it is crucial to assess the role of operator for an effective transition to Logistics 4.0 (Cimini et al., 2019), that can be categorised into two main hypotheses: (1) the operator is replaced by technology; or (2) the operator is supported by new technologies in order to perform more tasks than previously.

Usually, the first scenario regards to tasks that are strongly related to the use of physical force, such as manual material handling, and to continuous and repetitive tasks, such as, manual packaging and picking operations. Moreover, non-value added operations, such as inventory control or transportation can be easily performed by technology as well, which brings some benefits regarding productivity, flexibility and traceability, avoiding human errors, improving safety issues and enhancing the reliability of operations. The second hypothesis concerns to the use of technology to support workers and improve their performance, allowing them to employ their time in activities that requires decision-making and planning, benefiting from real-time information exchange in order to optimize the supply chain or even to augment their capabilities and enhance their performance. Furthermore, reducing the number of interactions between human and machine also allows the elimination of risks related to them and, therefore, increasing the level of safety in the work environment (Cimini et al., 2019).

Thus, automation and connectivity enabled by new technological advancements will reduced the need for several traditional tasks, while demanding much higher skills on many other tasks. Therefore, workers must be seen as creative thinkers, decision-makers and problem-solvers within a work environment where systems do not replace humans, but assist, augment and automate part of their work in order to achieve higher level of efficiency and productivity (Romero et al., 2020).

As the use of technology and machines increases, the HMI becomes more prevalent across every area. In ergonomics field, HMI can be described as a cooperative performance, communication and feedback between humans and technical systems (Karwowski & Zhang, 2021; Oborne, 1987). Its focus is to design systems that provide effective support for users, improving their performance, effectiveness, efficiency, satisfaction and well-being (Sarodnick & Brau, 2006).

Therefore, managers should design a strategy for human resources envisioning the future role of the workers, in order to align the introduction of new technologies with the operator's needs. Then, they will take full advantage of their potential and support their development within an environment characterised by the co-presence of human workers and technology as AR, placing the operator at the centre of every system (Fantini et al., 2020).

Moving toward Industry 4.0 paradigm and implementing AR will enable new type of interaction between humans and machines and, eventually, transform the current industrial workforce and workplace. The work environment is rapidly changing in the last few years due to disruptive technological advancements and Industry 4.0 is transforming jobs and required skills (Pereira et al., 2019). HMI and communication between workers and technology have to be designed properly, in order to allow the operators to perform their tasks effectively and efficiently (Cimini et al., 2019).

According to Cimini et al.(2021), in Logistics 4.0 context, there are two classes of HF that directly affect operators, having strong impact on their activities, namely: (1) physical HF; and (2) cognitive HF. These two above-mentioned domains are presented in Table 9, as well as the characteristics of humans to which each of them refers and the factors that affect operators.

Table 9. Human factors in Logistics 4.0
(Adapted from: Cimini et al.(2021))

| **Human factors** | **Human characteristics** | **Factors that affect operators** |
|---|---|---|
| Physical | • Anatomical<br>• Anthropometric<br>• Physiological<br>• Biomechanical | 1. Working postures<br>2. Materials handling<br>3. Repetitive movements<br>4. Workplace layout<br>5. Risk of accident<br>6. Suitability for duty<br>7. Reactivity to stimulus or signals<br>8. Perception of work environment<br>9. Available time |
| Cognitive | • Reasoning<br>• Memory<br>• Information acquisition<br>• Finding solutions<br>• Decision-making | 1. Memory<br>2. Decision-making<br>3. Tasks complexity<br>4. Skills and experience<br>5. Human error probability<br>6. Work stress<br>7. Training |

The most significant changes within this project context regard the new HMI paradigm that embraces the interaction between workers and a set of new ways of collaborative work (Kagermann et al., 2013a). This new paradigm will lead to deep impacts in worker tasks and demands in work environment, which will be characterized by the cooperation between smart machines and humans (Gorecky et al., 2014; Romero, Bernus, et al., 2016).

The number of robots and smart machines is increasing, while physical and virtual worlds are merging, which means that a significant transformation is being launched in the current work environment. The increasing relevance of HMI will promote the interaction between both production elements and the required communication between smart machines, smart products and employees, enhanced by the vision of IoT and IoS that is enabled by CPS.

AR is an emerging technology that intends to seamlessly enhance physical environments with virtual objects, creating a bridge between virtual and physical world and bringing them closer together. However, the importance of the interaction between human and machine has been growing as the technology develops. There are a lot of critical factors that have to be considered during the design of a technological solution that interacts with workers in an industrial environment. It is crucial to ensure the accuracy of the provided information in order to allow a correct understanding of the information and simplify tasks execution. A lack of communication between machine and human can result in error that can pledge the performance of tasks and, consequently, the quality of final product. For this reason, it is essential to make sure that the system provides relevant information to the workers, in order to avoid any human error (Khoshnevis & Lindberg, 2015).

For that reason, ergonomic issues should be taken into account in the context of industry 4.0 and future systems should have a focus on workers and their importance (Dombrowski & Wagner, 2014; Zuehlke, 2010). The integration of Industry 4.0 technologies, namely AR, in manufacturing systems and the increasing implementation of new technologies will have an impact on job profiles, as well as on work management, organization and planning. The main challenge in this context is to avoid what is known as technological unemployment, redefining current jobs and taking measures to adapt the workforce for the new jobs that will be created (Roblek et al., 2016).

To mitigate these impacts, there are several aspects to consider for AR implementation. The AR tools must be developed with functionalities that allow a user-friendly collaboration between human and technology, in order to enhance their experience and improve their performance and awareness in a non-intrusive way. Thus, it will be possible to meet the industrial requirements, allowing people to be more efficient and effective in their tasks (Michalos et al., 2016).

Regarding to HF, the adoption of AR demands further analysis, since there are some critical factors such as the use of wearables, fatigue effects and optical quality (Plavšic et al., 2009). Furthermore, during the design process of an AR application, there are some important issues to take into account regarding HMI. It is crucial to define who are the users, their needs, system effectiveness metrics, tasks to be performed and user's capabilities (Fjeld, 2003).

Weyer et al. (2015) states that industry 4.0 embraces the development of intelligent environments which are able to bring the real and virtual world together through the use of CPS, integrating devices, machines, production modules and products, triggering actions and controlling each other autonomously. However, this author emphasizes the importance of new HMI paradigm and the emergence of new kinds of jobs, categorizing the central aspects of Industry 4.0 into three main paradigms: (1) Smart Product; (2) Smart Machine; and (3) Augmented Operator (Figure 26).

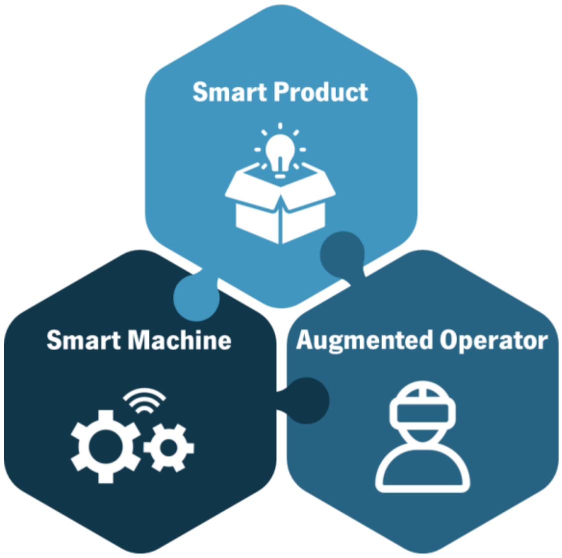

Figure 26. Central aspects of Industry 4.0 emphasizing new HMI paradigm
(Adapted from: Weyer et al. (2015))

The first aspect regards the emergence of new market requirements and the development of smart products. These products are able to store large amount of data and interact with their environment, being self-aware and communicating autonomously with industrial systems (Schmidt et al., 2015).

Moreover, the second paradigm, which is highly related with smart factory, regards the fact that, in the Industry 4.0 environment, machines are becoming CPS, which implies self-organized production systems with interconnected components, devices, production modules and products. The smart factory will be more intelligent, flexible and dynamic and smart machines will be able to improve production processes through self-optimization and autonomous decision-making process (Roblek et al., 2016).

Lastly, Augmented Operator paradigm, which is the main focus of this project, is related to the worker's technological support that is required in the manufacturing environment, which represents a challenge, since the operators will face a large variety of new tasks. Industry 4.0 introduces new types of interactions between operator and machines, as well as the coexistence between human and robots, which will completely change the current industrial workforce in order to answer the changing requirements and the increasing production variability (Romero, Bernus, et al., 2016).

In order to achieve a human-machine symbiosis that allows higher workforce capabilities and increased manufacturing flexibility in future production systems, it is essential taking into account several aspects regarding technical and economic benefits for companies, such as, higher quality, shorter production times, optimized processes, increased responsiveness and innovation and continuous improvement capacity. However, workers should be the focus of every manufacturing system and social-human benefits for workforce should be considered, including well-being and quality of working life, job satisfaction, improved ability and skills and higher personal flexibility and adaptation (Romero, Bernus, et al., 2016).

In augmentation and enhancement of human performance context, Human Cyber-Physical Systems (H-CPS) are the new approach for HMI, bringing together digital and physical worlds. H-CPS aim to achieve higher safety systems for workers, providing a sustainable human-centric production system where humans, machines and software dynamically interact within a cyber-physical world (Romero, Stahre, et al., 2016). Based on this context, H-CPS are designed to improve human abilities in order to interact with smart machines within a smart factory which are engineered to fit operator's cognitive and physical need. Furthermore, these systems intend to enhance cognitive capabilities through the use of technologies, such as wearable devices (Romero, Bernus, et al., 2016).

Neumann et al. (2021) identified a lack of literature and research works regarding the relationship between HF and Industry 4.0 and proposed a systematic framework for considering workers during the conceptualisation, design, and implementation of new emerging technologies in operations systems. This framework comprises five main steps: (1) technology definition; (2) identification of humans in the system; (3) identification of task scenarios; (4) task analysis and impacts of changes on humans; and (5) outcome analysis.

In HMI context, it is crucial to ensure that people develop their tasks without wastes and symptoms of wastes. Beyond *muda*, there are the *mura* and muri that are considered the symptoms of *muda*. Muri is the overburden or stress or, even, accidents that could occur in the workplace due to other symptom of waste, the unevenness, i.e. *mura*. All together these three Japanese words are called 3M (Liker, 2004).

As so, Lean impacts ergonomics of workplaces (Arezes et al., 2015). To systematically eliminate wastes, Womack and Jones (1996) have designed the Lean principles that happen cyclically and allow the continuous improvement, known as kaizen, through the people capability to think, feel, innovate and act (heads, heart and hands – 3H) (Alves et al., 2012).

### 2.6.2 Human Factors challenges for the implementation of Augmented Reality

The application of AR in industrial area is a growing area, being essential to design and implement integrated systems that are able to enhance processes, leading to shorter times, reduced costs and improved quality (Nee et al., 2012). One of the major drawbacks to adopting AR systems is the implementation cost. However, regarding HF, the use of this technology raises many questions about possible eye problems of prolonged use of smart glasses that are yet under study (de Silva & Liyanage, 2019).

Nevertheless, there are a number of challenges to overcome when considering HF in AR systems. These challenges regard to hardware issues and the limitations of displays, such as, resolution, field of view, as well as, brightness or contrast. Furthermore, there are software-related challenges, such as the features of developed algorithms, for instance, the accuracy, robustness and calibration (Livingston, 2005). Consequently, the workers' performance is highly affected by software and hardware features.

However, according to Livingston (2005), the most important factor to take into account is the comfort felt while using these devices, since the operator's well-being should be the main focus of every system. The users should also be able to interact with the devices in the most possible natural way, without the adoption of awkward postures and gestures, in order to enhance ergonomics and HF (Carmigniani et al., 2011).

Moreover, the application of this technology should be subtle and nonintrusive for workers, since there are possible long-term effects of prolonged wearing of AR devices, such as giddiness, nausea, headache or loss of attention (Livingston, 2005).

Additionally, another concern regarding AR systems regards to confidential information that needs to be protected and should not be shared with people in the surroundings. An extreme scenario using AR contact lenses to provide private information is presented by Parviz (2009).

Nakanishi et al. (2007) goes further and identified the basic HF requirements in using an AR and noted that the performance of the user may be affected by the following six factors, namely:

1. Effect of eyesight correction;
2. Effect of eye dominance;
3. Effect of surrounding illumination;
4. Workload;
5. Attention to surrounding;
6. Difficulty in preparing AR manuals.

In order to ensure that AR is implemented in the right areas and processes, making good use of its benefits and potentials, Livingston (2005) has emphasized the following two questions: (1) *How do we determine the most important needs of the AR user and the best methods of meeting those needs with AR interfaces*? and (2) *For which tasks are AR methods better than conventional methods?*

Thus, the long-term goal for many AR researchers and developers is to create usable applications that are able to support tasks performance, being preferable over conventional methods regarding usability and ergonomics. Moreover, attention must be paid to HF, assessing the time AR systems are used by workers, in order to ensure the most suitable ergonomic conditions and the workers well-being, while avoiding cognitive strain or undesirable effects related with the use of this technology (Nee et al., 2012).

### 2.6.3 Human Augmentation

HA techniques rely on the use of technologies that are able to augment human actions, senses, capabilities and cognition, allowing humans to perceive the real environment in a new and enhanced way. Based on augmenting technologies, such as AR, VR and MR, relevant information is provided to operators, in order to enhance human life and allow new HMI solutions (Kymäläinen et al., 2016).

This approach is centred on the AR users and based on human-centred real world merged with an information world (Tachi, 2013). An augmented human has extended capabilities regarding physical, sensing and cognitive abilities, as shown in Figure 27 (Romero, Bernus, et al., 2016).

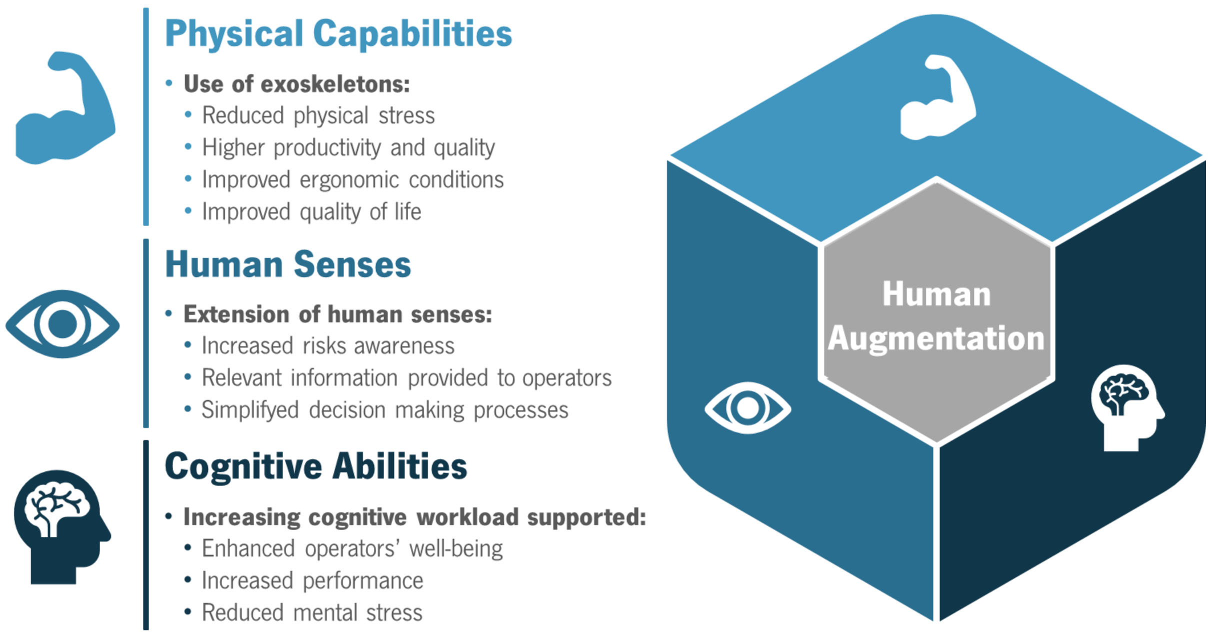


Figure 27. Fields of Human Augmentation
(Adapted from: Pereira et al. (2019))

Physical capabilities refer to operator's capacity to undertake physical activities required for daily work, such as, lifting, walking, manipulating and assembling. Regarding enhancement of physical capabilities, HA will allow the creation of super-strong workers encased in exoskeletons, being able to safely move and lift more heavy items. Exoskeletons in industrial environment allow humans and technology to cooperate in order to simplify tasks and reduce physical stress, while offering additional protection, support and strength to operators (Pereira et al., 2019).

Enhanced physical capabilities using exoskeletons technology provide improved ergonomic conditions, reduced injuries, accidents and OSH risks, higher productivity and quality. Furthermore, with a reduced physical workload, operators can relocate their energy to sensorial and cognitive capabilities, which promotes the sustainability of the workforce, allowing people to perform their tasks longer (Romero, Stahre, et al., 2016). Furthermore, people with special needs or elderly people will have their quality of life improved with these new solutions that allow new forms of human actions (Kymäläinen et al., 2016).

Alternatively, AR holds a great potential in sensory augmentation, which consists in the extension of human senses. Humans are dependent on their perception, based on their classical senses and enhancement of the existing spectrum of human senses by technological means has the potential to improve and facilitate human capabilities (Kiss & Poguntke, 2021).

Hence, the sensory augmentation relies on the use of devices that collect, convert and aggregate external signals that would not be accessible to operators, due to several reasons, such as available data, human limitations or personal limitations. These devices are able to transform one signal into another, allowing humans to identify relevant information and simplifying decision-making processes (Romero, Bernus, et al., 2016).

Thus, AR is able to augment every human sense, however, sight sense augmentation is one of the most studied field. Applications that convert light within a spectrum not visible to human eye into visible light, visualization of dark scenes through infrared or superimposed virtual images provided by wearables or projections are some examples about extensions of the human visual function. Nevertheless, augmentation is not limited to sight sense and other applications can extend hearing function by immersing users in an augmented environment by sound in place of information. Moreover, the sense of touch can also be augmented providing textures, sensations or radiant temperature that provide information to operators (Tachi, 2013).

Furthermore, cognitive capability relies on the ability to undertake mental tasks, such as memory, decision-making, responsiveness, perception and reasoning, that are essential to perform tasks (Carroll, 2009). In Industry 4.0 and smart factories context, the increasing demand for mental tasks can be addressed by AR technology and new approaches to HMI that support the increased cognitive workload, while considering operators well-being and performance and reducing mental stress (Romero, Bernus, et al., 2016).

Additionally, it is possible to intellectually augment humans in a human-centred environment superimposing information into real world regarding work instructions, personal information, directions or safety instructions (Tachi, 2013). In this context, AR technology provides a new HMI, displaying real-time information to operators, which improves decision-making and create new interactions between humans and products due to the available information about them, which allows their configuration and monitoring (Romero, Stahre, et al., 2016).

However, HA goes beyond the scope of AR, being able to augment spatial and temporal abilities. HA in time and space is known as telexistence. This is a concept that regards to a technology, such as AR, that can free humans from the constraints of time and space, allowing them to experience a real-time perception of being in other place and interact with a remote real, virtual or mixed environment (Tachi, 2013).

Operator 4.0 is a concept that has emerged in Industry 4.0 context and can be understood as a smart and skilled operator that performs collaborative work with machines and robots, being enabled by CPS and advanced technologies (Romero, Bernus, et al., 2016).

AR is a critical enabling technology for improving information transfer between digital world and smart operators in physical world (Ruppert et al., 2018). The term Operator 4.0 refers to smart and skilled operators, assisted and augmented by systems that enable a reduced physical and mental stress during tasks performance, allowing them to be more creative and innovative, fostering continuous improvement without compromising productivity (Romero, Bernus, et al., 2016).

Hence, Romero, Stahre, et al. (2016) suggested an Operator 4.0 typology, arguing that an operator within Industry 4.0 environment can assume several roles, as shown in Figure 28.


Figure 28. Operator 4.0 Typology
(Adapted from: David Romero, Stahre, et al. (2016))

On the one hand, the super-strength operators have their physical capabilities enhanced by exoskeletons, allowing them to safely lift and move heavy materials, while improving their ergonomic conditions, reducing the risk of injuries, accidents and MSD.

On the other hand, augmented and virtual operators are supported by AR and VR technologies, respectively, enhancing their cognitive capabilities (Romero, Stahre, et al., 2016). Moreover, Pereira et al. (2019) stated that an augmented operator can be defined as an operator that has their capabilities enhanced, regarding physical abilities, sensory and cognitive skills, which includes the above-mentioned Operator 4.0 typology that Romero, Stahre, et al. (2016) categorized.

Therefore, the Operator 4.0, or Augmented Operator, paradigm is enabling the engagement and empowerment of workers (Kaasinen et al., 2020), as the decreasing physical and cognitive workload can also reduce work time, giving people more time to learn, think and innovate.

Furthermore, healthy operators use wearable devices to track their well-being, measuring parameters as stress, heart rate, exercise activity and biometrics data, while smarter operators have their productivity and efficiency enhanced through the use of Artificial Intelligence.

Additionally, the collaborative operator works within a hybrid system that combines manual and automatic workstations, creating a symbiosis between humans and collaborative robots.

Moreover, the social operator is enabled by social networking between smart operators, allowing the real-time information exchange.

Lastly, the analytical operator is characterized by the ability of using Big Data analytics in order to monitor and control systems, improving the quality and lead times (Romero, Stahre, et al., 2016).

To successfully embrace opportunities enabled by Industry 4.0 and implement emerging technologies, namely AR, companies need to develop human-centric production systems that focus on workers and their needs. The application of this technology will directly affect operators and their workplaces, creating new interaction between humans and machines.

This new interaction will merge digital and physical worlds, resulting in a socio-technical transformation in smart factories and a new HMI paradigm, allowing the elimination of wastes in workplaces, non-value added activities and risk factors.

Furthermore, the operator's efforts during task performance can be reduced, promoting well-being within the organizations and ensuring equality for all workers, regardless their capabilities or disabilities, promoting a safe and secure working environment.

## 2.7 Critical review analysis

The fourth industrial revolution and the enabling technologies, namely AR, will bring together the digital and physical worlds, where humans and machines dynamically interact. Despite of this new manufacturing concept represents an opportunity to improve companies' productivity and efficiency, there are some concerns regarding HF, once this will deeply affect operators and their workplaces.

In industrial context, AR technology holds great potential, allowing higher work performance and efficiency in workplaces that results from HA, that consists in the creation of operators with augmented or enhanced physical, sensorial and cognitive capabilities.

However, the importance of HMI, in order to ensure a sustainable interaction between operators and machines, has been growing as the technology develops. There are a lot of critical factors regarding human errors, operator's well-being and industrial safety, being essential to ensure the accuracy of the provided information to simplify tasks performance and reduce workload and operator's effort.

Operators should be the main focus on every production system. For this reason, it is crucial to ensure that they develop their tasks without symptoms of wastes, such as overburden, stress or accidents that could occur due to the workplace unevenness.

AR application in industrial context allows the enhancement of HMI, reducing operation times and human efforts and improving ergonomic conditions, as well as, mitigating the risks and eliminating human errors in workplaces. Furthermore, achieving this, wastes are reduced that is one of the main issues in Lean contexts.

Lean Thinking is a philosophy that embraces every area from industry and services, helping organisations to continuously improve and fostering their competitiveness, in order to face the current and future challenges. This project focuses on three main domains of Lean Thinking: (1) Lean Ergonomics; (2) Lean Logistics; and (3) Lean Automation.

The first one addresses the combination of lean, safety and ergonomic aspects within a workstation, while the second domain regards to the application of lean to supply chain and warehouse management. Lastly, Lean Automation refers to the synergies between industry 4.0 and lean. Hence, the integration of these three above-mentioned lean domains is a novel approach, which constitutes the focus of this project, as shown in Figure 29.

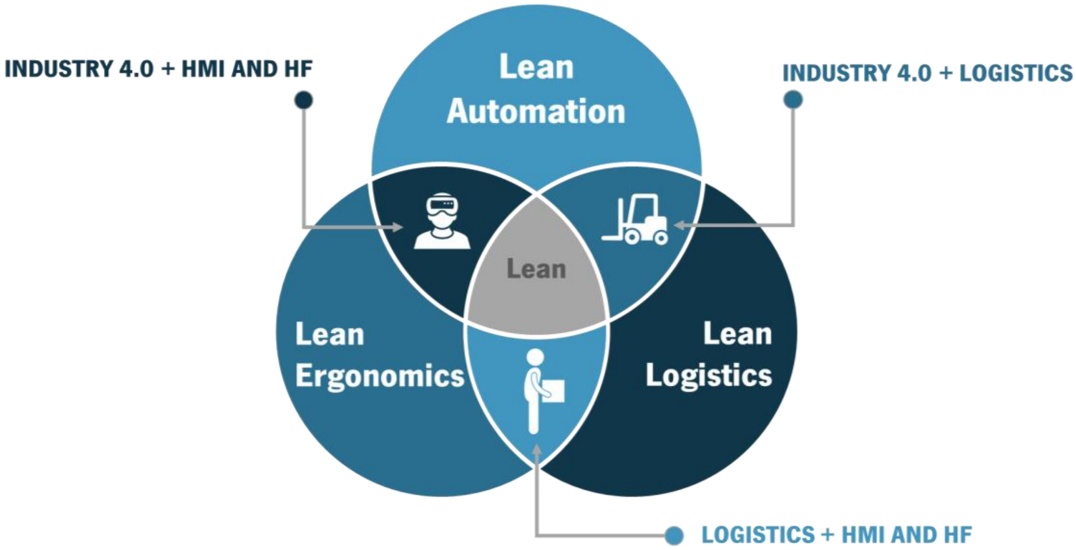


Figure 29. Integration of three lean domains

Within the manufacturing field, the relationship between Lean Production and Industry 4.0, known as Lean Automation, and its potential has been widely discussed recently, being the applications of AR an extensively researched topic in the last few years. However, unlike the production and assembly areas, the application of industry 4.0 technologies, namely AR, within logistic activities has been under-explored, which has been considered a literature gap, opening an opportunity for research and contribution to this topic that is known as Logistics 4.0.

Despite of its huge potential, there are some concerns, challenges and limitations that must be considered in order to enhance user's experience and ergonomic conditions, while mitigating risks in logistics using AR technology. For this reason, and in order to accomplish this project objectives, it was crucial to understand the relationship between HMI and HF in industry 4.0 context, as well as its implications and requirements for its implementation, which is not well reported in the literature and constitutes a question that remains and needs further research.

Furthermore, ergonomic and safety issues are topics widely discussed within production area and little attention has been paid to OSH risks in logistics areas, which comprise some of the activities with more hazards and more occurrences regarding work-related accidents during the last few years, such as storage and transportation tasks, as reviewed in section 2.4.1. Thus, the relationship between logistics and HF requires further research, which indicated a literature gap that has been addressed during the deployment of this project.

Furthermore, the accomplishment of this project addresses the Industry 5.0 paradigm, aiming to create sustainable, human-centric and resilient systems and attempting to balance the economic development with the resolution of societal issues (European Commission, 2021). In this case, the addressed issue regards to HF and the improvement of ergonomic conditions and creation of waste-free workplaces, promoting safe and secure working environments, and well-being within the organizations, while ensuring healthy workplaces, as well as equality for all workers, regardless their capabilities or disabilities.

Bearing in mind all the above-mentioned under-explored topics, this project intended to address the identified literature gaps and foster the creation of human-centric systems, proposing a methodology, which will be described in chapter 5, for analysing the requirements for implementing AR within logistic areas, through the assessment of risks within these areas and the proposal of mitigation measures using AR technology.

# 3 Research Methodology

Given the identified research gaps in the previous chapter and the objectives described in the section 1.2, it is necessary to address the research questions that have raised, presented in section 1.3. For this purpose, this chapter presents a detailed overview of the selected research design and methods used, explaining the development of the research design and case study.

## 3.1 Research design overview

The research design regards to a general plan of the research and how the research questions and objectives will be addressed. A clear definition of the research philosophies, research approaches, research strategies, research choices and time horizons are very important to ensure the successful deployment of the research project.

The way that research questions are addressed is highly influenced by the adopted research philosophy and approach. Consequently, the research questions raised in section 1.3, namely: *How can AR enhance human capabilities and senses in lean workplaces?* and *Which type of AR technology is more suitable for each logistic process?* determine the most suitable research strategy, the collection techniques and analysis procedures, as well as the time horizon over which the project is undertaken.

The overview of the research design adopted in this project is summarized in Figure 30.


Figure 30. Overview of research design adopted in this project

Mills and Birks (2014) defined philosophy as "a view of the world encompassing the questions and mechanisms for finding answers that inform that view". The research philosophy refers to the development and nature of knowledge related with the research and includes relevant assumptions about reality and how the researcher views the world and the way research process is considered (Saunders et al., 2009).

This research reflects the philosophy of positivism, since the data collection process is strongly based on an observable reality and the analysis and conclusions will result in law-like generalisations (Remenyi et al., 1998). Using this research philosophy, it is important to take into account that only observable phenomena can lead to the production of credible data (Saunders et al., 2009).

Depending on the desired outcome, there are two possible approaches for research: inductive and deductive. An inductive approach has been used during data collection and analysis, since this research has started without a predetermined theory or conceptual framework (Saunders et al., 2009; Yin, 2009).

The main aim was to build up a theory based on collected data, which addressed the research questions. As can be seen in Figure 31, the main difference between an inductive and a deductive approach is that the first one consists in a formulation of a theory based on collect and analysed data, while the second approach moves from general to specific and often begins with a theory to be validated (Saunders et al., 2009; Wallace, 1971).

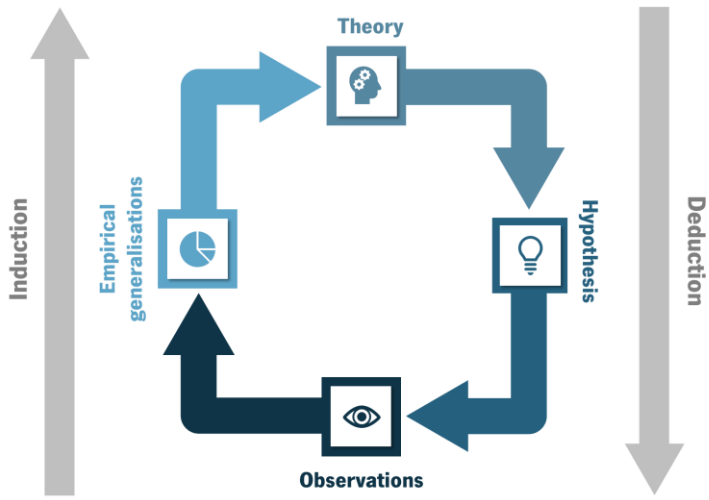


Figure 31. Science wheel
(Adapted from (Wallace, 1971))

The research strategy that is most appropriate to answer the research questions and address the objectives of this project is the case study, since it consists in an in-depth analysis upon an observable phenomenon within its real-life context. The strategy consists in a single case study combined, since it was deployed within a single organisation, with an embedded case that allows the analysis of multiple relevant units within that organisation.

Regarding research choices, there are several data collection techniques that can be used in case studies, typically combined, such as archives, interviews, questionnaires, and observations. On the other hand, the evidence may be qualitative, quantitative or both (Eisenhardt, 1989). Therefore, mixed methods, both qualitative and quantitative have been applied during the deployment of this case study, including several research instruments which have been used. The description of the development and application of the research methods will be detailed in in section 3.2.2.

Furthermore, two different time horizons might be applied to a research project: cross-sectional and longitudinal. The study in a particular time is what can be called cross-sectional while the study over a long period of time is considered longitudinal. A cross-sectional study has been developed upon the questions under investigation, since it studies a particular phenomenon at a particular time as well as its incidence to explain how factors are related (Saunders et al., 2009).

## 3.2 Case study

The case study methodology is a research strategy that consists in an in-depth analysis into a phenomenon within its real-life context or setting (Yin, 2018), focusing on the deeply understanding of the dynamics between both (Eisenhardt, 1989). Understanding the context and defining the "case" under study is fundamental and it may refer to a person, a group, an organisation, an association, a process change, an event, as well as many other subjects (Saunders et al., 2009).

One of the main differences between this research strategy and others is the little interaction and control of the researcher over phenomenon and its setting, as well as the limited ability to understand the impacts, since the boundaries between both are not clear and well defined (Yin, 2018).

According to (Yin, 2009), to define the research method to be used, it is necessary to analyse the research questions that have arisen. Furthermore, case study strategy is the most suitable method when the research addresses descriptive or explanatory questions, aiming to answer the "how" and "why" questions concerning the phenomenon of interest. Based upon two discrete dimensions, four case studies strategies have been categorized by (Yin, 2009):

- Single case vs multiple case;
- Holistic case vs embedded case.

A single case often represents a critical, extreme or unique case. Furthermore, its typical to select this strategy when it comes to a phenomenon that few have considered before. On the other hand, a multiple case strategy includes multiple cases and the aim is to generalise the findings. Conversely, the second dimension refers to the unit of analysis. The holistic strategy regards to the organisation as a whole, while embedded case study is concerns to more than one unit of analysis with an organisation (Saunders et al., 2009; Yin, 2009).

Based on the above-mentioned definitions, it is possible to conclude that case study, as a research method, is very helpful in order to understand, explore and describe events, in a real context with several factors involved simultaneously. Therefore, for this case study deployment, four stages have been applied, as described in Table 10, according to Yin (2011). In this table the tasks are also presented and the description of each in the context of this project.

Table 10. Stages of the case study

| Case study stages | Tasks | Description |
|---|---|---|
| 1. Design the case study | Protocol definition, research questions, procedures and general rules establishment | 1. Project scope, overview and main objectives<br>2. Field procedures<br>3. Preliminary research questions<br>4. General rules and guidelines |
| 2. Conduct the case study | Data collection | 1. Company visits and observations<br>2. Gemba walks and regular meetings<br>3. Unstructured interviews and conversations |
| 3. Analyse case study evidence | Qualitative and quantitative analysis | 1. Occurrence analysis<br>2. OSH risks evaluation<br>3. Ergonomic risks assessment<br>4. Mitigation measures using the most suitable AR solution to each risk |
| 4. Develop conclusions, recommendations and implications | Conclusions based on the evidence | 1. Analysis and discussion<br>2. Presentation of the findings |

The deployment of each above-mentioned phases of the case study will be reported in the next sections.

### 3.2.1 Design the case study

During the first stage, the case study protocol has been defined, according to Yin (2011) guidelines:

1. Overview of the case study project (project context, motivation, scope and main objectives detailed in sections 1.1 and 1.2);
2. Field procedures (each data collection method outlined in section 3.2.2);
3. Preliminary research questions (discussed in section 1.3);
4. Guide for the case study report: the deployment of case study, building of theories, implications and main conclusions will be reported along this thesis in the next chapters.

Thus, the first phase of the case study protocol consisted in the definition of scope, context, motivation and main objectives of the project. Afterwards, the field procedures have been implemented within case study in order to collect relevant data for the case study deployment, using the most suitable data collection methods for each phase of the working plan, including meetings, interviews, observations, questionnaires, company visits or *gemba* walks.

Subsequently, as reported previously in section 1.3, the research questions that have arisen are as follows:

- RQ 1 – *How can AR enhance human capabilities and senses in lean workplaces?*
    - RQ 1.1 – *How can AR enhance human capabilities and senses in order to mitigate risks?*
    - RQ 1.2 – *How can AR enhance human capabilities and senses in order to improve ergonomic conditions?*
- RQ 2 – *Which AR solutions are more suitable for logistic processes?*

Consequently, in order to answer the above-mentioned research questions, the focus was on the deployment of the case study that consisted in the development of a methodology to assess risks within logistic workplaces. Then, it was proposed mitigation measures based on AR (chapter 5), followed by the analysis of theories and results (chapter 6) and, lastly, by conclusions drawn (chapter 7).

### 3.2.2 Conduct the case study

The second stage regards to data collection phase and included company visits, regular meetings, interviews and process observations in company's facilities. More details about data collection moments, purposes, methods, responsible and location are given in Table 11.

Table 11. Data collection methods

| **When?** | **Why?** | **What?** | **Who?** | **Where?** |
|---|---|---|---|---|
| During which phase? | What was the reason or purpose? | What data collection method was used? | Who were the participants? | Where did it happen? |
| Phase 1:<br>Literature review and project scope | Definition of project scope | • Meetings<br>• Unstructured interviews | • Supervisory team<br>• Middle-level managers | Case study facilities |
| Phase 2:<br>Case study analysis | Analysis and mapping of logistic processes | • Company visits and observation<br>• Meetings<br>• Unstructured interviews<br>• *Gemba* walks | • Low-level managers<br>• Supervisors<br>• Workers | Case study facilities |
| Phase 3:<br>Methodology definition | Analysis of requirements for implementing AR in logistic processes | • Company visits and observation<br>• Meetings<br>• Unstructured interviews<br>• *Gemba* walks<br>• Video recording<br>• Video analysis | • Safety Specialist in Logistics<br>• Technician for Health and Safety at Work<br>• Plant Ergonomist | Case study facilities |
| | Proposal of mitigation measures using AR technology | Literature review | PhD candidate | University |
| Phase 4:<br>Analysis and discussion | Improvements potential assessment | Literature review | PhD candidate | University |
| | Analysis and discussion of obtained results | • Meetings<br>• Interviews<br>• Questionnaires | • Middle-level managers<br>• Low-level managers<br>• Plant Ergonomist<br>• Supervisors<br>• Workers | Case study facilities |

Therefore, a methodology was developed, that embraced the analysis of requirements for implementing AR and the proposal of mitigation measures. The data collection has occurred during all phases of the research methodology framework defined in section 1.3., being detailed bellow.

During the first phase, the scope of the project was defined, involving the PhD supervisory team and some middle-level managers in the case study. At the beginning, it involved the Industry 4.0 Coordinator, in order to decide which would be the most appropriate area to develop the project within the plant. Several meetings were held with this manager in order to define the scope of the project so that the company takes full advantage of the work developed.

Thus, after identifying the existing research gap regarding the use of AR technology in logistic processes in order to enhance ergonomics and human factors, the logistics area was selected to conduct the case study. Hence, the Head of Physical Logistic and Material Flow was involved in order to guide the deployment of the project and unstructured interviews, or informal conversations, were conducted with the objective of identifying the areas with more potential for improvement from an ergonomic and safety point of view.

Furthermore, throughout the development of the entire project, several meetings were held with this manager, who assumed the role of PhD project supervisor within the company where the case study was developed and forwarded the project in the best way to meet the needs of the different logistical areas within the scope of the project. The definition of project scope is presented in chapter 1, while the literature review is detailed in chapter 2.

The second phase, described in chapter 4, consisted in the analysis and mapping of logistic processes at case study, where low-level managers, supervisors and workers played a crucial role in order to identify the critical tasks to analyse and map the processes. Regular meetings and visits to operational areas, i.e. *gemba* walks, were held throughout the development of the project, as well as unstructured interviews were conducted with local key informants, namely, supervisors and workers, with the objective of identifying the most critical operations. These informal conversations during *gemba* walks and visits to logistics areas aimed to gather in-depth information about processes, main issues and discommodities experienced by operators regarding ergonomics and safety. Furthermore, the observation of processes in logistics areas was crucial to understand and map the processes and operations under study.

The third phase, detailed in chapter 5, consisted in the analysis of requirements for implementing AR and the proposal of mitigation measures through the use of AR. In what concerns to definition of requirements for implementing AR, it consisted in the establishment of a methodology to analyse case study in terms of occurrences, risk evaluation and ergonomic factors in order to quantify the risks regarding ergonomic conditions and physical safety that can be mitigated by the use of AR. The deployment of these analysis required a deep involvement of the employees, namely the Health and Safety Specialist in Logistics to support the occurrences analysis in the logistics area, the Technician for Health and Safety at Work to assist the risk evaluation and the Plant Ergonomist that was deeply involved in the ergonomic analyses.

Furthermore, these analyses, especially the ergonomic analyses, have required a significant number of visits to logistics area, *gemba* walks and process observations in order to collect information, data, measurements, pictures and videos that were essential for the analyses. Regarding the proposal of mitigation measures through the use of AR, it consisted in and extensive research about the available solutions and understanding how these measures can eliminate the risks identified in the previous step.

Lastly, the fourth phase that is presented in chapter 6, comprised the improvement potential assessment, which required research and analysis about the improvement potential of the solutions identified in the previous phase. Finally, this phase includes the analysis of the obtained results and, since this project intends to propose solutions to mitigate risks, the analysis of the improvements involved interviews and surveys to workers, supervisors, the ergonomist, technicians, specialists, low and middle-level managers within the case study in order to understand how the proposed solutions would be beneficial to the company.

### 3.2.3 Analyse case study evidence

During the third stage a qualitative and quantitative analysis were conducted (as described in chapter 6). In short, the qualitative and quantitative analyses are depicted in Table 12.

Table 12. Qualitative and quantitative analysis

| **Analysis** | **Qualitative Analysis** | **Quantitative analysis** |
|---|---|---|
| Occurrence analysis | • Accidents and incidents<br>• Most critical logistic areas<br>• Most critical processes<br>• Most common consequences of occurrences | • Number of accidents<br>• Number of incidents<br>• Type of injuries |
| OSH Risk Evaluation | • Hazards associated with each task performance<br>• OSH risk factors<br>• Human senses and capabilities to be augmented<br>• AR solutions to mitigate risks | • Score-based risk assessment (calculated based on the scores of frequency and severity) |
| Ergonomics Analysis | • Current situation and process mapping<br>• Extreme postures<br>• AR solutions to mitigate risks | • Score-based risk assessment (calculated based on the parameters of the selected ergonomic risk assessment method) |

### 3.2.4 Develop conclusions, recommendations and implications

Finally, the last stage concerns to conclusions based on the evidences from the data collected as well as the definition of mitigation measures for the risks identified, which is described in chapter 6, while the analysis and discussion are presented in chapter 6 and the conclusions of this thesis are depicted in chapter 7.

# 4 CASE STUDY PRESENTATION

This chapter presents the company where the case study project was carried out. It contains a brief description of the company, as well as the organization of the logistics department, where the work was carried out. The functions regarding ergonomics, health and safety are explained as well, followed by the presentation of the logistic processes under study.

## 4.1 Company characterization

The company of this study is a tier one supplier of automotive industry, being specialized in the manufacturing and development of multimedia systems, electronic equipment, namely navigation systems and instrumentation for automotive industry. Employing approximately 4000 employees, this company is located in Braga, Portugal, having started its activities in 1990. The management model of this company is based on Toyota Production System, being highly guided by Lean principles and promoting the use of its tools to increase competitiveness and eliminate wastes from existing processes.

## 4.2 Supply chain, production and material flow

The production of this company is the responsibility of the manufacturing department, which is divided into two different sections, namely, Surface-Mount Device (SMD) assembly and final assembly. The devices produced at the company are essentially made up of electronic and mechanical components. Electronic materials constitute the Printed Circuit Boards (PCB), that are automatically mounted in the SMD assembly area. Mechanical materials, on the other hand, are assembled in the final assembly area.

Initially, raw materials and components arrive at the incoming warehouse, being received, checked and prepared. This initial phase consists in the verification and inspection of the material quality, as well as the quantities, introducing this information into the IT management system. At the end of this phase, a Transfer Order (TO) is printed, determining which of the two possible flows the material will follow. On the one hand, mechanical components are stored on the shelves of the raw material warehouse. On the other hand, electronic components are directly directed to the SMD warehouse, awaiting their consumption by SMD assembly. The supply of electronic material to SMD lines is done by Automated Guided Vehicles (AGV) that follow an established route with defined cycle times. Once the assembly of the PCB boards is completed, they are sent to final assembly.

Hence, the mechanical components that are stored in raw materials warehouse are subsequently transferred to the repacking area and transferred to plastic boxes that meet the standards defined for the production area. Afterwards, electronic materials are stored in an intermediate supermarket and Point of User Provider (PoUP) is responsible to transport them and supply the final assembly lines.

Final assembly is composed by production systems that consist in manual insertion, supplied by several supermarkets located near the production lines storing mechanical materials such as displays, blends, metal boxes, screws, among others.

When the production process in the final assembly is completed, the finished products are packed on pallets and later transported to the finished products warehouse, from where they will be shipped to the final customers.

### 4.2.1 Logistics department

The logistics department is responsible for all material flow management from the supplier's facilities until the end customer. It is in charge of production planning operations, raw materials purchasing, warehouse management, shipments, billing and the entire internal logistical flow, fulfilling the customer orders, ensuring the existence of materials in the correct quantity, with the assured quality, in the correct place, at the exact time, to the right customer and at the right cost.

Thus, this department ensures the entire flow of internal materials and interconnects various activities in the company, being divided into seven sections:

1. Plant Logistics
2. Packaging design
3. Logistic Projects, IT System, Processes and LOG Quality
4. Material Flow and Physical Logistic
5. Logistic Planning and Fulfilment
6. Interface Supplier
7. Transport Management

The case study was deployed within Material Flow and Physical Logistics section, which is responsible for the internal storage, warehouses management, supply materials to production areas and transportation operations and comprises four main logistics areas (Figure 32):

1. Incoming;
2. Internal logistics for final assembly;
3. Internal logistics for SMD assembly;
4. Shipping.

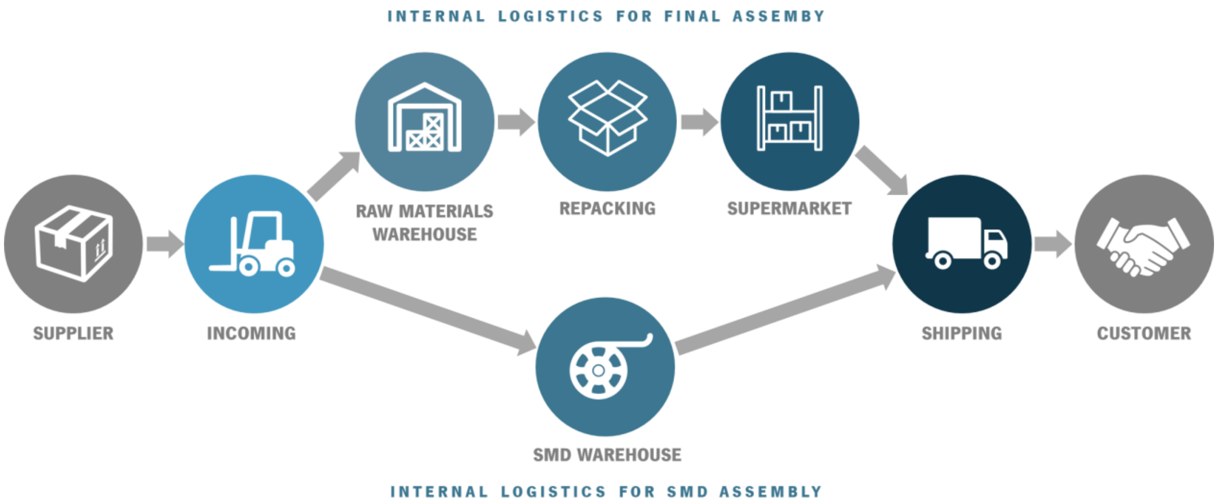


Figure 32. Areas of Material Flow and Physical Logistics section

In the section 4.2.2, the operations performed within each area of Material Flow and Physical Logistics section will be described in a detailed way.

### 4.2.2 Logistic processes description

This section describes the main logistic operations that were carried out in Material Flow and Physical Logistics section, which is divided into four different areas: (1) incoming; (2) internal logistics for final assembly; (3) internal logistics for SMD assembly; and (4) shipping.

#### 4.2.2.1 Incoming

The incoming process begins when items arrive in the raw materials warehouse. After unloading the materials, an employee registers the items, typically by scanning a bar code. From the unloading dock, warehouse activities are performed at different complexity levels depending on the type of materials and the storage method.

There is a wide range of material that is received in unloading docks, arriving from trucks or air individual transports and arriving in loose boxes that are unloaded by the operators from the floor to higher levels or accommodated in pallets, that can be standardized Euro pallets or non-standard pallets, in the case of Asian suppliers. In order to comply with the company's standards, that require the use of Euro pallets, operators have to perform the repalletization process of materials accommodate in non-standard pallets, so that they can be stored on the shelves of the raw material warehouse. After the unloading process, the material is placed in incoming area, as shown in Figure 33.

Figure 33. Incoming area

The put-away process consists in storing the items in the warehouse shelves at the right places. During this process, the pallets are separated by even and odd aisles and the stacker places the pallets in an area on the floor at the entrance to the aisle. Not every aisle is used to store whole pallets, since there are some individual boxes that are stored in specific locations that are reserved for this purpose. However, in the locations of individual boxes do not follow a proper logic, which makes the picking and put-away process very difficult, as the process of finding the locations is very confusing and slow.

#### 4.2.2.2 Internal logistics

After receiving the materials, they are checked and a TO is issued, determining the destination of each handling unit. Generally, mechanical materials are store in raw materials warehouse, going through the repacking process and then stored in the supermarket, from where they will be transported to the final assembly lines. In turn, electronic components go directly to the SMD supermarket, from where the SMD assembly lines will be supplied.

Therefore, the internal logistics is divided into two different areas: (1) internal logistics for final assembly; and (2) internal logistics for SMD assembly. These two areas and related processes are described in sections 4.2.2.2.1 and 4.2.2.2.2, correspondingly.

##### 4.2.2.2.1 Internal logistics for final assembly

In order to perform the put-away process and store a pallet composed by mechanical components in the raw materials warehouse (Figure 34), it is crucial to enter this information into the IT system. For this purpose, the operators use a Personal Digital Assistant (PDA) that uses the ALPE-Scan software to scan the barcode of the location indicated in the TO, followed by the barcode of the location on the shelf where the pallet will be placed.

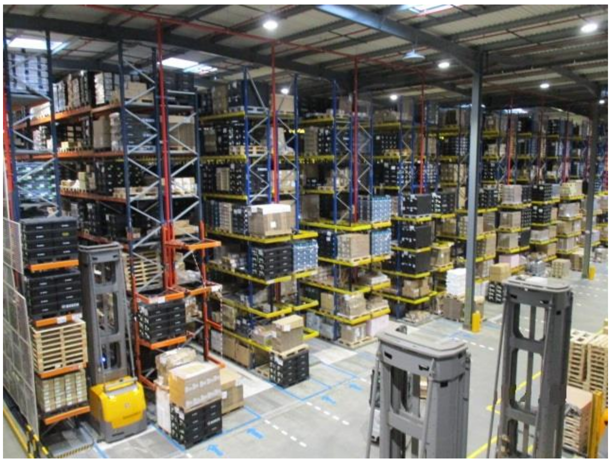

Figure 34. Raw materials warehouse

On the other hand, the picking process consists in the collection of needed material that is stored in warehouse shelves. In this warehouse, the shelves on the lower levels store material that will be used for repacking process. The picking of these materials is done manually by employees, without using transportation machines, such as stackers or forklifts. The operator selects the aisle where they are in and check the list of locations where they must pick material. The software provides information about the position, material reference, quantity to be removed and quantity remaining on the pallet. Similar to put-away process, the transference of material must be registered in IT system. Thus, the operator uses the PDA to scan the barcode on picking list and materials.

The picking area, inside the aisles, is shared by standing employees, picking material at lower levels, and by trilateral machines, that are used to pick material at the upper levels. It is crucial to ensure that operators and machines never cross, in order to avoid the risk of collision and injuries. Moreover, the incoming area is shared by forklifts, stackers and standing operators, which makes the tasks of receiving and checking material difficult, since operators have to be aware of moving machines, bypassing them whenever necessary.

Mechanical components that are stored in raw materials warehouse are further transferred to repacking area (Figure 35), where they are placed in boxes that meet the standards defined for the production area. This operation is absolutely fundamental in the electronics industry, due to the sensitivity of some components, such as displays and other IC, requiring an atmosphere free from dust and other micro particles. Furthermore, these components can be easily damaged by Electrostatic Discharge (ESD).

Given the above-mentioned requirements, it is necessary to remove from the production environment all materials that could compromise the quality of the products manufactured by Bosch. Since cardboard is a material that releases microparticles into the atmosphere and also accumulates static electricity, it must be removed from the manufacturing space.

Figure 35. Repacking area

Despite of negotiations with suppliers to ship the material in cardboard-free packaging with ESD protection, most of them ship the material in packages that are not allowed in manufacturing environment due to the above-mentioned issues. For this reason, repacking tasks are essential in order take the material out of the cardboard packaging and place it in a packaging made of a suitable material the production environment. In order to minimize stocks of plastic boxes with ESD protection, the company has standardized the boxes used for indoor and outdoor repacking operations, also using them as returnable packaging with suppliers.

After being conveniently packed in standard boxes, the mechanical materials are transferred to an intermediate supermarket area, shown in Figure 36, where the PoUP is responsible for supplying the final assembly lines, operating to ensure that the flow of raw materials needed for production is delivered in the smallest volume, in the shortest distance, in the right time and with the necessary information, allowing a reduction of supply ramps and less use of factory space.

Figure 36. Supermarket for final assembly

#### 4.2.2.2.2 Internal logistics for SMD assembly

The electrical components used in SMD assembly lines are directly stored in the SMD warehouse after being received in incoming area. The SMD assembly consists in a production system composed by automatic component insertion machines that is supplied by the SMD warehouse (Figure 37), where there are SMD reels storing various electrical components, as well as PCB – the boards where the electrical components are inserted during SMD assembly.

Figure 37. SMD warehouse

The SMD warehouse areas are divided by product type - reels and PCB. Reels area is, in turn, organized by size of the reels, as shown in Figure 38. The dimensions of the reels and PCB shelves are very variable, which demands a wide range of postures adopted during put-away and picking processes.


Figure 38. Reels and PCB shelves in SMD warehouse

The processes performed in SMD warehouse comprise put-away and picking processes for reels and PCB. During the put-away process, the ALPE-Scan software is used to register the entry of materials in the supermarket. Initially, the material is in location E08 (temporary location), proceeding to the SMD repacking area. In this area, it is checked whether it is a single allocation (only one reel) or a collective allocation, since there are individual and collective places. In addition, the software has information on how many reels can be stored at each location. The material is accompanied by a Transport Order (TO), and ALPE-Scan suggests the location where the material should be stored using the heuristic model and the type of coil (it is supposed to always group reels of the same type in the same car). The TO is then read with the material code and the suggested location.

The picking process is based on SOL software, following a heuristic model that generates the picking list with the shortest route. The software provides information about the location of the items for picking and each milk-run is associated with a list of SMD assembly lines. The picking process takes a long time, since the locations are very small in size and difficult to find. The materials location is composed by the following information: (1) aisle; (2) section; (3) shelf (4) place; and (5) individual place (QR code for single location).

#### 4.2.2.3 Shipping

As soon as the products finish processing in the production area, they are temporarily stored at the end of the packaging area of each of the lines, until they are collected. When possible, the pallets that are on hold are picked and transported to the finished product warehouse. Once the products arrive at the finished product warehouse, they are placed in the reception area and, afterwards, the put-away is done on the warehouse shelves, as shown in Figure 39.


Figure 39. Finished products warehouse

The shipping process starts after confirmation of the order by the planner. However, all activities are triggered from the shipping department, with the picking of the pallets to be shipped. Afterwards, the delivery note is created, where the respective pallets are associated. In this way, the picking list is generated, with the information on the pallets to be collected. This list is sent to the warehouse, where picking TO will be created, containing the location of each pallet to be collected.

Warehouse operators pick the pallets that are on the shelves, according to the locations indicated in the TO created previously. Once the picking operation is completed, the pallet label is generated and automatically printed in the warehouse. After this process, the label will be validated.

Simultaneously, in the shipping department, the cargo list is generated, which will be sent to the warehouse. After confirming the cargo list, the truck is loaded.

## 4.3 Ergonomics, health and safety functions

Despite being a large company, the factory only has one Plant Ergonomist, whose functions include ensuring that the designs of systems, equipment and facilities are suitable from an ergonomic point of view, providing the best levels of efficiency, comfort, health and safety for workers and promoting their well-being. The Plant Ergonomist is responsible for implementing Ergo checklists in order to evaluate the working conditions within the workplaces, as well as assess the ergonomic conditions through the implementation of ergonomic risk assessment methods, implementing solutions to enhance ergonomic conditions and reduce the risk of MSD. It is important to emphasize that the risk assessment methods are performed by a custom-made software – IGEL – that comprises the main ergonomic assessment methods and significantly reduces the calculation time for ergonomic evaluation process.

Furthermore, there is a Safety Specialist in logistics department that is responsible for analysing the occurrences – work accidents and incidents – in this department. At the same time, she promotes the best practices and implements correction and mitigation actions in order to eliminate risks. The Safety Specialist works closer to the workers, which facilitates the collection of opinions and suggestions, promoting their involvement in continuous improvement actions in order to improve safety conditions of logistics workstations and reduce the risk of work accidents or incidents.

Additionally, in the safety area, the company also has a Technician for Health and Safety at Work that is responsible for the risk evaluation of every area within the plant, identifying the risks, prioritizing and scoring them based on their frequency and severity. Based on this information, Technician for Health and Safety at Work, Plant Ergonomist and Safety Specialist can work together in order to promote workers well-being in workstations, reducing the risk of accidents, incidents and MSD, while promoting safer workplaces with better ergonomic conditions. Nevertheless, this was not always the case and efforts in this direction have not always been integrated with all stakeholders, since each professional uses their own methods and the conclusions drawn by each one, that are not always widely disseminated, so that everyone cannot take advantage of this information to improve their own work.

It was the need to group all ergonomic, health and safety functions under a common methodology that motivated this project. The objective involves the development of a risk assessment methodology in the logistics areas, promoting standard work among these employees and helping them to evaluate the risks to which logistic operators are exposed, allowing the proposal of mitigation measures based on AR technology to overcome them. The development of this methodology is described in the following chapter.

# 5 Development of a methodology for risk assessment for ergonomics and safety in logistics

The analysis and definition of AR implementation requirements within logistic workplaces is based on a methodology that will be detailed in this chapter. The Risk Assessment for Ergonomics and Safety in Logistics (RAES-Log) methodology intends to identify the critical logistic areas and processes in order to assess and evaluate the risks regarding safety and ergonomics during tasks execution in order to propose mitigation measures based on AR.

Thus, the requirements for implementing AR are defined after the identification and assessment of safety and ergonomic risks, as well as the identification of the human senses and capabilities that should be augmented in order to improve working condition in lean workplaces. The RAES-Log deployment was divided into three main phases and 13 steps, four for the first phase, five for the second and four for the third phase.

Despite of this project being focused on the use of AR, this methodology can be used to analyse implementation requirements for every disruptive technology that has the potential to offer mitigation solutions for risks regarding ergonomic conditions and physical safety in workplaces in order to enhance working conditions and workers' well-being, while reducing the risk of developing work-related MSD.

The main phases of RAES-Log methodology are: (1) Occurrence analysis; (2) OSH risk evaluation and mitigation measures and (3) ergonomic assessment and mitigation measures, as shown in Figure 40.


Figure 40. Three main phases of RAES-Log

In a more detailed way, each one of the three main phases of this methodology consists in an extensive and detailed application of studies, as well as, various methods and analyses. This is important to achieve the primary objective of this methodology, which consists in identifying the human senses and abilities to be improved in order to mitigate safety and ergonomic risks though the use of AR technology. The Figure 41 summarizes the main phases and every step of this RAES-Log.

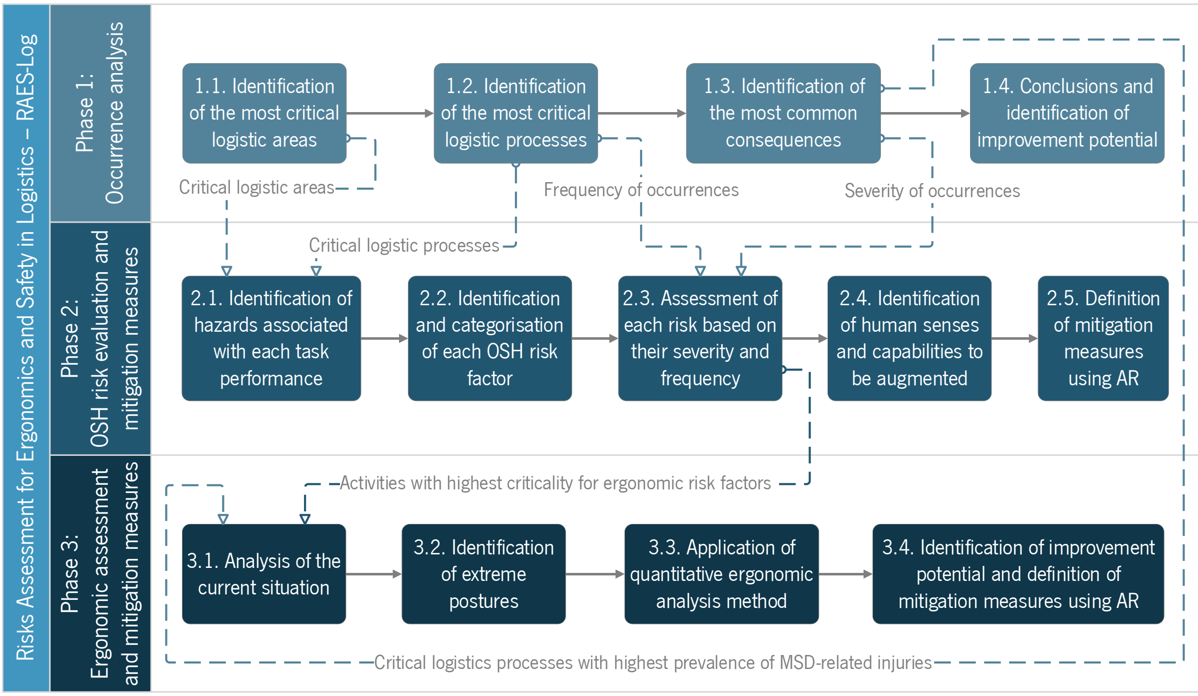


Figure 41. Overview of RAES-Log and detailed phases and steps

As mentioned before, the first phase of RAES-Log is the occurrence analysis, based on the number of work-related accidents and incidents within logistic workplaces over the last years, as detailed in section 5.1. This phase consists in the identification of the most critical logistic areas (step 1.1), followed by the identification of the most critical processes (step 1.2), that are the processes in which there is a greater frequency of occurrences.

Afterwards, the most common consequences of occurrences are identified (step 1.3), analysing the most injured parts of body, as well as the type of injury. This analysis will allow to draw some conclusions regarding occurrences incidence, frequency, and severity, as well as the improvement potential identification, which is the last step of occurrences analysis phase (step 1.4). Some outputs of the occurrence analysis will be crucial to deploy the next phases of this methodology, such as the identified most critical logistic areas, whose hazards and risk factors that will be further analysed during the OSH risk assessment (phase 2), detailed in section 5.2.

Furthermore, the identification of the most critical processes will be useful to determine the frequency, or probability, of the occurrence of a certain risk during the OSH risk assessment (phase 2), while the severity of the same risk is estimated based on the most common consequences and type of injuries that resulted from occurrences. Finally, the analysis of these consequences allowed the identification of the processes with highest prevalence of MSD-related injuries, which will be useful to select the processes that will be analysed during the third phase of this methodology, detailed in section 5.3, that consists in the ergonomic risk assessment of the most critical logistic processes regarding ergonomic issues.

During the second phase of RAES-Log methodology – OSH risk evaluation and mitigation measures – the most critical logistic areas identified during the step 1.1 are analysed in order to identify the main hazards associated to each task performance (step 2.1), followed by the identification and categorisation of each OSH risk factor (step 2.2).

Subsequently, during the step 2.3, each risk is assessed and scored based on their frequency or probability of occurrence, that is given by the occurrence analysis data about critical processes identified during step 1.2, and their severity, which is related with the consequences of occurrences, analysed during the step 1.3 of this methodology. After this assessment, the human senses and capabilities that should be augmented in order to mitigate OSH risks are identified (step 2.4) and, lastly, mitigation measures using AR solution are proposed (step 2.5). More details about this second phase of RAES-Log can be found in section 5.2.

Finally, the third phase of this methodology, which will be dealt with in more detail in section 5.3, consists in the ergonomic assessment and mitigation measures. In brief, the current situation will be analysed during step 3.1, and the processes the processes with highest prevalence of MSD-related injuries (identified in step 1.3), as well as, the processes with highest scores regarding ergonomic risks (identified in step 2.3) are analysed in order to identify the processes that involve ergonomic issues. Thus, the processes previously considered critical from an ergonomic point of view are studied and observed and the extreme postures are further identified (step 3.2).

Afterwards, the most suitable quantitative ergonomic analysis method is applied (step 3.3), based on the nature of performed tasks, in order to assess the ergonomic risks associated with tasks performance. Lastly, based on the results of this quantitative ergonomic analysis, mitigation measures using AR technology are proposed, in order to reduce the risk of developing MSD and enhance workers physical capabilities (step 3.4).

Moreover, every step that composes each one of the three phases of RAES-Log are further detailed during the next sections of this chapter. Also, the outcomes and conclusions drawn during the application of this methodology to the case study are summarized in section 5.4.

## 5.1 Phase 1: Occurrence analysis

Work-related occurrences can be categorised into two main groups: accidents and incidents. The first one refers to any occurrence during the execution of a service, whether inside or outside the company, that causes injuries and illness that include the loss or reduction, permanent or temporary, of the ability to work or, in extreme cases, the death of the employee. Thus, a work-related accident implies an absence of work for an indefinite time. Conversely, an incident refers to an unexpected work-related occurrence that does not result in any temporary or permanent physical or material damage, signalling an existing risk with the potential to become an accident, but not interfering with the employee's normal performance and not implying a loss of capacity for work.

The first phase of RAES-Log methodology consists in the occurrence analysis, that has been performed, based on existing data between January 2012 and December 2020 (2015 and 2017 data was not available), categorising the occurrences into accidents and incidents, according to its nature, identifying the logistic areas with the most occurrences and the most critical processes, as well as the consequences of the occurrences. The Figure 42 shows the main steps for the occurrence analysis.

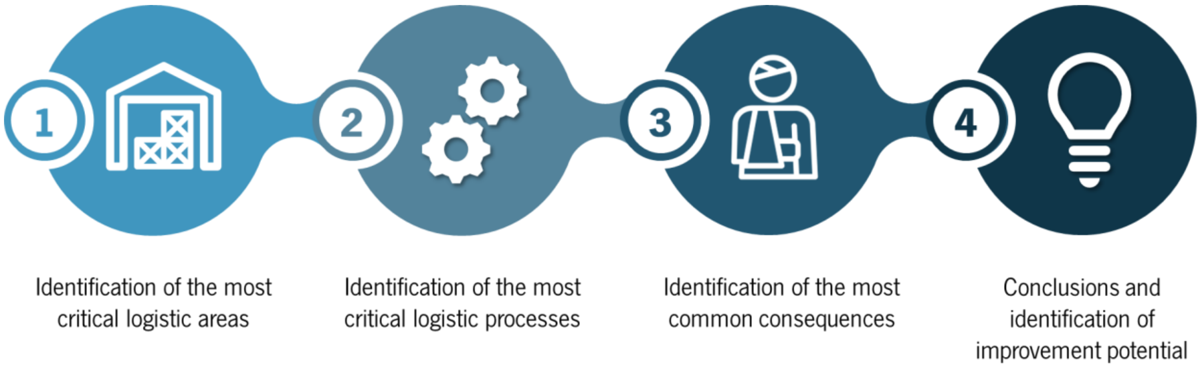


Figure 42. Steps of occurrence analysis

Step 1.1. of this methodology (described in section 5.1.1) consisted in a quantitative analysis, based on the available data about occurrences in logistic areas, in order to identify the areas with more incidence of accidents and incidents, regarding frequency and incidence, that have been considered the most critical areas.

Afterwards, step 1.2 (detailed in section 5.1.2) regards to the identification of the most critical processes, intending to identify which logistic task or process was being performed during each occurrence and the tasks with more incidence of occurrences.

Furthermore, step 1.3 of this analysis consists in the analysis of the consequences of each occurrence, namely the part of body injured and the type of injury, which is important to analyse the risks to which logistic operators are exposed (section 5.1.3).

Finally, some conclusions about the previous analysis were drawn and the improvement potential was identified (section 5.1.4). These conclusions were essential for focusing on the most critical areas and processes regarding safety and ergonomic risks during the next phases of this methodology, that will be described in sections 5.2 and 5.3.

Table 13 provides an overview of the first phase regarding the required information to perform each step or inputs, the methods applied during each process and the expected outputs or results. In the next sections, more details about each step that comprises occurrence analysis phase will be given.

Table 13. Overview of inputs, methods and outputs of each step of occurrence analysis

| Steps of phase 1 | Inputs | Methods | Outputs |
|---|---|---|---|
| Step 1.1: Identification of the most critical logistic areas | • Statistics of work-related accidents and incidents by logistic area | • Quantitative analysis | • Critical logistic areas |
| Step 1.2: Identification of the most critical processes | • Statistics of work-related accidents and incidents by logistic process | • Quantitative analysis | • Critical logistic processes<br>• Frequency of occurrences |
| Step 1.3: Identification of the most common consequences | • Statistics of work-related accidents and incidents by type of injury and part of body injured | • Quantitative analysis | • Common consequences of occurrences<br>• Severity of occurrences<br>• Critical logistic process with highest prevalence of MSD-related injuries |
| Step 1.4: Conclusions and identification of improvement potential | • Critical logistic areas (step 1.1)<br>• Critical logistic processes (step 1.2)<br>• Common consequences of occurrences (step 1.3) | • Quantitative analysis<br>• Qualitative analysis | • Improvement potential |

### 5.1.1 Step 1.1: Identification of the most critical logistic areas

The analysis of the number of occurrences has allowed the identification of the most critical logistic areas, based on the incidence of accidents and incidents in each area. This analysis was divided into two different phases. The first one regards to the analysis of the number of accidents, while the second regard to incidents occurrence.

Regarding work-related accidents in logistics workplaces, in 2012, there were a total of eight occurrences, with internal logistics accounting for 88% of the total number of accidents occurrence. There was a decrease of 50% between 2012 and 2013 and internal logistics area has accounted 100% of the four occurrences. During 2014, a total of six accidents occurred in logistics areas, which represents an increase of 50% when compared with the data from the previous year. Once more, internal logistics was the area with the highest frequency of work-related accidents (83%).

There is no available data during 2015 and a total of four accidents occurred during 2016, which represents a reduction of 50%, with incoming accounting three quarters of the total occurrences, which means that, for the first time during the studied period, internal logistics was not the logistic area with the highest incident of accidents. There were an additional six accidents at work in logistics during 2018, which represent an increase of 150% in comparison with 2016, since there is no available data during 2017.

Furthermore, during 2018, 80% of the occurrences concern the internal logistics area. It was registered a decrease of 30% during 2019, with internal logistics accounting 71% of the total work-related accidents. Finally, two accidents (both within internal logistics area) occurred during 2020, which represents a decrease of 71% in comparison with the previous year. This information is summarized in Figure 43.

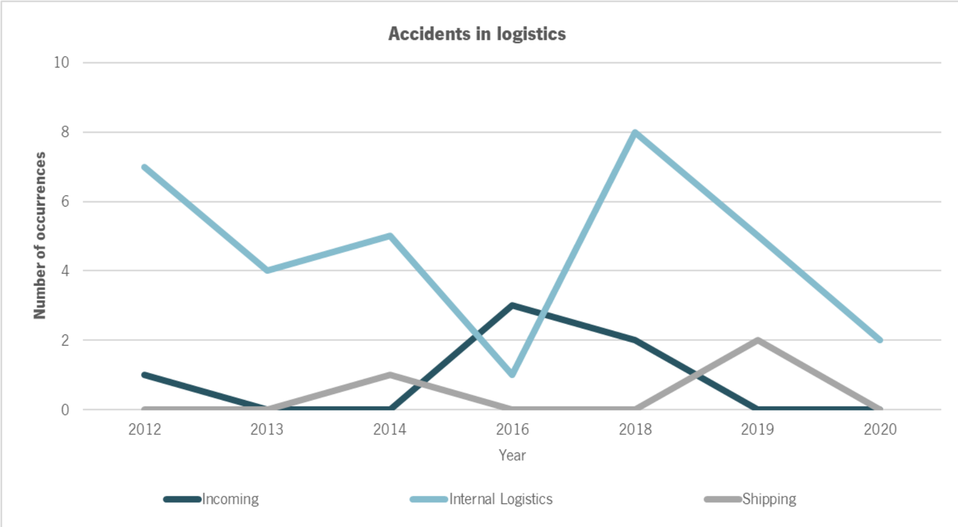


Figure 43. Number of work-related accidents in logistic areas (2012-2020)

In sum, between 2012 and 2020, incoming area accounted 15% of the total accidents, while internal logistics amounted to 78% of the accidents, being the logistic area with the highest frequency of work-related accidents. The area with the lowest frequency is the shipping area, with a total of 7% of accidents that occurred within logistics workplaces.

With regard to work-related incidents that occurred within logistics workplaces, a total of 12 incidents occurred during 2012, while 58% of these occurred within incoming area. An increase of 67% of incidents occurrence (20 in total) was registered during 2013, with internal logistics accounting for 80% of the total number of accidents occurrence.

A total of eight incidents occurred during 2014, which represents a reduction of 60% compared to the previous year, with internal logistics accounting 63% of the total occurrences. There is no available data during 2015 and during 2016, 16 incidents were listed, which means an increase of 100% in comparison with the numbers of 2014, with the highest frequency in internal logistics, accounting 56% of the total incidents.

Once more, there is no available data during 2017 and there was additional three incidents at work in logistics during 2018, being the internal logistics the area with the highest incident, accounting 84% of the total. The number of work-related incidents in logistics increased to a total of 20 occurrences during

2019, with internal logistics accounting 80% of the total. Lastly, 19 incidents occurred during 2020 and 68% of this occurred within internal logistics workplaces. This information is represented in Figure 44.

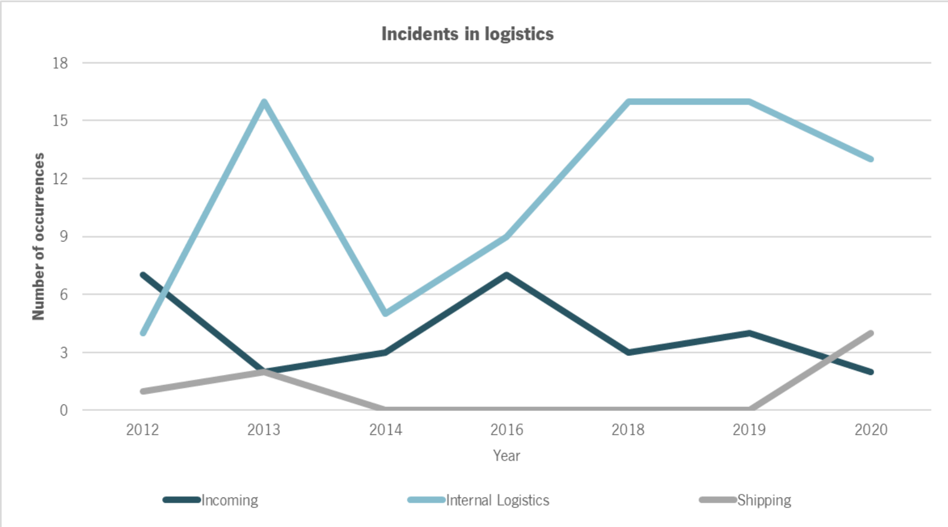


Figure 44. Number of work-related incidents in logistic areas (2012-2020)

Hence, likewise the analysis about the accidents' occurrence, between 2012 and 2020, internal logistics was the area with the highest frequency of work-related incidents, accounting a total of 69% of incidents. Moreover, incoming area amounted to 25% of the total incidents, while shipping was the area with the lowest frequency rate, with a total of 6% of incidents that occurred within logistics workplaces.

Given the previous analyses, it is clear that the area that accounts the highest frequency for accidents and incidents is the internal logistics. However, based on the total of occurrences, 114 incidents and 41 accidents, between 2012 and 2020, the percentage of occurrences within each logistic area is summarised in Figure 45.

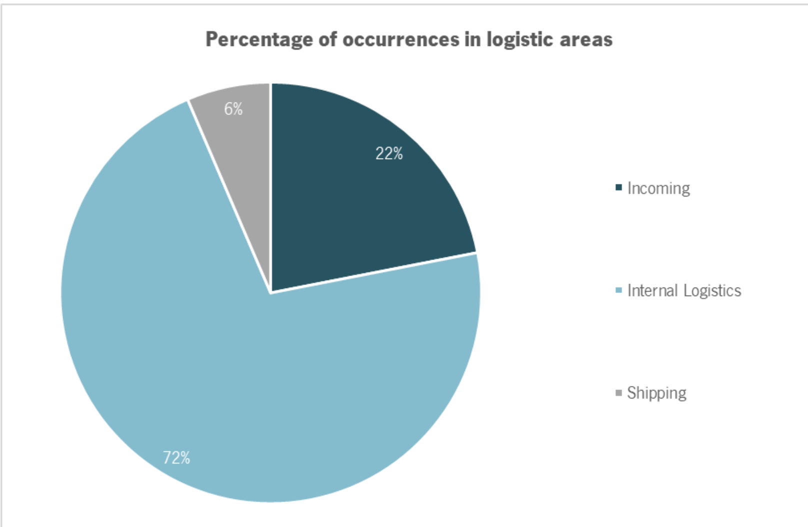


Figure 45. Percentage of occurrences in logistics areas (2012-2020)

Therefore, it is possible to conclude that the most critical area is internal logistics, accounting 72% of the total occurrences over the last years. Incoming area represents a significant frequency rate of occurrences (22%), while the least critical logistic area is shipping, with only 6% of the total.

However, after considering the frequency of occurrences, it is important to consider the incidence as well, taking into account the number of workers in each logistic area. Hence, the incidence rate that refers to the ratio of the number of occurrences per 1000 employees over a year. Using incidence rates rather than frequency rates allows a better understanding about the most critical areas, since the number of employees is critical to determine this criticality. Thus, the number of workers in each logistic area is presented in Table 14.

Table 14. Number of workers in logistic areas

| **Logistic area** | **Number of workers** |
|---|---|
| Incoming | 38 |
| Internal logistics | 150 |
| Shipping | 62 |

Bearing in mind that the occurrence analysis has been made between 2012 and 2020 and there is no available data for 2015 and 2017, seven years have been considered in order to calculate the average incidence rate.

Thus, the frequency of occurrences during the period under study has been used to determine the average annual frequency of accidents and incidents for each logistic area. Afterwards, the incidence rate was calculated, resulting in the average number of occurrences per 1000 employees over a year.

The frequency of work-related accidents within logistic areas during the period under study and the average incidence rates are detailed in Table 15.

Table 15. Frequency and incidence rate of work-related accidents in logistic areas (2012-2020)

| **Logistic area** | **Accidents (2012-2020)** | |
|---|---|---|
| | **Frequency** | **Incidence rate** |
| Incoming | 6 | 23 |
| Internal logistics | 32 | 30 |
| Shipping | 3 | 7 |

It is possible to conclude that the logistic area that accounts the highest incidence rate is the internal logistics, where, in average, occur 30 accidents per 1000 employees over a year. Furthermore, incoming area also presents a high incidence rate, with 23 accidents per 1000 employees within the same period.

Regarding the occurrence of work-related incidents within logistic areas, the information about frequency and average incidence rate is shown in Table 16.

Table 16. Frequency and incidence rate of work-related incidents in logistic areas (2012-2020)

| **Logistic area** | **Incidents (2012-2020)** | |
|---|---|---|
| | **Frequency** | **Incidence rate** |
| Incoming | 28 | 105 |
| Internal logistics | 79 | 75 |
| Shipping | 7 | 16 |

In this case, the highest incidence rate regards to incoming area, which accounts an average incidence rate of 105 incidents per 1000 employees over a year. Moreover, internal logistics area presents the second highest incidence rate, with 75 incidents per 1000 employees within the same period.

Therefore, similar to the conclusions drawn regarding frequency, the calculation of incidence rate for each logistic area shows that the least critical logistic area is shipping, while the two most critical area are incoming area and internal logistics.

The above-mentioned findings will be useful during the step 2.1 of this methodology (section 5.2.1), where the most critical logistic areas will be analysed, in order to understand and identify the main hazards associated with each activity performance within these areas.

### 5.1.2 Step 1.2: Identification of the most critical logistic processes

After identifying the critical logistic areas in the previous step, based on occurrences, it was crucial to analyse the data in order to identify the most critical logistic processes, that consist in the processes that account a higher frequency and incidence of occurrences during their execution.

There are some inconsistencies in the data obtained, since, in addition to not existing records for the years 2015 and 2017, a significant part of the records does not specify the process where the occurrence took place.

However, a study was carried out taking into account the occurrences with complete records available during the last years, between 2012 and 2020, which indicate the process that was being performed at the time of the occurrence. These data were used to carry out a quantitative analysis regarding the frequency and incidence rate of occurrences in each logistic process and draw conclusions about the most critical processes within logistics areas.

In order to carry out this analysis, logistic processes were categorised into five main types of activities: (1) materials handling; (2) transportation; (3) picking; (4) line supply and (5) load preparation. The Figure 46 shows the percentage of accidents and incidents that occurred during the performance of each process.

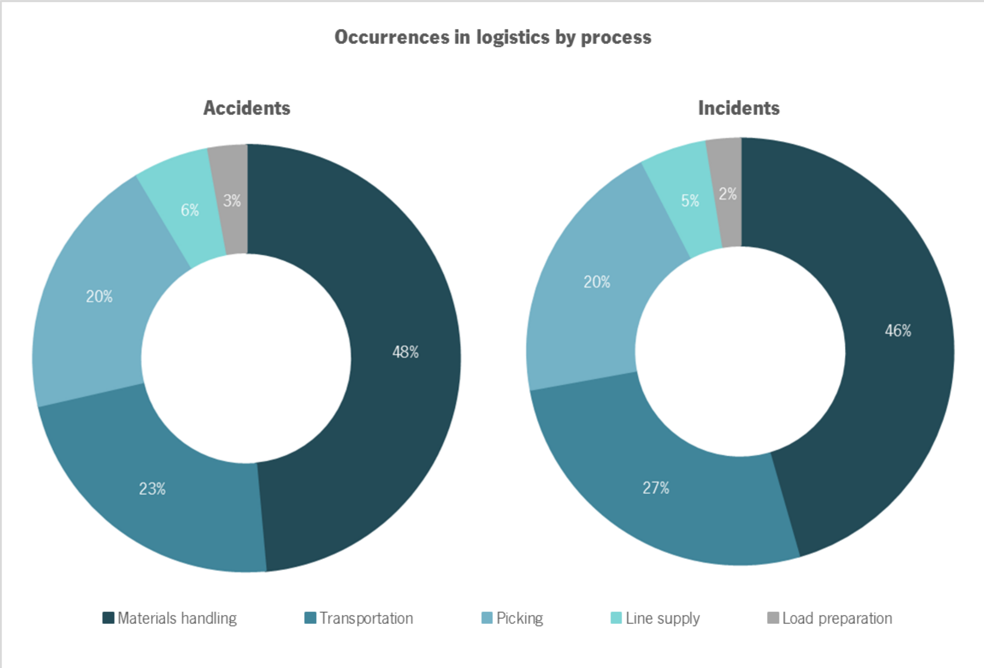

Figure 46. Percentage of occurrences in logistics by process (2012-2020)

The frequency of occurrences in each logistic process is consistent regarding to data on accidents and incidents, having a similar percentage for the same process and varying a few percentage points between the two types of occurrences. The process with the higher percentage of occurrences is materials handling, accounting 48% of the accidents and 46% of incidents that occurred during the last years.

The second highest frequency rate refers to transportation activities, that amount 23% of the total accidents and 27% of the total incidents that occurred over the last years. Picking activities also account a high percentage of occurrences within logistic areas, accounting 20% of the total for both occurrences. Lastly, activities that are related with line supply and load preparation represent 8% of total accidents and 7% of total incidents that occurred, which means that these two processes were not considered critical.

Hence, the most critical processes are materials handling, transportation and picking, accounting 91% of accidents and 93% of incidents that occurred between 2012 and 2020. Moreover, it is important to take into account that these three processes are transversal to every logistic area.

### 5.1.3 Step 1.3: Identification of the most common consequences

The last step of occurrences analysis consists in the identification of the most common consequences for workers who suffered an accident or incident. For this purpose, an analysis about the part of body injured and the type of injury was carried out. The Figure 47 shows the percentage of accidents and incidents that have resulted in each part of body injured.

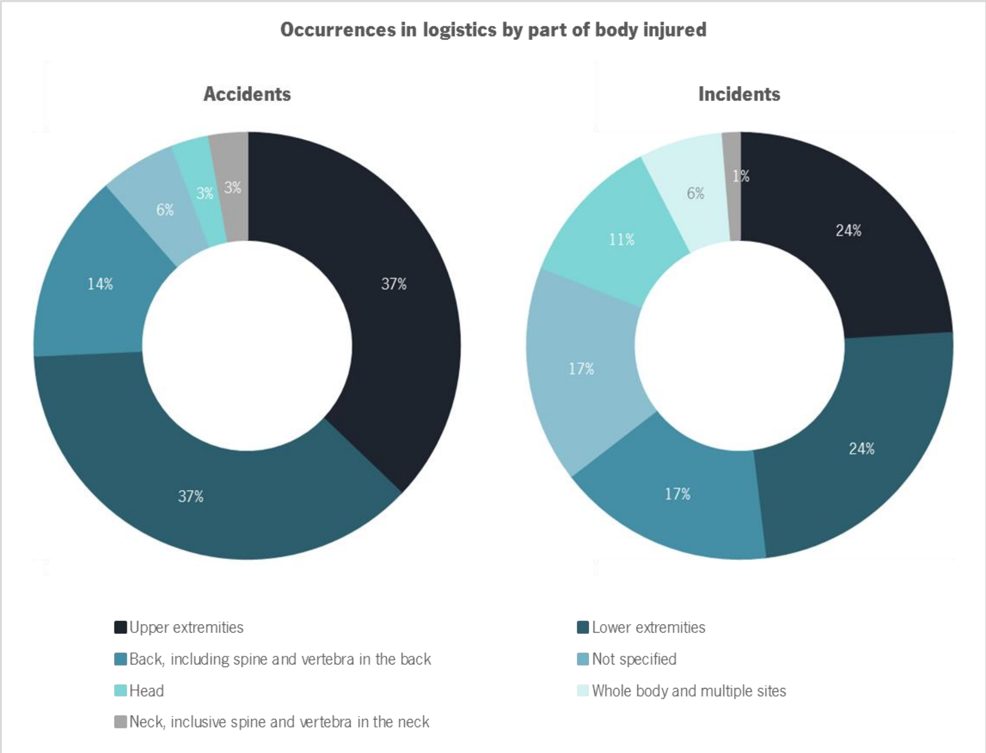


Figure 47. Percentage of occurrences in logistics by part of body injured (2012-2020)

The two highest rates regarding frequency of injuries occur on upper and lower extremities, since 37% of accidents and 24% of incidents have injured each of these two parts of body. Moreover, the third part of the body injured during occurrences is the back (injured on 14% of the total accidents and on 17% of the total incidents).

About 6% of the records for accidents and 17% for incidents do not specify the part of body that was injured, while the head accounts 3% of injuries during accidents and 11% during incidents. Workers were injured in the neck during 3% of accidents and 1% of incidents, while 6% of incidents have resulted in injuries over the whole body in multiple sites.

Thus, it is possible to conclude that occurrences result mostly in injuries on upper and lower extremities, as well as on the back. These three parts of body account 88% of total accidents and 65% of incidents that occurred over the last years within logistic areas.

Furthermore, the most common type of injury that results from accidents is dislocations, sprains and strains (40%), followed by wounds and superficial injuries (34%) and bone fractures (17%). Regarding incidents, 49% of them resulted in wounds and superficial injuries, while 27% caused dislocations, sprains and strains (Figure 48).

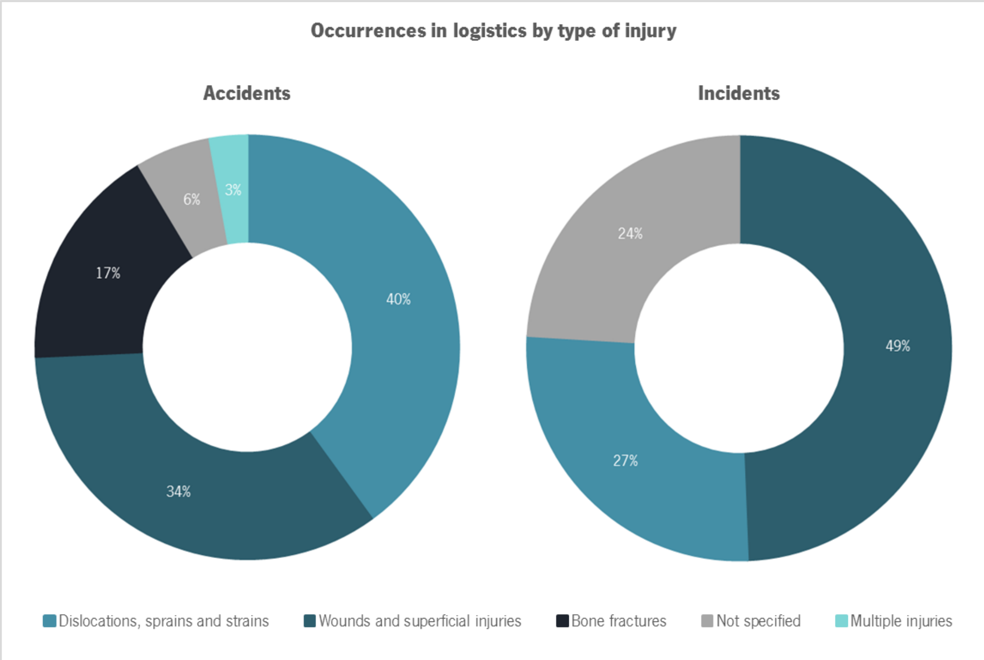


Figure 48. Percentage of occurrences in logistics by type of injury (2012-2020)

Hence, the biggest concerns regard occurrences that result in wounds and superficial injuries, as well as, in dislocations, sprains and strains. Taking into account the total occurrence of accidents (41) and incidents (114) between 2012 and 2020, it is possible to extrapolate this data and consider these numbers, concluding that about 14 accidents and 56 incidents have resulted in in wounds and superficial injuries, while dislocations, sprains and strains were the main consequence of 16 accidents and 30 incidents. Regarding to bone fractures, it was the result of about seven accidents, while only one accident resulted in multiple injuries over the last years.

### 5.1.4 Step 1.4: Conclusions and identification of improvement potential

The analysis of the available data regarding occurrences in logistics workplaces has shown an unambiguous identification of the most critical logistic areas, namely, internal logistics and incoming. Hence, the next step of this methodology, which consists in the OSH risk evaluation and mitigation measures (phase 2 – section 5.2), was focused on these two critical areas. Despite the area of shipping having registered a significant number of occurrences in the last years, it concerns only 6% of the total occurrences in logistics, reason why it was not included in the next step.

Furthermore, it was possible to conclude that processes with higher frequency of occurrences comprise materials handling, transportation activities and picking. This analysis would require more reliable data, since some of the records do not specify the activity that was being carried out at the time of the occurrence. However, taking into account the occurrences registered correctly, it was possible to extrapolate these values, obtaining the percentage of occurrences in each logistic process and concluding that the sum of these three above-mentioned processes represents a total of 91% in the case of accidents and 93% in case of incidents during the last years. These conclusions were essential to understand the processes that entail more risks, being further analysed, based on the consequences of occurrences, in order to understand how the ergonomic conditions can be enhanced and risks can be mitigated.

Regarding the consequences of occurrences, the two highest rates of injuries occur on upper and lower extremities, accounting each of these two parts of body a total of 37% of accidents and 24% of incidents. Moreover, the most common types of injury that results from accidents is dislocations, sprains and strains (40%), as well as, wounds and superficial injuries (34%) and bone fractures (17%). On the other hand, 49% of the incidents resulted in wounds and superficial injuries, while 27% caused dislocations, sprains and strains over the last years.

In order to identify the improvement potential regarding the improvement of ergonomic conditions and mitigation of risks, it was crucial to establish a relationship between the execution of critical activities and the injuries and lesion that occurred during accidents and incidents. For this purpose, the three most critical processes identified in section 5.1.2 (materials handling, transportation and picking) were analysed, as well as the injuries that resulted from occurrences during these activities. Furthermore, these processes refer to lean wastes do not add value to the final product. The information about the percentage of type of injury that resulted from the total of accidents and incidents that occurred during the execution of each one of these critical processes is depicted in Table 17.

Table 17. Percentage of type of injury that resulted from total occurrences by critical process (2012-2020)

| **Critical process** | **Wounds and superficial injuries** | **Dislocations, sprains and strains** | **Bone fractures** | **Multiple injuries** | **Not specified** |
|---|---|---|---|---|---|
| Materials handling | 39% | 35% | 13% | 4% | 9% |
| Transportation | 42% | 34% | 4% | 0% | 21% |
| Picking | 59% | 27% | 3% | 0% | 21% |

Considering the total of accidents and incidents that occurred during the performance of materials handling activities, 39% of them resulted in wounds and superficial injuries, while 35% of these occurrences caused dislocations, sprains and strains to the involved workers. The occurrences during transportation activities resulted in in wounds and superficial injuries 42% of times and 34% caused dislocations, sprains and strains to workers. About 59% of the total of accidents and incidents that occurred within picking workplaces caused wounds and superficial injuries, while 27% of them resulted in dislocations, sprains and strains.

Assuming that wounds and superficial injuries, as well as bone fractures, are caused by materials drop, fall of the workers or even a collision with material, equipment or other workers, it is possible to affirm that this type of injury is caused by a wide range of risks that can be mitigated. In section 5.2, the related hazards will be further identified in a detailed way (step 2.1) and the risks categorised (step 2.2) and assessed (step 2.3) in order to understand which human senses and capabilities should be augmented (step 2.4) and propose solutions using AR to mitigate the risks (step 2.5).

On the other hand, inappropriate ergonomic conditions during the performance of critical processes, such as bad postures, excessive weight or materials stored at too high or too low levels, are the main cause of dislocations, sprains and strains at workplace, which indicate ergonomic issues and frequently leads to the development of permanent lesions and MSD.

The risk of developing MSD and the analysis of ergonomic conditions regarding to the most critical processes will be further analysed during the third phase of RAES-Log methodology (section 5.3), in order to quantify the ergonomic risk, understand the improvement potential and propose mitigation measures using AR technology solutions.

## 5.2 Phase 2: OSH risk evaluation and mitigation measures

After the occurrence analysis detailed in section 5.1, it is known which is the most critical area of logistics, that is the area with the highest frequency and incidence rate of accidents and incidents at work. Thus, it is on the most critical areas of logistics that the second phase of RAES-Log methodology focuses.

This phase consists in the OSH risk evaluation and proposal of mitigation measures using AR technology, starting with the identification of every hazard associated with each task performance (step 2.1 – section 5.2.1). Subsequently, the OSH risks are identified and further categorised, depending on their characteristics, main causes and nature (step 2.2 – section 5.2.2).

Moreover, the assessment of each risk is based on the product between the frequency and severity of the same occurrence, where the severity takes into account the potential for harm associated with the hazard and the frequency (or probability) takes into account the exposure to the hazard (step 2.3 – section 5.2.3). When the assessment of risks is completed, every risk is scored and prioritised, being crucial to identify which human senses and capabilities should be augmented in order to mitigate the identified risks (step 2.4 – section 5.2.4), especially the most critical ones, based on their score.

Finally, based on the selected human senses and capabilities to augment, the mitigation measures using AR technology are defined (step 2.5– section 5.2.5). The above-mentioned steps of OSH risk evaluation and mitigation measures are summarised in Figure 49.

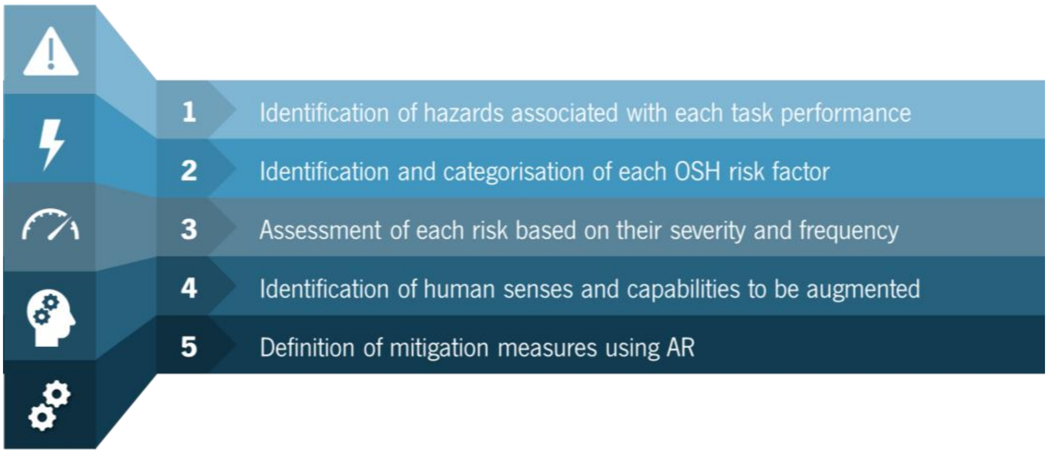


Figure 49. Steps of OSH risk evaluation and mitigation measures

The Table 18 provides an overview of the second phase of this methodology, presenting the required information to perform each step (inputs), as well as the methods applied during each process and the expected outputs or results. Hence, the steps of OSH risk assessment phase will be described in the sections below.

Table 18. Overview of inputs, methods and outputs of each step of OSH risk evaluation and mitigation measures

| Steps of phase 2 | Inputs | Methods | Outputs |
|---|---|---|---|
| Step 2.1: Identification of hazards associated with each task performance | • Critical logistic areas (step 1.1)<br>• Critical logistic processes (step 1.2) | • Qualitative analysis | • Hazards associated with each task performance |
| Step 2.2: Identification and categorisation of each OSH risk factor | • Hazards associated with each task performance (step 2.1) | • Qualitative analysis | • OSH risk factors |
| Step 2.3: Assessment of each risk based on their severity and frequency | • Ergonomic risk factors (step 2.2)<br>• Physical safety risk factors (step 22)<br>• Frequency of occurrences (step 1.2)<br>• Severity of occurrences (step 1.3) | • Quantitative analysis<br>• Qualitative analysis | • Activities with highest criticality for physical safety and ergonomic risk factors |
| Step 2.4: Identification of human senses and capabilities to be augmented | • Senses and capabilities that must be augmented to mitigate OSH risk factors | • Qualitative analysis<br>• Literature review | • Human senses and capabilities to be augmented |
| Step 2.5: Definition of mitigation measures using AR | • Human senses and capabilities to be augmented to mitigate physical safety risk factors (step 2.4)<br>• Available AR solutions | • Qualitative analysis<br>• Literature review | • Mitigation measures using AR for physical safety risk factors |

### 5.2.1 Step 2.1: Identification of hazards associated with each task performance

Based on the occurrence analysis, there are two most critical logistics areas identified in step 1.1 (section 5.1.1): (1) internal logistics and (2) incoming. For this reason, these two areas were given particular attention during this OSH risk assessment and are analysed in this section, in order to understand and identify the main hazards associated with each activity performance within these areas.

Thus, the activities executed in these two areas were identified and it was intended to understand what kind of materials were handled by employees during their performance. In addition, all the tools and substances involved were also identified using a checklist, as well as the logistic transportation equipment that are used in these areas and that are necessary for the execution of each of the logistic tasks.

After analysing all the activities that are performed in each critical logistic area, it was important to identify all the hazards associated with the execution of each task, in order to understand later what risks workers are exposed to in their workplaces.

This analysis has led to the conclusion that workers from internal logistics are mainly exposed to raw materials stored in cardboard boxes or plastic packages, pallets, frequently handling different size boxes and sometimes needing to use sharp tools to perform their tasks. Regarding transportation equipment, these workers have to use and share the same space as stackers, order pickers and trilateral stackers for warehousing activities, milk-runs, material carts, pallet trucks and, in some cases, forklifts (in repacking), hydraulics (in supermarkets) and AGV (in lines supply).

Moreover, the identification of the above-mentioned factors has allowed the identification of hazards associated with each activity within internal logistics area, which can be seen in Table 19.

Table 19. Identification of hazards associated with each task performance within internal logistics area

| Activity | Materials, tools and substances | Transportation equipment | Hazards associated with the activity |
|---|---|---|---|
| Warehousing | • Raw material packaging<br>• Pallets<br>• Different size boxes<br>• Pallet racks | • Forklifts<br>• Trilateral stackers<br>• Manual/ electric pallet trucks<br>• Order picker | Circulation of forklifts and similar vehicles<br>Circulation of people<br>Pallets stacking at different height levels<br>Verification and control of materials<br>Manual handling of loads<br>Picking<br>Put-away<br>Working environment conditions |
| Repacking | • Cardboard boxes with raw material<br>• Pallets<br>• Different size boxes<br>• Plastic packages<br>• Cutter | • Milk-runs<br>• Material carts<br>• Manual pallet trucks<br>• Forklifts | Circulation of forklifts, milk-runs and similar vehicles<br>Circulation of people<br>Verification and control of materials<br>Manual handling of loads<br>Pick up packages of different weights and sizes<br>Repack materials<br>Place boxes at different height levels<br>Working environment conditions |
| Final and SMD assembly supermarkets<br>Lines supply | • Different size boxes<br>• Plastic packages | • Milk-runs<br>• Material carts<br>• Manual pallet truck<br>• Hydraulics<br>• AGV | Circulation of milk-runs, AGV and material carts<br>Circulation of people<br>Verification and control of materials<br>Manual handling of loads<br>Pick up packages of different weights and sizes<br>Working environment conditions |

Furthermore, the above-mentioned four activities performed within internal logistics area include materials handling, picking and transportation processes, which are the three most critical processes identified during step 1.2 (section 5.1.2).

Alternatively, workers from incoming area are exposed to raw material packaging, finished product, pallets and different size boxes that they must store on pallet racks, in raw materials warehouse, or put them on material check stations. Concerning transportation equipment, there are a lot of vehicles and tools that are needed to perform these tasks, such as, forklifts, stackers, hydraulics, vacuum handles, strapping machines and roller ramps. In addition to having to use all this equipment to transport material, workers also have to share the area of their workstations with them during the execution of other tasks.

After analysing the above-mentioned characteristics of incoming area, it was possible to identify the main hazards associated with incoming activities, as shown in Table 20.

Table 20. Identification of hazards associated with each task performance within incoming area

| **Activity** | **Materials, tools and substances** | **Transportation equipment** | **Hazards associated with the activity** |
|---|---|---|---|
| Incoming | • Raw material packaging<br>• Chemical goods<br>• Pallets<br>• Different size boxes<br>• Finished product<br>• Material check stations<br>• Ladders | • Forklifts<br>• Stackers<br>• Electric/manual hydraulics<br>• Vacuum handle<br>• Automatic strapping machine<br>• Roller ramps | Circulation of forklifts and similar vehicles |
| | | | Circulation of people |
| | | | Verification and control of materials |
| | | | Manual handling of loads |
| | | | Exposure to chemical products |
| | | | Pick up packages of different weights and sizes |
| | | | Pallets stacking at different height levels |
| | | | Remove pallets from trucks |
| | | | Working environment conditions |

Hence, the above-mentioned activities performed within incoming area include materials handling and transportation processes, which are two of the most critical processes identified during step 1.2 (section 5.1.2).

Most of the identified hazards are transversal to all critical logistic areas and activities analysed, with the most common hazards being related to the circulation of vehicles and people, manual handling of materials and loads, exposure to chemical products, storing materials of different weights and sizes at different height levels and working environment conditions.

It is important to note that a hazard is understood as anything that can cause harm within a workplace, while a risk is the chance that any hazard causes somebody or something harm. For this reason, after identifying the hazards that can cause a harm to workers, it was crucial to understand the consequences, or risk factors, in which these hazards may result. The OSH risk factors will be identified and categorised in the next section.

### 5.2.2 Step 2.2: Identification and categorisation of each OSH risk factor

The second step of OSH risk evaluation is the identification and categorisation of OSH risk factors within the critical logistic areas previously identified in step 1.1 (section 5.1.1). The identification of hazards associated with each task performance, described in the previous section (step 2.1), has allowed the identification of OSH risk factors, that have been classified into six different categories: (1) physical safety; (2) ergonomics; (3) working environment; (4) chemical; (5) biological and (6) psychosocial, as shown in Table 21.

Table 21. Categorization of OSH risk factors

| **Category** | | **OSH risk factor** |
|---|---|---|
| Physical safety | Slips, trips or falls | Fall to the same level |
| | | Fall from height |
| | Circulation of vehicles and people | Running over |
| | | Collision |
| | | Entrapment |
| | | Squeeze |
| | | Crash against obstacle |
| | Objects and material drop | Hit by an object |
| | | Material drop |
| | | Collapse |
| | Contact with hazardous objects | Contact with sharp object |
| | | Contact with chemical goods |
| | | Electric Shock |
| Ergonomics | | Force |
| | | Working posture (Awkward posture/ Static posture) |
| | | Duration of exposure and repetitive movements |
| Working environment | | Fire |
| | | Thermal comfort |
| | | Vibration |
| | | Lightning |
| | | Total Particles and Dusts |
| | | Noise |
| Chemical | | Exposure to chemical products |
| | | Relative humidity |
| Biological | | Microbiological: Bacteria and Fungi |
| | | Epidemic / Pandemic |
| Psychosocial | | Stress |

Physical safety risks comprise biomechanical factors, such as traumas and injuries that result from slips, trips or falls to the same level or from height, as well as exposure to collisions with objects and equipment that can harm a certain part of the worker's body. Moreover, material drop, hazardous objects and electric shocks that can injury workers are included into this category. These risks may occur through direct exposure to hazardous situations that are divided into four categories: (1) slips, trips or falls of workers; (2) circulation of vehicles and people within the same place; (3) objects and materials drop; and (4) contact with hazardous objects.

The OSH risk factors associated to physical safety for each task will be identified and assessed in the following section (5.2.3) in the step 2.3, followed by the identification of human senses and capabilities to be augmented in order to mitigate these risks in step 2.4 (section 5.2.4) and the proposal of mitigation measures using AR in step 2.5 of this methodology (section 5.2.5).

Furthermore, ergonomic risks can result from several factors, such as the force applied during manual materials handling or the adopted working posture, being important to understand if workers adopt awkward postures, such as bending or arms far from the neutral position, during tasks performance, as well as the duration of exposure to such factors and the frequency and repetition of movements during the workday.

These OSH risk factors will be further assessed in the following step 2.3 (section 5.2.3), based on information about their severity and frequency, followed by the identification of human senses and capabilities to be augmented in order to mitigate these risks in step 2.4 (section 5.2.4) and the proposal of mitigation measures using AR in step 2.5 (section 5.2.5).

Furthermore, regarding ergonomic risk factors, it is crucial to consider the combination of risk factors, such as force, working postures, duration of exposure and frequency of movements, reason why the tasks with greater ergonomic risk levels and criticality will be further analysed using ergonomic risk assessment methods in section 5.3 and mitigation measures though the use of AR technology will be proposed.

Conversely, working environment refers to aspects of the physical work environment that can increase the risk for workers, including aspects such as, fire, temperature, noise, vibration, lighting or the presence of particles and dusts. Chemical risk factors regard to the exposure to chemical agents and the relative humidity of the workplace, while biological risk factors are related to microbiological factors and epidemic or pandemic situations. Finally, the psychological response of workers to their work and workplace conditions has influence on their health and, in this case, stress is referred to as one of psychosocial risk factors.

Although several risks of these four above-mentioned risk factors categories (work environment, chemical, biological and psychosocial) are associated to the performance of logistic tasks, the main aim of this methodology is the use of AR technology to mitigate physical safety and ergonomic risk factors. Hence, these four categories will not be further considered on the next steps of this methodology, since these are factors external to the workers and their behaviour and actions cannot directly contribute to their elimination or mitigation.

In this case, the application of technology will not have a direct impact on risk factors associated with the work environment, presence of chemical agents, biological and psychosocial risks, being these risks mainly associated with the design of workplaces. Although, organisations should take these risks into account and implement preventive measures when designing workplaces, in order to provide the best working environment conditions that reduce these risks, as well as, implement measures to minimise chemical, biological and psychosocial risk factors.

### 5.2.3 Step 2.3: Assessment of each risk based on their severity and frequency

The assessment of each risk has been based on the product between the frequency and severity of the same occurrence, giving result to the score that represents the criticality of the potential risk, which will define the acceptability criteria for each identified OSH risk factor.

Risk assessment involved the quantification of the risk of an incident, based on two main aspects: (1) the likelihood of a risk, or frequency; and (2) the impact or consequence of the risk occurring, or severity. Bearing the above-mentioned aspects in mind, the risk level of an activity represents the amount of injury that is expected to occur as a result of a potential work-related occurrence, being estimated by multiplying the severity and the frequency of an occurrence.

On the one hand, the frequency of exposure to hazardous conditions regards to the probability of a hazard occurring and originating a damage, being ranked also on a four-point scale, as follows: (1) low; (2) medium; (3) high and (4) very high. Regarding the frequency, this parameter has been defined taking into account the identification of the most critical processes and the number of and type of occurrences during the performance of each task, which has been analysed in step 1.2 (section 5.1.2).

On the other hand, the severity refers to the potential for harm associated with the hazard or risk factor, considering the possible consequences, the exposure to risk factors (taking into account legal exposure values or medical data for occupational diseases), as well as the fraction of workers that are at risk. Thus, severity of each risk factor refers to who might be harmed, describing the highest level of damage possible when an accident or incident occurs from a particular hazard.

Therefore, the severity of each OSH risk factor is based on the most common consequences and injuries of occurrences, analysed in step 1.3 (section 5.1.3). This methodology ranks the severity of an occurrence on a four-point scale, as follows: (1) minor; (2) moderate; (3) critical and (4) catastrophic.

The matrix used for this OSH risk assessment was based on and adapted from the existing matrices for this purpose, described in section 2.4.2, being a 4x4 matrix, with four levels of frequency and severity, further resulting in four risk levels, or criticality. These parameters, severity and frequency, have been standardised and broken down in the Table 22.

Table 22. Parameterisation of risk evaluation criteria

| Severity | | Frequency | |
|---|---|---|---|
| **1** (Minor) | • Accident without loss of capacity;<br>• Reduced exposure to risk factors<br>• Direct workers affected | **1** (Low) | Once a month or less |
| **2** (Moderate) | • Accident with temporary loss of capacity<br>• Moderate exposure to risk factors Direct workers and/or neighbouring jobs affected | **2** (Medium) | Weekly, occasional |
| **3** (Critical) | • Serious accident with loss of permanent capacity and/or loss of life and/or involvement of several people<br>• Moderate to high exposure to risk factors<br>• Direct workers and/or neighbouring jobs affected | **3** (High) | Daily |
| **4** (Catastrophic) | • Loss of life(s), high degree of material destruction<br>• Emergency situations (e.g., fire, explosion, fatal or very serious accident, leakage of gas or very harmful chemical).<br>• People across the organisation affected | **4** (Very high) | Frequent or continuous |

Thus, taking into account the above-mentioned parameterisation of risk evaluation criteria, assessment of the criticality of the potential risk was carried out taking into account the product between the frequency and severity of the same occurrence, as stated before. Therefore, the resulting scores, that represent the criticality of the potential risks can be assessed according to the hierarchy matrix presented in Table 23.

Table 23. Risk management and criticality of the potential risk hierarchy matrix

| | | **Frequency** | | | |
|---|---|---|---|---|---|
| | | Low | Medium | High | Very high |
| **Severity** | Minor | 1 | 2 | 3 | 4 |
| | Moderate | 2 | 4 | 6 | 8 |
| | Critical | 3 | 6 | 9 | 12 |
| | Catastrophic | 4 | 8 | 12 | 16 |

This matrix has been used to further prioritise risks based on their scores, following a traffic-light scheme and categorising criticality of OSH risk factors as extreme (red), high (orange), medium (yellow) and low (green).

According to the obtained results and criticality, risk factors are prioritised and the acceptability criteria has been established, in order to determine the actions and safety measures to be implemented to control risks and protect workers that are exposed to them, as well as the level of priority for implementing such measures and control risks.

Risk control can include design, planning and implementation of safety control measures, as well as training and providing additional information to workers. Furthermore, the acceptability criteria determine whether a risk should be fully eliminated or reduced and minimised through mitigation measures.

The defined acceptability criteria and necessary actions to reduce or eliminate OSH risk factors, based on the criticality, are depicted in Table 24.

Table 24. Acceptability criteria and necessary actions based on criticality of risk factors

| Criticality | Acceptability criteria | Necessary actions |
|---|---|---|
| Low | Low priority (Acceptable) | No further action and additional controls are necessary, unless they can be implemented at a very low cost, considering time, effort and investment. |
| Medium | Moderate priority (Should be lowered to be acceptable) | The risk factor should be considered and lowered to an acceptable level, taking into account the costs of additional measures. |
| High | High priority (Should be reduced to be acceptable) | Substantial efforts should be made and resources should be allocated to implement additional measures in order to reduce the risk to an acceptable level. |
| Extreme | Very high priority (Unacceptable) | Substantial improvements are immediately necessary in order to fully eliminate or reduce the risk to an acceptable level. |

After defining the criticality, acceptability criteria and necessary further actions the control risk factors, the tasks performed within the two most critical logistic areas have been analysed to identify the OSH risk factors associated to each task execution.

Afterwards, the risk assessment has been performed and every risk factor has been scored, based on their severity and frequency. The result of risk assessment is given by the product between these two parameters for the same occurrence and, based on the resulting scores, the criticality of each risk has been defined.

The first critical logistic area to be analysed was the internal logistics area, as identified in step 1.1 (section 5.1.1). This area comprises warehousing operations, repacking tasks, logistic activities within final and SMD assembly supermarkets and lines supply operations.

The risk assessment for warehousing tasks, has been performed, as shown in Table 25, considering every risk factor associated to the performance of such tasks, as well as their severity and frequency, which allowed the definition of the criticality level.

Table 25. Risk assessment for warehousing tasks (internal logistics area)

| Category | OSH Risk factors in warehousing tasks | Risk assessment | | | Criticality |
|---|---|---|---|---|---|
| | | Severity | Frequency | Result | |
| Physical safety | Fall to the same level | 2 | 3 | 6 | Medium |
| | Fall from height | 3 | 3 | 9 | High |
| | Running over | 2 | 3 | 6 | Medium |
| | Collison | 2 | 3 | 6 | Medium |
| | Entrapment | 2 | 3 | 6 | Medium |
| | Squeeze | 3 | 3 | 9 | High |
| | Crash against obstacle | 2 | 3 | 6 | Medium |
| | Hit by an object | 2 | 2 | 4 | Medium |
| | Material drop | 2 | 3 | 6 | Medium |
| | Collapse | 3 | 3 | 9 | High |
| | Contact with sharp object | 2 | 3 | 6 | Medium |
| | Electric Shock | 3 | 2 | 6 | Medium |
| Ergonomics | Force | 2 | 3 | 6 | Medium |
| | Working posture | 2 | 3 | 6 | Medium |
| | Duration of exposure and repetitive movements | 2 | 3 | 6 | Medium |

During warehousing tasks, the priority OSH risk factors due to its high level of criticality are mainly related to the storage of pallets in racks using trilateral stackers, which can lead to occurrences associated to squeeze between shelves and trilateral stacker, fall from height during picking and put-away operations, as well as collapse of material stored in shelves. These risk factors represent a high criticality, being urgent to allocate resources to implement additional measures to reduce the risks to an acceptable level.

Moreover, the remaining risk factors have been categorised with medium criticality level, which means that additional measures to lower them should be considered.

Additionally, the risk assessment for repacking tasks, based on the severity and frequency of the identified risk factors, and the definition of the criticality level for each identified OSH risk factor is presented in Table 26.

Table 26. Risk assessment for repacking tasks (internal logistics area)

| **Category** | **OSH Risk factors in repacking tasks** | **Risk assessment** | | | **Criticality** |
|---|---|---|---|---|---|
| | | **Severity** | **Frequency** | **Result** | |
| Physical safety | Fall to the same level | 2 | 3 | 6 | Medium |
| | Running over | 2 | 3 | 6 | Medium |
| | Collison | 2 | 3 | 6 | Medium |
| | Entrapment | 2 | 3 | 6 | Medium |
| | Crash against obstacle | 2 | 3 | 6 | Medium |
| | Hit by an object | 2 | 3 | 6 | Medium |
| | Material drop | 2 | 3 | 6 | Medium |
| | Contact with sharp object | 2 | 3 | 6 | Medium |
| Ergonomics | Force | 2 | 3 | 6 | Medium |
| | Working posture | 2 | 3 | 6 | Medium |
| | Duration of exposure and repetitive movements | 2 | 3 | 6 | Medium |

All the OSH risk factors identified during repacking tasks regarding physical safety and ergonomics represent a medium criticality level, which means that they should be taken into account and lowered to an acceptable level, considering the implementation of additional measures.

Furthermore, during the analysis of the tasks related to the internal logistics area, the existing OSH risk factors within final and SMD assembly supermarkets were also identified and scored, based on their severity and frequency, which allowed the determination of criticality level for each of them, information that is presented in Table 27.

During the performance of supermarket activities, the most worrying risk factors are related to the collision with transportation equipment that share the same workplace as workers, as well as, ergonomics, such as force or exertion, working postures and duration of exposure and frequency of repetitive movements. The above-mentioned risk factors represent a high level of criticality, which means that substantial efforts should be made in order to implement additional measures to reduce these risks to an acceptable level.

Table 27. Risk assessment for final and SMD assembly supermarkets tasks (internal logistics area)

| Category | OSH Risk factors in final and SMD assembly supermarket tasks | Risk assessment | | | Criticality |
|---|---|---|---|---|---|
| | | Severity | Frequency | Result | |
| Physical safety | Fall to the same level | 2 | 3 | 6 | Medium |
| | Running over | 2 | 3 | 6 | Medium |
| | Collision | 3 | 3 | 9 | High |
| | Crash against obstacle | 2 | 3 | 6 | Medium |
| | Hit by an object | 2 | 3 | 6 | Medium |
| | Material drop | 2 | 3 | 6 | Medium |
| | Contact with sharp object | 2 | 3 | 6 | Medium |
| | Electric Shock | 3 | 1 | 3 | Low |
| Ergonomics | Force | 2 | 4 | 8 | High |
| | Working posture | 2 | 4 | 8 | High |
| | Duration of exposure and repetitive movements | 2 | 4 | 8 | High |

Also, the majority of the remaining risk factors represent a medium level of criticality, being necessary to consider additional measures to lower them. Furthermore, there is a risk factor – electric shock – categorised with low criticality, which means that no further actions are necessary.

Moreover, activities within final and SMD assembly supermarkets represent high scores and criticality for ergonomic risk factors due to the high force demand and awkward working postures that workers need to adopt during picking operations, being further analysed using a suitable ergonomic risk assessment method during the third phase of this methodology (section 5.3.1).

Finally, the lines supply tasks in the area of internal logistics were analysed, considering the OSH risk factors associated to these tasks performance and considering their severity and frequency, which have resulted in a score and a criticality level for each risk, as shown in Table 28.

Table 28. Risk assessment for lines supply tasks (internal logistics area)

| Category | OSH Risk factors in lines supply tasks | Risk assessment | | | Criticality |
|---|---|---|---|---|---|
| | | Severity | Frequency | Result | |
| Physical safety | Fall to the same level | 2 | 2 | 4 | Medium |
| | Running over | 2 | 2 | 4 | Medium |
| | Collision | 3 | 2 | 6 | Medium |
| | Crash against obstacle | 2 | 2 | 4 | Medium |
| | Hit by an object | 2 | 2 | 4 | Medium |
| | Material drop | 2 | 2 | 4 | Medium |
| | Contact with sharp object | 2 | 2 | 4 | Medium |
| Ergonomics | Force | 2 | 3 | 6 | Medium |
| | Working posture | 2 | 3 | 6 | Medium |
| | Duration of exposure and repetitive movements | 2 | 3 | 6 | Medium |

Regarding line supply activities, the criticality of the identified OSH risk factors is medium for all of them, being necessary to consider the implementation of additional measures in order to lower them to an acceptable level of criticality.

Furthermore, the second critical logistic area identified in step 1.1 (section 5.1.1) was the incoming area, comprising incoming tasks. The risk assessment for such tasks, including the identification of OSH risk factors, scoring based on severity and frequency and definition of criticality level is depicted in Table 29.

Table 29. Risk assessment for incoming tasks (incoming area)

| Category | OSH Risk factors in incoming tasks | Risk assessment | | | Criticality |
|---|---|---|---|---|---|
| | | Severity | Frequency | Result | |
| Physical safety | Fall to the same level | 2 | 3 | 6 | Medium |
| | Running over | 2 | 3 | 6 | Medium |
| | Collison | 2 | 3 | 6 | Medium |
| | Entrapment | 2 | 3 | 6 | Medium |
| | Crash against obstacle | 2 | 3 | 6 | Medium |
| | Hit by an object | 2 | 3 | 6 | Medium |
| | Material drop | 2 | 3 | 6 | Medium |
| | Contact with sharp object | 2 | 3 | 6 | Medium |
| | Contact with chemical goods | 2 | 3 | 6 | Medium |
| Ergonomics | Force | 2 | 4 | 8 | High |
| | Working posture | 2 | 4 | 8 | High |
| | Duration of exposure and repetitive movements | 2 | 4 | 8 | High |

On the one hand, all the risk factors resulting from physical safety hazards are categorised with medium level of criticality, being necessary to lower them through the implementation of additional measures.

On the other hand, the risk factors associated to ergonomics represent a high criticality level, which means that it is crucial to allocate resources to immediately implement additional measures to reduce the risks to an acceptable level.

Furthermore, the incoming tasks represent high scores and criticality for ergonomic risk factors due to the high prevalence of lifting and lowering loads activities, which require high force demand and awkward working postures. These activities will be further analysed using a suitable ergonomic risk assessment method in phase 3 of RAES-Log methodology (section 5.3.2).

After identifying and prioritising each risk factor within the two most critical logistic areas – internal logistics and incoming area – the identification of the human senses and capabilities that should be augmented in order to mitigate them will be identified during the step 2.4 of this methodology, described in the following section.

### 5.2.4 Step 2.4: Identification of human senses and capabilities to be augmented

Based on the acceptability criteria defined in the previous section, OSH risk factors categorised with low criticality will not be further considered in this methodology, since these risks are considered acceptable and, due to their low priority, no further actions are necessary to control them. For this reason, risk factors categorised with medium, high or extreme criticality during step 2.3 described in the previous section, will be further analysed in this section in order to identify which human capabilities and senses should be augmented in order to reduce the risks to an acceptable level or even fully eliminate them.

The main aim is to augment human perception of space through the augmentation of senses, as well as the enhancement of worker's capabilities in order to avoid, mitigate or eliminate risks within logistic workplaces, increasing worker's awareness and perception of existing risks and improving their working conditions.

On the one hand, sensory augmentation consists in building an additional functionality, based on AR technology, and providing virtual signals that will be overlapped with physical environment, in order to enhance human natural senses, such as sight or hearing, allowing humans to identify relevant information and increase their awareness regarding risks within the workplaces. On the other hand, the enhancement of cognitive capabilities fosters the worker's ability to undertake mental tasks, such as memory, decision-making, responsiveness, perception, reasoning and awareness. Lastly, the augmentation of worker's physical capabilities relies on the use of equipment to safely move and lift more heavy items, providing improved ergonomic conditions, reduced injuries and work-related accidents.

Hence, an analysis was carried out about the human senses (sight and hearing) that, when augmented, have the potential to mitigate the identified OSH risk factors. Furthermore, such analysis also included two human capabilities (cognitive and physical) that can be enhanced to mitigate or eliminate these risk factors, as shown in Table 30.

Table 30. Senses and capabilities to be augmented in order to mitigate each OSH risk factor

| **Category** | | **OSH risk factor** | **Senses** | | **Capabilities** | |
|---|---|---|---|---|---|---|
| | | | Sight | Hearing | Cognitive | Physical |
| Physical safety | Slips, trips or falls | Fall to the same level | ● | | ● | |
| | | Fall from height | ● | | ● | |
| | Circulation of vehicles and people | Running over | ● | ● | ● | |
| | | Collision | ● | ● | ● | |
| | | Entrapment | ● | ● | ● | |
| | | Squeeze | ● | ● | ● | |
| | | Crash against obstacle | ● | ● | ● | |
| | Objects and material drop | Hit by an object | ● | | ● | |
| | | Material drop | ● | | ● | |
| | | Collapse | ● | | ● | |
| | Contact with hazardous objects | Contact with sharp object | ● | | ● | |
| | | Contact with chemical goods | ● | | ● | |
| | | Electric Shock | ● | | ● | |
| Ergonomics | | Force | ● | | ● | ● |
| | | Working posture | ● | | ● | ● |
| | | Duration of exposure and repetitive movements | ● | | ● | ● |

Regarding sensory augmentation, the enhancement of sight sense holds a great potential regarding the human perception of space, providing relevant information to workers. It is possible to increase their awareness about several risk factors, providing and visual safety alerts regarding:

- Slips, trips or falls: to reduce the number of occurrences due to falls to the same level or from height;
- Circulation of vehicles and people: to avoid running over other workers, objects, vehicles or equipment, collisions, entrapments and squeezes between people and vehicles, machines or shelves, as well as, crashes against obstacles;
- Objects and material drop: to increase awareness and attention of people towards the risk of being hit by an object, material drop or collapse from shelves;
- Contact with hazardous objects: to alert workers regarding the risk associated with the use of sharp objects, chemical goods and the risk of electrical shock, ensuring the compliance with all safety instructions;
- Ergonomics: to make sure that workers comply with all safety instructions during materials handling, use the correct equipment or tools and do not lift excessive weight.

Furthermore, the augmentation of the hearing sense has the potential to avoid several occurrences mainly related with circulation of vehicles and people, providing audio signals and warnings to increase the risks awareness of workers within logistic workplaces. This way, it would be possible to prevent running over situations, collisions and crashes between vehicles, people and objects, as well as, entrapments and squeezes between people and vehicles, machines or shelves.

Moreover, the definition of mitigation measures through the augmentation of sight and hearing senses will be dealt in detail during step 2.5 and described in sections 5.2.5.1 and 5.2.5.2, respectively.

The augmentation of cognitive capabilities can be useful and holds a huge potential to avoid or mitigate every identified safety and ergonomic risk, through the sharing of relevant information, such as, guidelines, best practices, safety procedures and work instructions with workers. This way, the provision of safety information will avoid hazardous situations, reducing behaviours that may result in an occurrence and improving the workers' awareness regarding risks within workplaces. Therefore, the step 2.5 of this methodology also comprises the definition of cognitive capabilities augmentation to mitigate risks, being described in section 5.2.5.3

Furthermore, in what concerns to physical capabilities augmentation, enhancing the workers' capacity to lift and lower heavier loads can reduce or even eliminate the prevalence of work-related MSD and injuries resulting from ergonomic risk factors. Thus, the augmentation of physical capabilities is approached during step 2.5 (section 5.2.5.4), however, it is dealt with more detail during the step 3.4 of the last and third phase of this methodology (section 5.3), after an extensive ergonomic risk assessment that intends to quantify the ergonomic risk associated to tasks performance.

### 5.2.5 Step 2.5: Definition of mitigation measures

After identifying the human senses and capabilities that should be augmented to mitigate physical safety and ergonomic risk factors, a clear definition of mitigation measures using AR technology to enhance such senses and capabilities will be summarized in this section.

Therefore, the enhancement of human senses and capabilities will not only allow the mitigation of risk factors within logistics workplaces, but will also increase the efficiency and productivity, reduce wastes at workplaces, as well as decrease the operation times.

However, the enhancement of ergonomic conditions and elimination of risks within the workplaces is the main focus of this project. For this purpose, it is crucial to ensure that workers are aware of the existence of risk and well informed about how to protect themselves and avoid occurrences and development of MSD.

Such measures are categorized into four domains, depending on the human sense or capability that is augmented through the implementation of these solutions: (1) sight sense; (2) hearing sense; (3) cognitive capabilities; and (4) physical capabilities.

#### 5.2.5.1 Augmentation of sight sense

AR technology can be used to extend human sight sense, creating a virtual environment that is superimposed on the physical work, allowing the collection of information. Most of the information is collect visually and this technology holds the potential to enhance sight sense, allowing people to see both digital and physical information, which is more information that what is naturally visible and available.

The use of AR solutions that can augment the natural human sight sense, such as HMD, HHD or SAR holds a huge potential regarding the enhancement of safety conditions within the workplaces. As mentioned before, these devices merge computer-generated information with the existing information within the physical environment.

Equipped with IoT and CPS technology and integrated with sensors placed at critical points in the workstation, such as vehicles and people, these devices are able to communicate with their users in real-time, providing information and warnings about the existing and imminent safety hazards, such as moving vehicles, circulation of people, falling objects and obstacle to avoid. Thus, in case operators are not paying attention or cannot see or hear the hazards coming, these devices can avoid collisions between machines and people, accidents or congestions.

Moreover, in order to ensure the correct understanding of the safety instructions and procedures, these devices provide hazard alerts in order to ensure that operators are fully aware of the risks within their workplaces, know how to protect themselves, how to correctly use the personal protection equipment and adopt appropriate working postures to avoid the development of work-related MSD.

For this purpose, the AR system can display warnings related to objects or processes, providing information about the safest way to handle the goods, the weight to be lifted, the equipment or tools that should be used in order to comply with safety procedures or the specifications of the process.

Additionally, a camera-based examination can provide information about the hazards associated to a specific object, in case of dangerous or chemical products, warning the workers regarding the local to place these objects, the safety distance to meet and comply with the safety procedures.

In addition to the sense of sight, these devices also play a crucial role regarding the augmentation of cognitive capabilities (detailed in section 5.2.5.3), providing relevant information to support the performance of logistic tasks. Hence, logistic workers can be provided with useful information about step-by-step work instructions, workload, material locations and fastest routes.

Moreover, HMD systems are usually used to provide dynamic navigation instructions to warehouse operators, allowing them to choose the best route to the target location, during picking or put-away operations, displaying a map of warehouse and the real-time updated traffic information. These solutions not only reduce the operations times, but also avoid congestions and work-related accidents. Additionally, the workers are exempted from memorizing all warehouse locations and these tasks are easier for new workers.

Furthermore, the cognitive load is decreased and the efficiency is increased through the provision of other relevant information about the products, processes and tasks, which also allows reduced operation times and shortened training process.

#### 5.2.5.2 Augmentation of hearing sense

The use of wearable AAR devices equipped with advanced technology and IoT to communicate in real-time, it is possible to enhance workers' safety conditions. For this purpose, devices or transportation vehicles are equipped with sensors that are able to recognize imminent safety hazards, such as vehicles, people, falling objects and obstacles whether or not people can see or hear them coming, avoiding collisions, accidents or congestion.

Additionally, AAR devices are usually wireless headphones that are useful to provide relevant information through audio signals and warnings on incoming safety hazards, safety instructions and workplace hazard alerts. These safety alerts would ensure that workers are aware of the existing risks and there is enough information about how to protect themselves, guaranteeing the correct assimilation of safety instructions, the accurate use of personal protection equipment and the adoption of appropriate working postures to avoid health problems.

Furthermore, similarly to augmentation of the sense of sight, these devices can also provide relevant information in order to augment cognitive capabilities (detailed in section 5.2.5.3) and support the performance of logistic tasks. For instance, information about work instructions, material locations, fastest routes, tasks to be performed and other relevant information about the products and tasks can be provided in order to improve efficiency, reduce operation times, shorten training process and decrease the cognitive and mental load of operators.

Moreover, AR can empower workers to hear and communicate with distant peers or even go beyond human-to-human voice communications, allowing humans to give instructions or request information from the machines around them. This technology also allows the enhancement of working conditions, blocking the extraneous background noise and allowing workers to clearly hear or recognize speech on a busy industrial environment, while keeping both hands free.

#### 5.2.5.3 Augmentation of cognitive capabilities

As stated in the previous sections, the augmentation of sight and hearing senses consist on the provision of warning or safety instructions, as well as, other relevant information that is transmitted to the employee with help of optical or acoustic signals.

Therefore, the provision of this information also fosters the augmentation of cognitive capabilities, since workers are more aware of the existence of risk and well informed about how to protect themselves and avoid health problems, complying with safety procedures, using correctly the protection equipment and adopting the correct working postures.

Thus, AR solutions hold the potential to enhance workers cognitive capabilities, improving decision-making processes, as well as worker’s perception, memory, reasoning and responsiveness, supporting workers during tasks execution that involve a high cognitive workload and allowing them to reduce their mental effort during several situations, as follows:

- Assimilate information;
- Memorize work instructions;
- Know all the tasks to perform;
- Detect errors or failures in processes;
- Know every product information to check;
- Know the specifications of each product and process;
- Find the fastest route during picking, put-away or lines supply and quickly find product locations;
- Pay attention to all existing risks at the workplace;
- Know and comply with all safety instructions.

Furthermore, the provision of relevant information about safety and instructions for handling goods and operation instructions can assist the learning phase and support the training of new employees, helping them to overcome competency and skills inequalities, making the existing information accessible to every employee, regardless their knowledge or language.

#### 5.2.5.4 Augmentation of physical capabilities

The augmentation of physical capabilities intends to mitigate the ergonomic risks identified and evaluated over this section. For this purpose, it is crucial to enhance physical capabilities of workers in order to reduce the physical loads, fatigue and risk of injury and MSD, as well as improve their ergonomic conditions and eliminate awkward postures during tasks performance. The introduction of exoskeletons to augment physical capabilities, creating super-strength operators, is a possible mitigation measure within AR technology field that will increase physical capabilities, allowing operators to lift and lower heavier loads, that would not be possible without the use of this equipment.

Furthermore, workers use heavy equipment to perform picking and put-aways tasks, such as PDA. These devices could be replaced by WWD, that are lighter and equipped with barcode reading functionality, which would decrease the physical overload and free the operators' hands, reducing the risk associated with carrying this equipment throughout the working day.

Therefore, the mitigation of ergonomic risk factors, such as the force exerted, adopted working postures, duration of exposure and frequency of repetitive movements, is the focus of these solutions based on the use of exoskeletons or even WWD in order to augment physical capabilities.

Hence, as mentioned during the assessment of risks, presented in step 2.3 (section 5.2.3), there are some logistic tasks that represent high scores and criticality for ergonomic risk factors. These tasks will be further analysed using a suitable ergonomic risk assessment method in phase 3 (section 5.3) in order to assess the need of using a suitable exoskeleton to reduce worker's physical workload.

#### 5.2.5.5 Summary of mitigation measures

The Table 31 presents a summary of the proposed mitigation measures and potential uses. These AR solutions depend on the nature of the hazards (identified during step 2.1 – section 5.2.1), the OSH risk factors (categorized during step 2.2 and assessed during step 2.3 – sections 5.2.2 and 5.2.3), as well as, the human senses and capabilities to be augmented (defined during step 2.4 – section 5.2.4).

Table 31. AR solutions and potential use to mitigate each OSH risk factor

<table>
<tr><th colspan="2">Category</th><th>OSH risk factor</th><th>Augmented senses or capabilities</th><th>AR Solution</th><th>Potential use</th></tr>
<tr><td rowspan="5">Physical safety</td><td>Slips, trips or falls</td><td>• Fall to the same level<br>• Fall from height</td><td>• Sight<br>• Cognitive</td><td>• HMD<br>• HHD<br>• SAR</td><td>• Display of safety information;<br>• Display of warnings;<br>• Camera-based recognition of hazards, steps or unevenness in the floor;</td></tr>
<tr><td rowspan="2">Circulation of vehicles and people</td><td rowspan="2">• Running over<br>• Collision<br>• Entrapment<br>• Squeeze<br>• Crash against obstacle</td><td>• Sight<br>• Cognitive</td><td>• HMD<br>• HHD<br>• SAR</td><td>• Display of safety information<br>• Camera-based recognition of vehicles, obstacles and people;<br>• Dynamic navigation instructions to choose the best route to the target location with the aid of displayed maps of warehouse and real-time traffic information in order to avoid accidents or congestion;</td></tr>
<tr><td>• Hearing<br>• Cognitive</td><td>• AAR</td><td>• Warning or safety instruction transmitted through acoustic signals;</td></tr>
<tr><td>Objects and material drop</td><td>• Hit by an object<br>• Material drop<br>• Collapse</td><td>• Sight<br>• Cognitive</td><td>• HMD<br>• HHD<br>• SAR</td><td>• Display of safety information;<br>• Display of warnings;<br>• Camera-based recognition of hazards and falling objects;</td></tr>
<tr><td>Contact with hazardous objects</td><td>• Contact with sharp object<br>• Contact with chemical goods<br>• Electric Shock</td><td>• Sight<br>• Cognitive</td><td>• HMD<br>• HHD<br>• SAR</td><td>• Display of safety information about objects, materials, substances and hazards<br>• Automated camera-based examination of hazardous goods and provision of object-related information, such as the safest way to handle them and safety procedures</td></tr>
<tr><td colspan="2" rowspan="2">Ergonomics</td><td rowspan="2">• Force<br>• Working posture<br>• Duration of exposure and repetitive movements</td><td>• Sight<br>• Cognitive</td><td>• HMD<br>• HHD<br>• SAR</td><td>• Display of safety information regarding maximum exerted force, correct working postures and ergonomic best practices<br>• Automated examination of goods and provision of object-related information, such as weight, safest way to handle them and equipment to use</td></tr>
<tr><td>• Physical</td><td>• WWD<br>• Exoskeleton</td><td>• Use of exoskeleton and WWD to decrease the workers' physical load and force exertion, while improving working postures</td></tr>
</table>

#### 5.2.5.6 Selection of the most suitable models for each AR solution

Moreover, depending on the task's nature and requirements, as well as the worker's needs, it is crucial to select the most suitable model for each proposed AR solution.

This decision-making process involves the establishment of criteria with different importance and alternatives to choose from. A possible approach to address this issue is the multi-criteria decision-making using the Analytic Hierarchy Process (AHP), proposed by Saaty (2004).

Wearable technology is crucial for keeping workers connected, productive and, most important: safe. However, it is essential to ensure that workers perform their tasks in the most comfortable as safest way, and, at the same time, ensure that the used technology meets the task requirements and workplace restrictions.

For this purpose, a list was created containing the key characteristics to be taken into account when making a decision about the model to choose for each of the proposed AR solutions. Concerning the augmentation of each sense or capability and the related AR solutions, the key characteristics to take into account regarding such technologies are depicted in Table 32.

Table 32. Key characteristics to take into account to select the most suitable models for each AR solution

| **AR Solution** | **Augmented senses or capabilities** | **Key characteristics** | |
|---|---|---|---|
| HMD<br>HHD<br>SAR | • Sight<br>• Cognitive | • Weight<br>• Battery Life;<br>• Connectivity;<br>• Durability and resistance to impact, heat, cold and water;<br>• Light conditions in workplace;<br>• Design and comfort; | • Field of view;<br>• Camera resolution;<br>• Microphone quality;<br>• Operating system;<br>• Do not limit the movements of workers;<br>• Equipment cost. |
| AAR | • Hearing<br>• Cognitive | • Weight<br>• Battery Life;<br>• Connectivity;<br>• Noise conditions in workplace;<br>• Design and comfort; | • Durability and resistance to impact, heat, cold and water;<br>• Do not disturb the users' daily activities;<br>• Equipment cost. |
| WWD | • Physical | • Weight;<br>• Reliability of data;<br>• Durability and resistance to impact, heat, cold and water; | • User interface and customization;<br>• Design and comfort;<br>• Do not disturb the users' daily activities;<br>• Equipment cost. |
| Exoskeletons | • Physical | • Weight;<br>• Durability and resistance to impact, heat, cold and water;<br>• User interface and intuitive use;<br>• Sizes and regulations to fit the device on specific users;<br>• Design and comfort;<br>• Breathable material and no overheating;<br>• Weight capacity of handling of loads; | • Contact area to distribute reaction forces without causing high force points;<br>• Shoulder and upper-limbs motion freedom;<br>• Absence of encumbrance or entanglement;<br>• Ease of cleaning;<br>• Does not interfere with body postures;<br>• Equipment cost. |

## 5.3 Phase 3: Ergonomic assessment and mitigation measures

In order to measure the risk factors within logistics workplaces that may lead to the development of MSD and injuries, an ergonomic risk assessment has been performed in the most critical operations. For this purpose, a methodology was proposed, in order to identify the main risk factors, as well as, the improvement potential for these operations and proposal of mitigation measures based on the use of AR technology. Thus, the third phase of RAES-Log methodology focuses on ergonomic risk assessment and mitigation measures, comprising four main steps during its deployment, which are depicted in Figure 50 and further explained in this section.

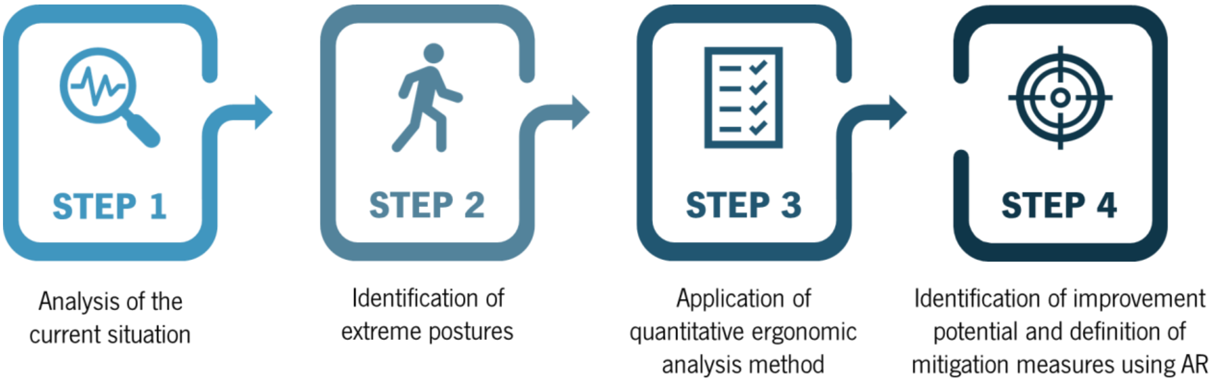


Figure 50. Steps of ergonomic risk assessment and mitigation measures

The first step (step 3.1) has been the analysis of the current situation made through observation, meetings, conversations with workers and supervisors as well as *gemba* walks. This was fundamentally to identify critical tasks, observation of task performance, measurement of shelves' dimensions or vertical and horizontal distance of hands when lifting or lowering a weight, material's weight, determination of tasks' frequency, as well as photographs and videos recording.

Afterwards, the critical dimensions have been measured and the different adopted postures have been analysed in order to evaluate body postures and quantify angular displacement, identifying extreme postures reached during the work cycle, such as bending or crouching movements due to low levels reaching (step 3.2). Furthermore, it is important to identify hands and arms above shoulder or head due to high levels reaching. Moreover, the lifting of heavy materials, which could represent a high physical workload to operators, were identified during this phase.

The third step of this phase (step 3.3) consists in the application of the quantitative ergonomic analysis method to support the assessment of workstations and tasks performance. There are several useful methods and approaches to evaluate the ergonomics of working conditions. The main aim of these quantitative approaches is to quantify the risk of musculoskeletal disorders associated to the performance of certain tasks. Each ergonomic analysis has been supported by the most suitable method considering the nature of tasks under study, frequency, applied forces, lifted weights and adopted postures. For this purpose, it is important to analyse the task in question, in order to determine which method is most suitable to analyse the task under study, taking into account their major characteristics and the most relevant limitations.

For instance, ergonomic analysis of tasks that require asymmetrical lifting and lowering tasks with both hands have been supported by NIOSH method, a hole-body workload assessment tool discussed in section 2.4.3.1, in order to determine the load that nearly all healthy workers could lift over a substantial period of time without risks (Waters et al., 1993).

On the other hand, ergonomic analyses of repetitive loads and cycling tasks have been supported by Ergonomic Assessment Worksheet (EAWS) method, discussed in section 2.4.3.2. According to Schaub et al. (2013), the EAWS comprises four different sections to evaluate ergonomic conditions of works. The first three sections regard to the whole-body evaluation, namely: working postures and movements with low additional physical efforts; action forces of the whole body or hand-finger system; and manual materials handling. In turn, the fourth section regards to repetitive loads of the upper limbs.

EAWS method has been applied in order to perform ergonomic analysis, quickly screening the adopted postures and assessing the risk associated to physical workload regarding whole-body and upper limbs. The critical postures adopted by workers during work cycle have been quantified concerning their duration in order to score them, as well as the weight of materials to handle, frequency, duration of cycles, forces applied and other factors, in order to conclude which may represent a risk for workers.

After the assessment of risk regarding whole body and upper limbs, it was possible to identify the main critical factors that may lead to discomforts, injuries, lesions or work-related MSD, as well as, the improvements potential and mitigation measures. Thus, the fourth and last step (4.4) of the third phase of this methodology consists in the identification of these factors, which will allow a further proposal of measures to avoid or mitigate them using AR technology, redesigning the system and improve the corresponding ergonomic conditions.

Moreover, the ergonomic risk assessment has been based on anthropometric percentiles, in order to consider the ergonomic differences between the two extremes: the smallest female and the tallest male workers. The individuals that participated in the study represent these two extremes within the case study and the stature of the female is 1520 mm and the stature of the male is 1815 mm. Based on anthropometric measures for adult Portuguese population (Barroso et al., 2005), the male individual's stature corresponds to $95^{th}$ male percentile. Since the Portuguese anthropometric database comprises only information about the $1^{st}$, $5^{th}$, $95^{th}$ and $99^{th}$ male and female percentiles, it was necessary to determine the percentile corresponding to the stature dimensions of the considered female individual. It was concluded that this stature corresponds to $25^{th}$ female percentile (Appendix I – Determination of the female percentile for a stature of 1520 mm).

Furthermore, it is important to take into account the stature or head level of each percentile under study, as well as the shoulders and knee heights. These values, based on anthropometric measures for adult Portuguese population (Barroso et al., 2005) are presented in Table 33. As mentioned before, the Portuguese anthropometric database does not comprise information about measurements of $25^{th}$ percentiles. The calculation of the dimensions for $25^{th}$ female percentile is presented on Appendix II – Calculation of anthropometric dimensions for $25^{th}$ female percentile.

Table 33. Stature, shoulders and knees height of percentiles under study

| **Dimensions** | **P25F** | **P95M** |
|---|---|---|
| Stature | 1520 mm | 1814 mm |
| Shoulders height | 1257 mm | 1501 mm |
| Knees height | 461 mm | 575 mm |

The Table 34 provides an overview of the third phase of this methodology, presenting the required information to perform each process, as well as the methods applied during each step and the expected outputs or results.

Table 34. Overview of inputs, methods and outputs of each step of ergonomic risk assessment and mitigation measures

| **Steps of phase 3** | **Inputs** | **Methods** | **Outputs** |
|---|---|---|---|
| Step 3.1: Analysis of the current situation | • Critical logistic process with highest prevalence of MSD-related injuries (step 1.3)<br>• Activities with highest criticality for ergonomic risk factors (step 2.3) | • Qualitative analysis | • Duration of exposure<br>• Frequency and repetition of movements<br>• Force demands |
| Step 3.2: Identification of extreme postures | • Dimensions of levels to be reached during tasks performance | • Quantitative analysis Qualitative analysis | • Adopted working postures |
| Step 3.3: Application of quantitative ergonomic analysis method | • Nature and characteristics of tasks<br>• Duration of exposure<br>• Frequency and repetition of movements<br>• Force demands | • Quantitative analysis | • Level of risk to which workers are exposed regarding ergonomic conditions (score) |
| Step 3.4: Identification of improvement potential and definition of mitigation measures using AR | • Capabilities to be augmented to mitigate ergonomic risk factors (step 2.4)<br>• Available AR solutions | • Qualitative analysis<br>• Literature review | • Mitigation measures using AR for ergonomic risk factors |

This ergonomic risk assessment methodology has been applied in several logistic operations within the case study in order to support the ergonomic analysis and risk assessment during the performance of the most critical tasks from an ergonomic point of view. The definition of these operations has been based on the processes with highest prevalence of MSD-related injuries, identified in section 5.1.4 (step 1.4) during occurrences analysis phase, as well as, the activities that represent high scores and criticality for ergonomic risk factors, identified in section 5.2.3 (step 2.3) during the phase of OSH risk evaluation. The processes identified with highest prevalence of MSD-related injuries during occurrences analysis were: (1) materials handling; (2) transportation; and (3) picking. After the OSH risk evaluation, it was concluded that the logistics activities that have scored higher results and criticality regarding ergonomic risk factors were mainly performed within; (1) supermarket for final assembly and SMD warehouse tasks in internal logistics area; and (2) incoming, located in incoming area. These activities will be further analysed in the next sections.

### 5.3.1 Application on picking operations

During the assessment of risk factors within internal logistics area (step 2.3), described in section 5.2.3, it was concluded that the activities that are performed in final and SMD assembly supermarkets represent the highest scores and criticality for ergonomic risk factors. This is mainly due to the high force demand and awkward postures adopted during picking operations.

After several observations over the time, process mapping and informal interviews made to managers, supervisors and employees of internal logistics within final and SMD assembly supermarkets areas, it was concluded that the most critical operations regarding ergonomic risks within internal logistics operations were mainly concentrated in the SMD warehouse area, where the picking operations of reels and PCB are performed to supply the SMD assembly area.

The conclusion of this analysis corroborates the conclusions obtained in step 1.4 of this methodology (section 5.1.4) during occurrences analysis phase, where it was defined that picking process was one of the most critical processes with highest prevalence of MSD-related injuries. Thus, the SMD warehouse comprises picking operations within two different areas – reels and PCB – which picking operations will be further analysed in what regards ergonomic risks.

In this section, the assessment carried out for reels' picking process is presented, following the four main steps of this third phase of methodology mentioned at the beginning of section 5.3, namely: (1) analysis of the current situation; (2) identification of extreme postures; (3) application of quantitative ergonomic analysis method; and (4) identification of improvement potential and definition of mitigation measures using AR.

However, the analysis carried out regarding picking operations within PCB area in SMD warehouse was very similar to the analysis performed within reels area and, for this reason, is presented in Appendix III – Application in PCB area of phase 3 (ergonomic assessment and mitigation measures for picking operations) .

#### 5.3.1.1 Step 3.1: Analysis of the current situation

The picking of reels occurs on reels area, where three types of shelves with different number of levels are located. The ergonomic analysis comprises the evaluation of every posture adopted considering every type of shelf. During picking operations, the operators have to reach different levels of shelves, many of them located above head or shoulder level as well as below knee level. For this reason, a study about the dimension of shelves levels has been carried out in order to identify critical postures. Figure 51 represents the stature, shoulder and knee height values for the 95th male and 25th female percentiles, as well as the three types of reels shelves, which corresponds to the different reel sizes (small, medium and large).

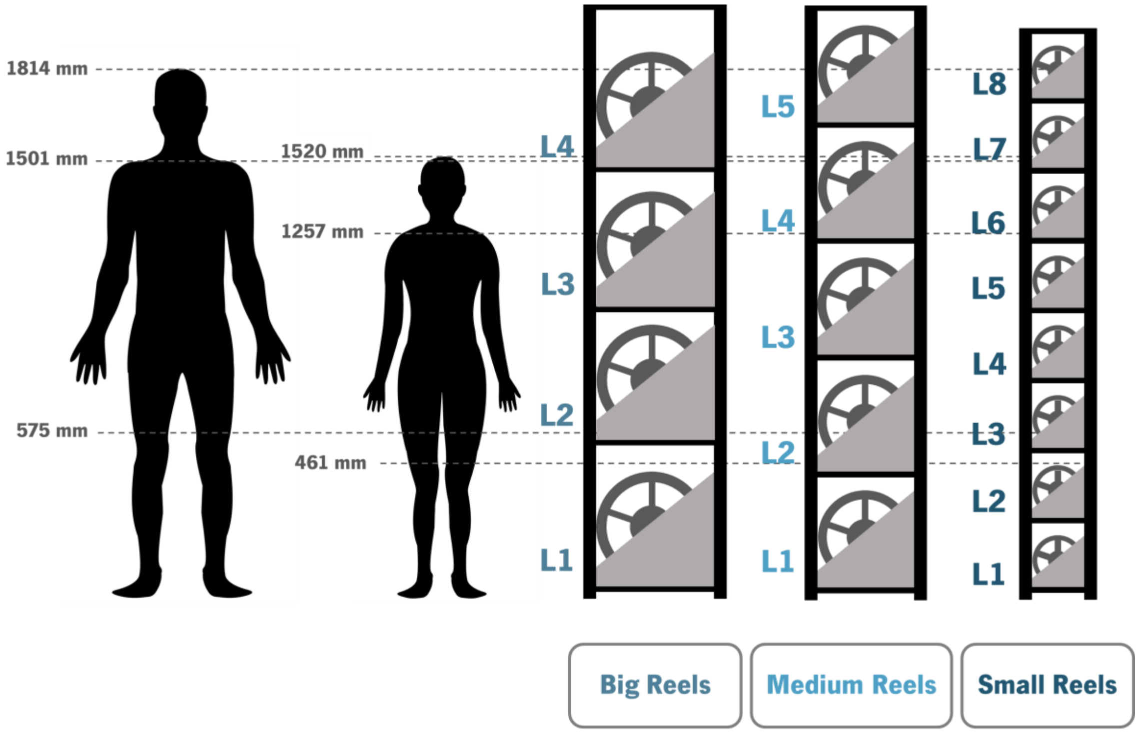


Figure 51. Representation of reels shelves levels (3 different sizes) with stature and shoulder height of 95th male percentile and 25th female percentile

It is important to analyse the measurement of each one of the shelves, in order to evaluate the posture adopted during picking at each level. The shelves have been measured and the reach level is the dimension considered for each level. Moreover, the materials to be handled were weighed (Figure 52) in order to assess the risk associated to picking process performance. Thus, a big reel weights 3 kg, while a medium weights 1.6 kg and the smaller one weights 0.2 kg.

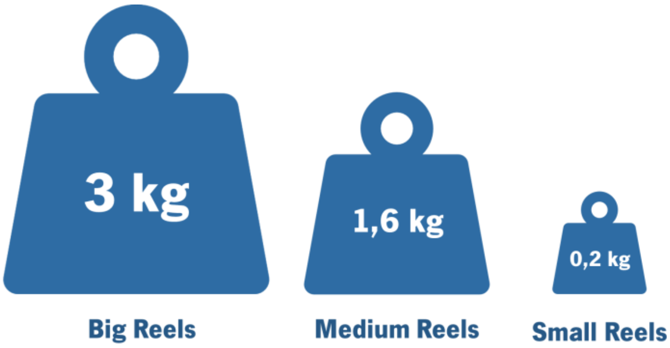


Figure 52. Reels weight

A cycle of picking lasts 20 minutes, with 23 cycles per day (460 minutes of workday). After a statistical study that was carried out covering a period of six months (between October 1st, 2020 and March 31st, 2021), it was concluded that the average number of reels picked in each cycle is 19. This means that, considering this average number and considering the worst-case scenario from an ergonomic point of view (collecting only the bigger and heaviest reels), the total weight of all materials collected can rise to 57 kg.

To the weight calculated above, the weight of the empty reel carriage, which is 65 kg, has to be added. Therefore, it can be considered that in a worst-case scenario, the operator will have to push a total of 122 kg during the reels picking route, which represents a total travelled distance of 464 m (Table 35).

Table 35. Data for reels picking process (per route cycle)

| | |
|---|---|
| **Duration** | 20 minutes |
| **Average number of reels picked** | 19 reels |
| **Total weight of reels (worst-case scenario)** | 57 kg |
| **Weight of reel carriage (empty)** | 65 kg |
| **Total weight (reels and carriage)** | 122 kg |
| **Travelled distance** | 464 m |

Furthermore, it is important to take into account that the operators carry PDA throughout the journey for each 20-minute cycle, which represents an additional load in the right hand of 400 grams during the whole workday.

Lastly, during a 20-minute cycle, there is a percentage of time that operators are standing and walking in alternation, pushing the reel carriage along the way. On the other hand, during the remaining time, they are performing the picking operations, collecting the reels from the shelves and adopting different postures, such as, upright, bending, kneeling or even with arms above head or shoulder level. The definition of these percentages is extremely important for the characterization of postures during the application of EAWS method. After analysing the recorded videos, it was possible to infer that 60% of the time in each 20-minute cycle is dedicated to the picking process, with operators spending the remaining 40% pushing the reels carriage. It means that, during the workday (460 minutes), the operator spends 184 minutes pushing the reels carriage that weights a total of 122 kg.

#### 5.3.1.2 Step 3.2: Identification of extreme postures

The analysis of the current situation allowed the identification of critical or extreme postures reached during the work cycle that can represent a risk for workers.

The shelves were modelled and every posture adopted during picking process was recorded or photographed. This allowed the analysis and evaluation of postures and the quantification of angular displacement of limbs during tasks performance.

The most critical postures are those that represent the greatest risk regarding ergonomics for the operator, such as reaching high levels that require the positioning of the arms above head or shoulder height or even reaching levels below knees height, which leads to bending, crouching or kneeling postures (Figure 53). For this reason, it is important to identify which selves' levels are above head and shoulders height as well as the ones that are below the knee's height to the percentiles under study (95$^{th}$ male and 25$^{th}$ female).

Figure 53. Unfavourable posture during picking process

The shelves where big reels are stored contain 4 different levels whose dimensions are represented in Figure 54, that shows the maximum and minimum dimensions and reach level. It is crucial to take into account that the dimension considered for each level is the reach level, which corresponds to the average value between the minimum and maximum levels of each shelf level. Analysing the figure, it is possible to conclude that there are higher and lower levels to reach that require the adoption of unfavourable postures.

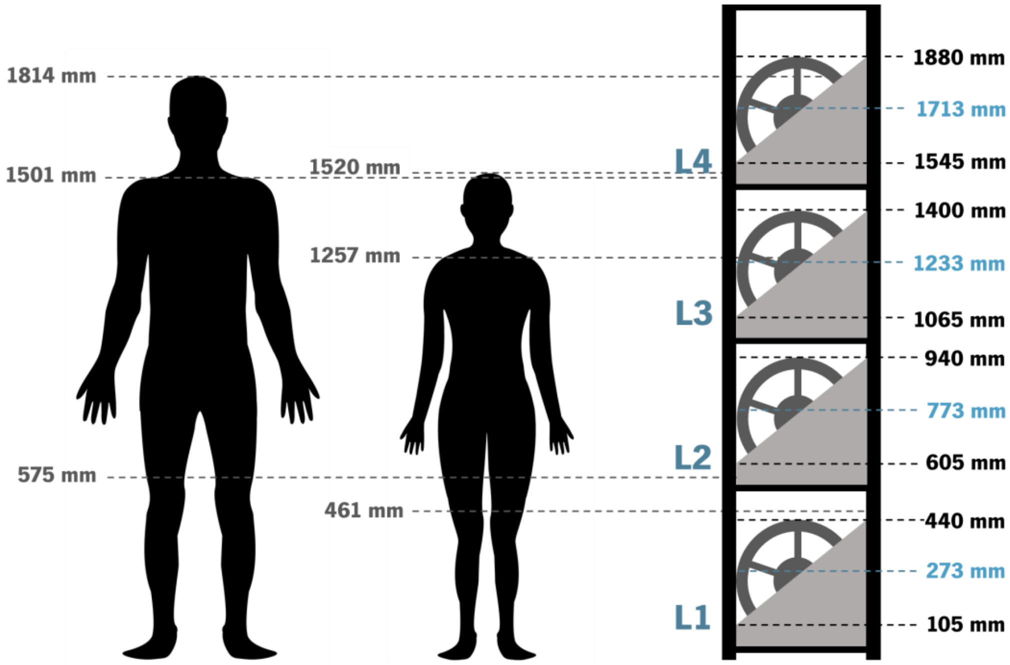


Figure 54. Dimensions of big reels shelves in comparison with stature and shoulder height of 95th male percentile and 25th female percentile

In the Table 36, the levels that require the adoption of inappropriate postures during the picking of big reels that are stored in a 4-level shelf are identified. The first level is lower than knees height for both percentiles under study.

Thus, reaching materials on this level requires the adoption of bending, crouching or kneeling postures. Reaching the fourth level is also critical because this level is higher than shoulder height in case of 95th male percentile and higher than head level in case of 25th female percentile.

Table 36. Unfavourable postures during the picking of big reels for 95th male percentile and 25th female percentile

| **Big Reels** | | | | | |
|---|---|---|---|---|---|
| **Shelf level** | | **L1** | **L2** | **L3** | **L4** |
| P95M | Above head level | | | | |
| | Above shoulder height | | | | x |
| | Bellow knee height | x | | | |
| P25F | Above head level | | | | x |
| | Above shoulder height | | | | |
| | Bellow knee height | x | | | |

Medium reels are stored in 5-level shelves, whose dimensions are represented in Figure 55, which shows the maximum and minimum dimensions and reach level. Like big reels shelves, there are higher and lower levels to reach that require the adoption of critical postures.

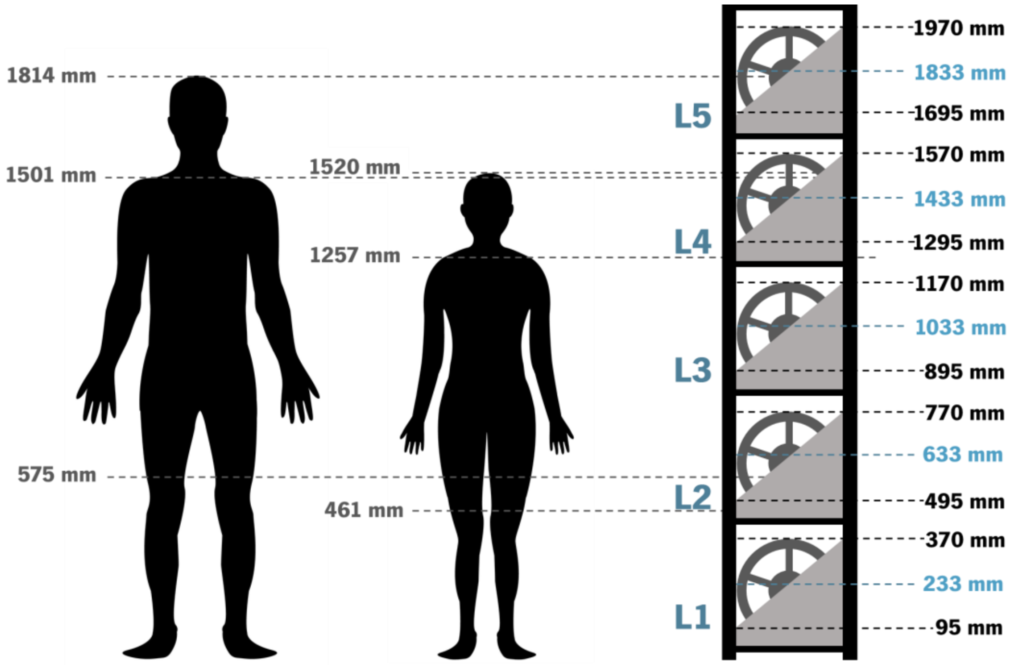


Figure 55. Dimensions of medium reels shelves in comparison with stature and shoulder height of 95th male percentile and 25th female percentile

In the Table 37, the levels that require the adoption of critical postures during the picking of medium reels in a 5-level shelf are outlined, considering the reach level. The first level is lower than knees height for both percentiles under study.

Consequently, picking reels on this level requires the adoption of bending, crouching or kneeling postures. Reaching the fourth level is critical for 25th female percentile, once it is higher than shoulder height. Furthermore, both percentiles under study adopt unfavourable postures when they reach the fifth level, since it is located above head level.

Table 37. Unfavourable postures during the picking of medium reels for 95th male percentile and 25th female percentile

| **Medium Reels** | | | | | | |
|---|---|---|---|---|---|---|
| **Shelf level** | | **L1** | **L2** | **L3** | **L4** | **L5** |
| P95M | Above head level | | | | | x |
| | Above shoulder height | | | | | |
| | Bellow knee height | x | | | | |
| P25F | Above head level | | | | | x |
| | Above shoulder height | | | | x | |
| | Bellow knee height | x | | | | |

Lastly, the smallest reels are stored in 8-level shelves, whose maximum and minimum dimensions and reach level are represented in Figure 56. Some levels require critical postures to be reached, such as the highest and lowest levels.

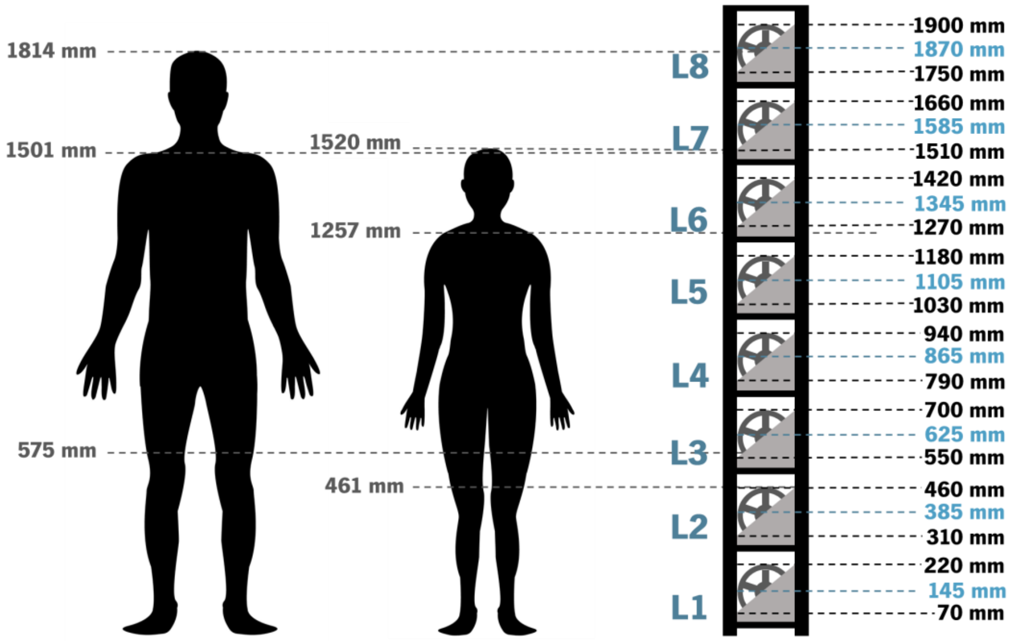


Figure 56. Dimensions of small reels shelves in comparison with stature and shoulder height of 95th male percentile and 25th female percentile

In the Table 38, it is possible to identify the levels that require the adoption of critical postures during the picking of small reels in a 8-level shelf, considering the reach level. The first and second levels are lower than knees height for both percentiles under study.

Table 38. Unfavourable postures during the picking of small reels for 95th male percentile and 25th female percentile

| Small Reels | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Shelf level** | | **L1** | **L2** | **L3** | **L4** | **L5** | **L6** | **L7** | **L8** |
| P95M | Above head level | | | | | | | | x |
| | Above shoulder height | | | | | | | x | |
| | Bellow knee height | x | x | | | | | | |
| P25F | Above head level | | | | | | | x | x |
| | Above shoulder height | | | | | | x | | |
| | Bellow knee height | x | x | | | | | | |

Therefore, picking reels on these levels requires the adoption of bending, crouching or kneeling postures. Reaching the sixth level is critical for 25th female percentile, since it is higher than shoulder height. The seventh level requires the adoption of critical postures, because it is higher than 25th female percentile's head level and higher than 95th male percentile's shoulder level. Furthermore, both percentiles under study adopt unfavourable postures when they reach the eighth level, since it is located above head level of both.

#### 5.3.1.3 Step 3.3: Application of quantitative ergonomic analysis method

This ergonomic analysis was supported by EAWS method, since this process includes repetitive loads and cycling tasks, being performed for the two percentiles under study (25th female and 95th male). EAWS comprises two main domains to evaluate: whole-body and upper limbs.

#### 5.3.1.3.1 Analysis of whole-body

The ergonomic analysis of whole-body contemplated two possible scenarios for the lower limbs (Figure 57) that are the adoption of a bending posture or, in contrast, the adoption of a kneeling and crouching posture when reaching the lowest levels.

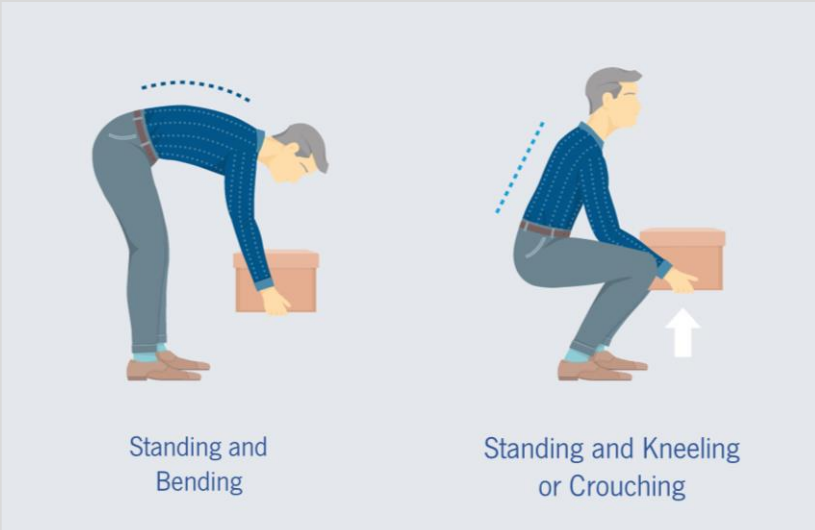


Figure 57. Two possible scenarios under study for reaching lower levels
(Adapted from: Rehab Concepts Physical Therapy (2021))

The first factors to take into account when evaluating the whole body is what percentage of the total time operators adopt each posture. As mentioned before, 40% of the time is spent upright standing and walking in alternation while pushing the carriage. During the remaining 60% of the time, operators can adopt a range of postures and some of them represent a high ergonomic risk. For this reason, it is crucial to assess the amount of time spent in unfavourable postures and try to avoid them.

This amount of time is expressed in percentage. These percentages were calculated based on assumption that the probability of picking each type of reel size is the same to the three types. Based on this, the probability of picking each one is 33.3%. In the case of big reels, this probability is divided by four levels (8.3% for each), five levels in case of medium reels (6.7% for each) and eight level for small reels (4.2% for each). It was assumed that the probability of picking is the same for all levels.

Furthermore, every posture adopted picking every level of shelves was photographed and analysed in order to evaluate the angular displacement of limbs, bending or kneeling postures and position of arms above shoulders or head height. The kind of posture adopted for each level is identified and the probability of occurrence picking on each level is multiplied by 60%, which is the percentage spent picking the reels.

The Table 39 presents the percentage of time spent adopting each posture in a scenario where operators are standing and adopting bending postures to reach lower levels for 25$^{th}$ female percentile.

Table 39. Postures and scores of 25th female percentile – standing and bending

| | | | | Standing | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Reel Size** | **Shelf Level** | **Probability of picking each reel size** | **Probability of picking each level** | **Bend, strongly forward >60º** | **Bend, slightly forward 20º -60º** | **Upright, no standing aid** | **Upright, with standing aid** | **Upright standing and walking in alternation** | **Upright, arms at or above shoulder height** | **Upright, arms above head level** |
| Big | 1 | 33.3% | 8.3% | 0% | 5% | 0% | 0% | 40% | 0% | 0% |
| | 2 | | 8.3% | 0% | 5% | 0% | 0% | | 0% | 0% |
| | 3 | | 8.3% | 0% | 0% | 5% | 0% | | 0% | 0% |
| | 4 | | 8.3% | 0% | 0% | 0.0% | 0% | | 0% | 5% |
| Medium | 1 | 33.3% | 6.7% | 4% | 0% | 0% | 0% | | 0% | 0% |
| | 2 | | 6.7% | 0% | 4% | 0% | 0% | | 0% | 0% |
| | 3 | | 6.7% | 0% | 0% | 4% | 0% | | 0% | 0% |
| | 4 | | 6.7% | 0% | 0% | 0% | 0% | | 4% | 0% |
| | 5 | | 6.7% | 0% | 0% | 0% | 0% | | 0% | 4% |
| Small | 1 | 33.3% | 4.2% | 2.5% | 0% | 0% | 0% | | 0% | 0% |
| | 2 | | 4.2% | 2.5% | 0% | 0% | 0% | | 0% | 0% |
| | 3 | | 4.2% | 0% | 2.5% | 0% | 0% | | 0% | 0% |
| | 4 | | 4.2% | 0% | 2.5% | 0% | 0% | | 0% | 0% |
| | 5 | | 4.2% | 0% | 0% | 2.5% | 0% | | 0% | 0% |
| | 6 | | 4.2% | 0% | 0% | 0% | 0% | | 2.5% | 0% |
| | 7 | | 4.2% | 0% | 0% | 0% | 0% | | 0% | 2.5% |
| | 8 | | 4.2% | 0% | 0% | 0% | 0% | | 0% | 2.5% |
| | | Total: | 100 % | 9% | 19% | 11.5% | 0% | 40% | 6.5% | 14.0% |
| | | | Score for each posture: | 6.4 | 8.7 | 1.5 | 0 | 1 | 5 | 17.5 |
| | | | Total postures score: | 40.1 points | | | | | | |

It is possible to conclude that the 25th female percentile is adopting unfavourable postures of arms during 20.5% of the time, which is around 94 minutes per working day. Unfavourable postures are those who require arms above shoulder or head level. Moreover, operators in this percentile spent around 129 minutes (28% of the time) adopting bending positions, which represent a risk, especially those with and angular displacement of trunk higher than 60°. The adoption of these postures makes a total score of 40.1 points.

It is possible to avoid most of bending positions, replacing them by kneeling and crouching positions to reach lower levels. Table 40 presents the scores for postures and the percentage of time spent adopting each posture in a scenario where operators are standing and adopting kneeling or crouching postures to reach lower levels for 25th female percentile.

Table 40. Postures and scores of 25th female percentile – standing and kneeling or crouching

| Reel Size | Shelf Level | Probability of picking each reel size | Probability of picking each level | Standing | | | | | | | Kneeling or crouching | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Bend, strongly forward >60º** | **Bend, slightly forward 20º -60º** | **Upright, no standing aid** | **Upright, with standing aid** | **Upright standing and walking in alternation** | **Upright, arms at or above shoulder height** | **Upright, arms above head level** | **Bent forward** | **Upright** | **Elbow at / above shoulder level (90º)** |
| | 1 | | 8.3% | 0% | 0% | 0% | 0% | | 0% | 0% | 5% | 0% | 0% |
| Big | 2 | 33.3% | 8.3% | 0% | 0% | 0% | 0% | | 0% | 0% | 0% | 5% | 0% |
| | 3 | | 8.3% | 0% | 0% | 5% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 4 | | 8.3% | 0% | 0% | 0% | 0% | | 0% | 5% | 0% | 0% | 0% |
| | 1 | | 6.7% | 0% | 0% | 0% | 0% | | 0% | 0% | 4% | 0% | 0% |
| | 2 | | 6.7% | 0% | 0% | 0% | 0% | | 0% | 0% | 4% | 0% | 0% |
| Medium | 3 | 33.3% | 6.7% | 0% | 0% | 4% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 4 | | 6.7% | 0% | 0% | 0% | 0% | | 4% | 0% | 0% | 0% | 0% |
| | 5 | | 6.7% | 0% | 0% | 0% | 0% | 40% | 0% | 4% | 0% | 0% | 0% |
| | 1 | | 4.2% | 0% | 0% | 0% | 0% | | 0% | 0% | 3% | 0% | 0% |
| | 2 | | 4.2% | 0% | 0% | 0% | 0% | | 0% | 0% | 3% | 0% | 0% |
| | 3 | | 4.2% | 0% | 0% | 0% | 0% | | 0% | 0% | 0% | 2.5% | 0% |
| Small | 4 | 33.3% | 4.2% | 0% | 2.5% | 0% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 5 | | 4.2% | 0% | 0% | 2.5% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 6 | | 4.2% | 0% | 0% | 0% | 0% | | 2.5% | 0% | 0% | 0% | 0% |
| | 7 | | 4.2% | 0% | 0% | 0% | 0% | | 0% | 2.5% | 0% | 0% | 0% |
| | 8 | | 4.2% | 0% | 0% | 0% | 0% | | 0% | 2.5% | 0% | 0% | 0% |
| | | Total: | 100% | 0% | 2.5% | 11.5% | 0% | 40% | 6.5% | 14% | 18% | 7.5% | 0% |
| | | | Score for each posture: | 0 | 3 | 1.5 | 0 | 1 | 5 | 17.5 | 16.9 | 5 | 0 |
| | | | Total postures score: | 49.9 points | | | | | | | | | |

In this case, operators of 25th female percentile spend the same amount of time with unfavourable postures of arms, however, bending postures are adopted only during 2.5% of the working time (11.5 minutes) and it is not with a strong angular displacement. However, kneeling and crouching postures are adopted during a considerable amount of time (117 minutes – 25.5% of the total working time) and it is important to take into account that the biggest percentage regards to a bending position while kneeling (18% – around 83 minutes), which is highly unfavourable regarding ergonomics. The final score for postures section in this scenario makes a total of 49.9 points, which is a worse score when compared to the standing and banding scenario for this percentile.

This analysis of both scenarios was replicated for 95th male percentile. Table 41 presents the amount of time spent adopting each posture in a scenario where operators are standing and adopting bending postures to reach lower levels for 95th male percentile, as well as the final scores for postures section.

Table 41. Postures and scores of 95th male percentile – standing and bending

| Reel Size | Shelf Level | Probability of picking each reel size | Probability of picking each level | Standing | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Bend, strongly forward >60º | Bend, slightly forward 20º -60º | Upright, no standing aid | Upright, with standing aid | Upright standing and walking in alternation | Upright, arms at or above shoulder height | Upright, arms above head level |
| Big | 1 | 33.3% | 8.3% | 5% | 0% | 0% | 0% | 40% | 0% | 0% |
| | 2 | | 8.3% | 0% | 5.0% | 0% | 0% | | 0% | 0% |
| | 3 | | 8.3% | 0% | 0% | 5% | 0% | | 0% | 0% |
| | 4 | | 8.3% | 0% | 0% | 0% | 0% | | 5% | 0% |
| Medium | 1 | 33.3% | 6.7% | 4% | 0% | 0% | 0% | | 0% | 0% |
| | 2 | | 6.7% | 0% | 4% | 0% | 0% | | 0% | 0% |
| | 3 | | 6.7% | 0% | 0% | 4% | 0% | | 0% | 0% |
| | 4 | | 6.7% | 0% | 0% | 4% | 0% | | 0% | 0% |
| | 5 | | 6.7% | 0% | 0% | 0% | 0% | | 0% | 4% |
| Small | 1 | 33.3% | 4.2% | 2.5% | 0% | 0% | 0% | | 0% | 0% |
| | 2 | | 4.2% | 2.5% | 0% | 0% | 0% | | 0% | 0% |
| | 3 | | 4.2% | 0% | 2.5% | 0% | 0% | | 0% | 0% |
| | 4 | | 4.2% | 0% | 2.5% | 0% | 0% | | 0% | 0% |
| | 5 | | 4.2% | 0% | 0% | 2.5% | 0% | | 0% | 0% |
| | 6 | | 4.2% | 0% | 0% | 2.5% | 0% | | 0% | 0% |
| | 7 | | 4.2% | 0% | 0% | 0% | 0% | | 2.5% | 0% |
| | 8 | | 4.2% | 0% | 0% | 0% | 0% | | 0% | 2.5% |
| Total: | | | 100% | 14% | 14% | 18% | 0% | 40% | 7.5% | 6.5% |
| Score for each posture: | | | | 11.1 | 6.5 | 2.5 | 0 | 1 | 5 | 8 |
| Total postures score: | | | | 34.1 points | | | | | | |

Operators of 95th male percentile are adopting bending positions during 28% of time (around 129 minutes per day), however the strong bend (higher than 60°) has increased in comparison with 25th female percentile. That is because 95th male percentile is higher and reaching lower positions requires a stronger bend.

Furthermore, this percentile is positioning their arms above shoulder or head level during 14% (64 minutes), which decreased in comparison with 25th female percentile, because these workers are higher and do not have difficulties in reaching higher levels. In total, these postures make a total of 34.1 points.

On the other hand, Table 42 presents the final scores for postures, as well as the percentage of time spent adopting each posture in a scenario where operators are standing and adopting kneeling or crouching postures to reach lower levels for 95th male percentile.

Table 42. Postures and scores of 95th male percentile – standing and kneeling or crouching

| | | | | **Standing** | | | | | | | **Kneeling or crouching** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Reel Size** | **Shelf Level** | **Probability of picking each reel size** | **Probability of picking each level** | **Bend, strongly forward >60º** | **Bend, slightly forward 20º -60º** | **Upright, no standing aid** | **Upright, with standing aid** | **Upright standing and walking in alternation** | **Upright, arms at or above shoulder height** | **Upright, arms above head level** | **Bent forward** | **Upright** | **Elbow at / above shoulder level (90º)** |
| Big | 1 | 33.3% | 8.3% | 0% | 0% | 0% | 0% | 40% | 0% | 0% | 5% | 0% | 0% |
| | 2 | | 8.3% | 0% | 0% | 0% | 0% | | 0% | 0% | 0% | 5% | 0% |
| | 3 | | 8.3% | 0% | 0% | 5% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 4 | | 8.3% | 0% | 0% | 0% | 0% | | 5% | 0% | 0% | 0% | 0% |
| Medium | 1 | 33.3% | 6.7% | 0% | 0% | 0% | 0% | | 0% | 0% | 4% | 0% | 0% |
| | 2 | | 6.7% | 0% | 0% | 0% | 0% | | 0% | 0% | 4% | 0% | 0% |
| | 3 | | 6.7% | 0% | 0% | 4% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 4 | | 6.7% | 0% | 0% | 4% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 5 | | 6.7% | 0% | 0% | 0% | 0% | | 0% | 4% | 0% | 0% | 0% |
| Small | 1 | 33.3% | 4.2% | 0% | 0% | 0% | 0% | | 0% | 0% | 2.5% | 0% | 0% |
| | 2 | | 4.2% | 0% | 0% | 0% | 0% | | 0% | 0% | 2.5% | 0% | 0% |
| | 3 | | 4.2% | 0% | 0% | 0% | 0% | | 0% | 0% | 2.5% | 0% | 0% |
| | 4 | | 4.2% | 0% | 2.5% | 0% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 5 | | 4.2% | 0% | 0% | 2.5% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 6 | | 4.2% | 0% | 0% | 2.5% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 7 | | 4.2% | 0% | 0% | 0% | 0% | | 2.5% | 0% | 0% | 0% | 0% |
| | 8 | | 4.2% | 0% | 0% | 0% | 0% | | 0% | 2.5% | 0% | 0% | 0% |
| Total: | | | 100% | 0% | 2.5% | 18% | 0% | 40% | 7.5% | 6.5% | 20.5% | 5% | 0% |
| Score for each posture: | | | | 0 | 3 | 2.5 | 0 | 1 | 5 | 8 | 19.3 | 5 | 0 |
| Total postures score: | | | | 43.8 points | | | | | | | | | |

In this case, operators of 95th male percentile spend the same amount of time with unfavourable postures of arms, however, bending postures are adopted only during 2.5% of the working time (11.5 minutes) and it is not with a strong angular displacement.

Nevertheless, kneeling and crouching postures are adopted during a considerable amount of time (117 minutes – 25.5% of the total working time) and it is important to take into account that the biggest percentage regards to a bending position while kneeling (20.5% – around 94 minutes), which is highly unfavourable regarding ergonomics. The adoption of these postures during the workday scores a total of 43.8 points.

The final scores for postures section considering each scenario for each percentile during reels' picking process are summarised in Table 43.

Table 43. Postures – total score for different scenarios during reels' picking

| Scenarios | Postures score |
|---|---|
| 25th female percentile – standing and bending | 40.1 |
| 25th female percentile – standing and kneeling or crouching | 49.9 |
| 95th male percentile – standing and bending | 34.1 |
| 95th male percentile – standing and kneeling or crouching | 43.8 |

After determining the percentage of time adopting each posture, it is important to consider the actions forces, which comprise the finger forces and the whole-body forces with no load. Action forces are not applicable to this analysis, adding no points to final score of whole-body analysis.

In what concerns to manual materials handling section, it is important to consider repositioning, holding and carrying operations, which regard to tasks with a duration of less than 5 seconds and a distance of less than 5 meters. Also, pushing and pulling operations (different analysis for less or more than 5 meters) are also very relevant for the analysis of manual materials handling.

For this ergonomic analysis, holding, carrying and pushing and pulling (<=5m) operations are not applicable. For this reason, just the repositioning operations and pushing and pulling (>5m) activities will be analysed in order to calculate the scores related with the performance of these actions during the workday. Figure 58 depicts and classifies the possible postures and positions of load into four categories, with a score associated (1, 2, 4 or 8 points).

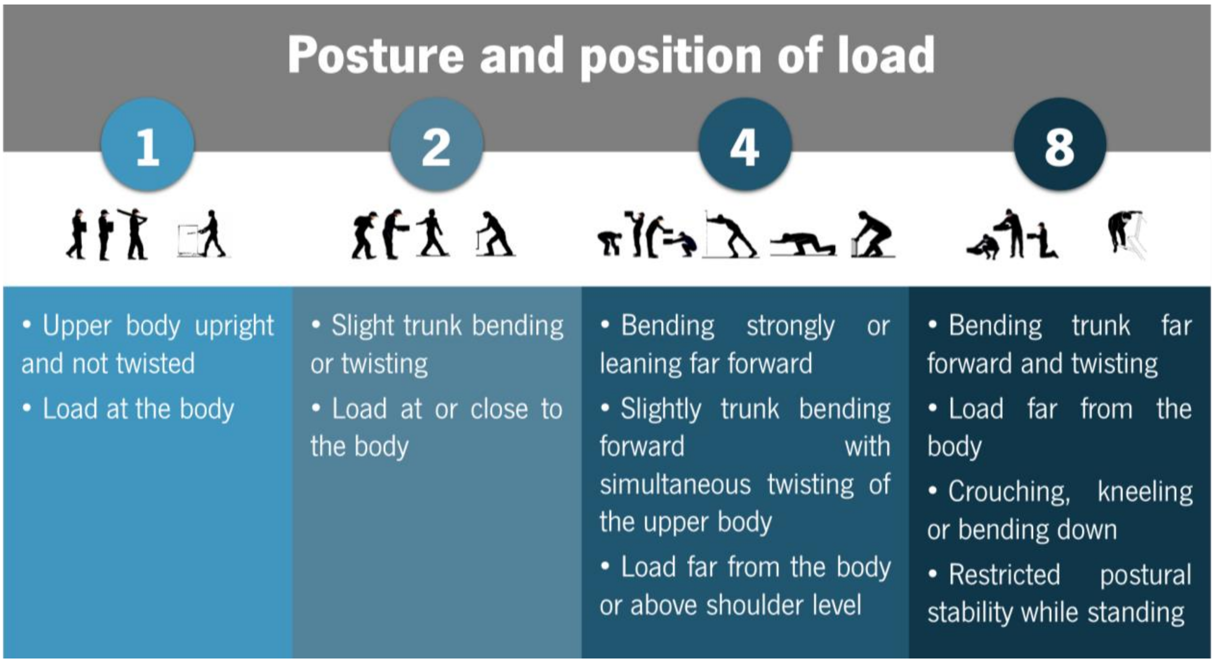

Figure 58. Posture and positions of load, score and descriptions

Before the calculation of the final score for repositioning operations in EAWS method, it is important to take into account that workers can adopt several postures and positions when loading weights that require further analysis. Hence, it is crucial to consider the postures and positions of load and assign an individual score to this parameter. For this purpose, the conclusions previously obtained regarding the amount of time spent adopting each posture in each scenario is essential to calculate this individual score.

After the identification of the amount of time spent adopting each posture in each scenario (previously calculated in postures section), it is important to consider that every possible adopted posture fits into one of that four categories of postures and positions of load that have a score associated (Table 44).

Table 44. Categories of each posture adopted by workers during picking operations

| **Posture adopted** | | **Category (score)** | **Description** |
|---|---|---|---|
| Standing | Bend, strongly forward >60° | Bending (4 points) | • Bending strongly or leaning far forward<br>• Slightly trunk bending forward with simultaneous twisting of the upper body<br>• Load far from the body or above shoulder level |
| | Bend, slightly forward 20°-60° | | |
| | Upright, no standing aid | Upright (2 points) | • Slight trunk bending or twisting<br>• Load at or close to the body |
| | Upright, with standing aid | | |
| | Upright standing and walking in alternation | | |
| | Upright, arms at or above shoulder height | Arms above shoulder or head (4 points) | • Bending strongly or leaning far forward<br>• Slightly trunk bending forward with simultaneous twisting of the upper body<br>• Load far from the body or above shoulder level |
| | Upright, arms above head level | | |
| Kneeling or crouching | Bent forward | Kneeling or crouching (8 points) | • Bending trunk far forward and twisting<br>• Load far from the body<br>• Crouching, kneeling or bending down<br>• Restricted postural stability while standing |
| | Upright | | |
| | Elbow at / above shoulder level (90°) | | |

For this purpose, a weighted calculation for every scenario is done, where each percentage of time spend adopting each posture is multiplied by the score associated to the category of postures and positions of load where it is categorised.

Hence, all weighted values for each scenario are added, resulting in an individual score for postures and positions of load, which, in turn, will be used to calculate the repositioning score.

Furthermore, during repositioning operations, workers can handle a load weight of 3 kg (which represents an individual score of 1.2 points for females and 1 point for males), at the worst scenario, with an average frequency of 19 reels per cycle (scored with 1.7 points).

The information regarding repositioning operations during manual materials handling, as well as the weighted calculation of postures and positions, and the scores for repositioning operations are summarised in Table 45 for 25th female percentile when adopting standing and bending postures to reach lower levels, resulting in a total score for repositioning operations of 7.1 points.

Table 45. Manual materials handling (repositioning operations) for 25th female percentile – standing and bending scenario in reels' picking

| Characteristics | Parameters | Score |
|---|---|---|
| Load weight when repositioning | 3 kg | 1.2 |
| Posture and position of load | 2 points × 51.5% (upright) = 1.03<br>4 points × 48.5% (bending and arms above shoulder or head) = 1.94 | 3 |
| Frequency of handling of loads | 19 reels | 1.7 |
| | Repositioning score = (load score + posture score) × frequency score | 7.1 |

In case of 25th female percentile adopting standing and kneeling postures, the final score for repositioning operations makes a total of 8.8 points and the individual scores are summarised in Table 46.

Table 46. Manual materials handling (repositioning operations) for 25th female percentile – standing and kneeling or crouching scenario in reels' picking

| Characteristics | Parameters | Score |
|---|---|---|
| Load weight when repositioning | 3 kg | 1.2 |
| Posture and position of load | 2 points × 51.5% (upright) = 1.03<br>4 points × 23% (bending and arms above shoulder or head) = 0.92<br>8 points × 25.5% (kneeling or crouching) = 2.04 | 4 |
| Frequency of handling of loads | 19 reels | 1.7 |
| | Repositioning score = (load score + posture score) × frequency score | 8.8 |

On the other hand, regarding workers from 95th male percentile, the information and parameters that concern to repositioning operations during manual materials handling are presented in Table 47 when standing and bending postures are adopted to reach lower levels, scoring a total of 6.5 points.

Table 47. Manual materials handling (repositioning operations) for 95th male percentile – standing and bending scenario in reels' picking

| Characteristics | Parameters | Score |
|---|---|---|
| Load weight when repositioning | 3 kg | 1 |
| Posture and position of load | 2 points × 58% (upright) = 1.16<br>4 points × 42% (bending and arms above shoulder or head) = 1.68 | 2.8 |
| Frequency of handling of loads | 19 reels | 1.7 |
| | Repositioning score = (load score + posture score) × frequency score | 6.5 |

The last scenario for repositioning operations regards to 95th male percentile, when the workers adopt standing and kneeling postures to reach lower levels. Making a total score of 8.3, the information and parameters that regard this scenario are presented in Table 48.

Table 48. Manual materials handling (repositioning operations) for 95th male percentile – standing and kneeling or crouching scenario in reels' picking

| Characteristics | Parameters | Score |
|---|---|---|
| Load weight when repositioning | 3 kg | 1 |
| Posture and position of load | 2 points × 58% (upright) = 1.16<br>4 points × 16.5% (bending and arms above shoulder or head) = 0.66<br>8 points × 25.5% (kneeling or crouching) = 2.04 | 3.9 |
| Frequency of handling of loads | 19 reels | 1.7 |
| | Repositioning score = (load score + posture score) × frequency score | 8.3 |

Furthermore, pushing and pulling (>5m) operations during manual material handling are relevant when workers are pushing the carriage along the way during each 20-minute cycle. It is crucial to take into account that the total load weight of the reels' carriage is 122 kg, pushing a trolley with two steering rollers and two fixed rollers with small resistance to rolling.

The distance is 464 meters and workers adopt postures that require trunk upright and load at the body. The final score calculated for these operations depends on the gender, since the score associated to the load weight varies from female to male workers. This information and respective scores are summarised in Table 49. Workers from 25th female percentile score a total of 3.8 points regarding pushing and pulling operations for distances longer than five meters, while workers from 95th male percentile make a total of 3.5 for the above-mentioned operations.

Table 49. Manual materials handling – pushing and pulling (>5m) operations in reels' picking

| **Characteristics** | **Parameters** | **Score** | |
|---|---|---|---|
| Load weight when pushing and pulling | 122 kg | F | 1.5 |
| Means of transport | Trolley with fixed rollers (0-2 steering rollers and 2-4 fixed rollers) | M | 1.3 |
| Posture and position of load | • Upper body upright and not twisted<br>• Load at the body | 1 | |
| Working Conditions by pushing and pulling | Small resistance to rolling | 0 | |
| Distance | 464 m | 1.5 | |
| Pushing and pulling (>5m) score =(load score + posture score + workplace conditions score) × distance score | | F | 3.8 |
| | | M | 3.5 |

In order to calculate the final score for manual materials handling section, it is necessary to add the scores of all operations that concern to this section. In this case, the score for repositioning and the score for pushing and pulling (>5m) operations must be considered.

The final scores for manual materials handling considering each scenario for each percentile under study are presented in Table 50.

Table 50. Manual materials handling – total score for different scenarios in reels' picking

| **Scenarios** | **Repositioning score** | **Pushing and pulling (>5m) score** | **Manual materials handling score** |
|---|---|---|---|
| 25th female percentile – standing and bending | 7.1 | 3.8 | 10.9 |
| 25th female percentile – standing and kneeling or crouching | 8.8 | 3.8 | 12.6 |
| 95th male percentile – standing and bending | 6.5 | 3.5 | 10 |
| 95th male percentile – standing and kneeling or crouching | 8.3 | 3.5 | 11.8 |

Finally, additional workloads consider joint positions of wrist, countershocks, impulses, vibrations, adverse effects by working on moving objects, accessibility factors or another physical workload. None of these factors are applicable to this analysis and no score was considered.

The Table 51 summarises the final scores regarding whole-body analysis for all scenarios, depicting the different sections previously analysed and their individual scores that were added together, giving rise to the final scores for whole-body.

Table 51. Whole-body – total score for different scenarios in reels' picking

| Scenarios | Postures score | Action forces score | Manual materials handling score | Additional workloads score | Whole-body score |
|---|---|---|---|---|---|
| $25^{th}$ female percentile – standing and bending | 40.1 | 0 | 10.9 | 0 | **51** |
| $25^{th}$ female percentile – standing and kneeling or crouching | 49.9 | 0 | 12.6 | 0 | **62.5** |
| $95^{th}$ male percentile – standing and bending | 34.1 | 0 | 10 | 0 | **44.1** |
| $95^{th}$ male percentile – standing and kneeling or crouching | 43.8 | 0 | 11.8 | 0 | **55.6** |

#### 5.3.1.3.2 Analysis of upper limbs

This analysis is transversal to both percentiles and scenarios and analyses de duration of tasks, force, posture of upper limbs and additional factors for repetitive tasks. The workday's duration is 480 minutes, however, it comprises 15 minutes of official breaks and 5 minutes for the daily meeting. Thus, the actual duration of picking tasks is 460 minutes. Each picking cycle lasts 20 minutes, which means that each operator performs a total of 23 picking cycles during the workday. These parameters regarding workload duration for repetitive tasks score a total of 7.7 points for upper limbs, which corresponds to the value of the net duration of repetitive tasks expressed in hours (460 min = 7.7 h).

Furthermore, there are two recovery periods longer than eight minutes along the workday, which makes an additional 0.5 point that will be subtracted from the previous score, and it is important to consider that work interruptions are possible anytime, which means that this parameter adds no points to final score. The total score for duration is 7.2 points and these values and related scores are presented in Table 52.

Table 52. Parameters and scores of duration section for reels' picking operations

| Parameters | | Values | Score |
|---|---|---|---|
| Duration of repetitive tasks | Duration of task (min) | 480 | 7.7 |
| | Official breaks (min) | 15 | |
| | Additional breaks (min) | 0 | |
| | Non-repetitive tasks (min) | 5 | |
| | Net duration of repetitive tasks (min) | 460 | |
| | Number of cycles | 23 | |
| | Net cycle time (seg) | 1200 | |
| | Measured cycle time (seg) | 1200 | |
| | Deviation of the net cycle time from the measured cycle time (%) | 0 | |
| Recovery | Number of recovery periods > 8 minutes | 2 | 0.5 |
| Work organisation | Work interruptions | Possible anytime | 0 |
| Duration score = Duration of repetitive tasks score + work organisation score – recovery breaks score | | | 7.2 |

Furthermore, the forces applied by upper limbs during tasks performance play an important role in ergonomic evaluation.

Every time a reel is picked up from the shelves, there are three dynamic real actions (reach, grab and place) assumed to be left-handed. At the worst case, the worker lifts a load of 3kg, which is the heaviest reel, with a force applied of 29N, calculated according to Newton's second law (Kosky et al., 2013), where the constant mass of the reel (3kg) is multiplied by its acceleration, which is given by the value of gravitational acceleration (9.8m/s2). A dynamic physical work includes all tasks that involve a movement or contraction of the force-exerting muscles. This action is not quantified in time of duration but in number of real actions. Once it comprises three real actions and the average number of picked reels is 19 per cycle with a total of 23 cycle throughout the workday, it is considered a total of 1311 real actions (3 real actions x 19 reels per cycle x 23 cycles).

During the picking operations of reels, operators are grabbing and pushing the carriage with both hands during 40% of the time, which represents a total of 184 minutes. This posture is considered static because a muscular strength is necessary to hold the carriage but there is no movement of upper limbs, being longer than four seconds. The force applied is 40N, which was measured by a dynamometer.

At the same time that a reel is reached, grabbed and placed in the carriage by left hand, the operator uses the right hand to screen the code on reel, carrying the PDA (Figure 59), which is a static action and represents an actual force of 4N (calculated according to the above-mentioned Newton's second law). This force is applied during the whole day (460 minutes), however, 60% of the working time (276 min) regards to this static action during picking, while the remaining 40% (184 min) concerns carrying the PDA while the carriage is being pushed through the SMD warehouse. For that reason, these 4N were added to the force applied by the right hand during the carriage pushing process, totalling a force of 44N during 184 minutes.

Figure 59. Operator scanning a reel's barcode with PDA

The information about the forces that are applied by upper limbs during reels' picking and related scores are presented in Table 53.

Table 53. Forces applied by upper limbs during reels' picking

| Description | Actual force (N) | Real action | Hand | Number (n) | Duration (min) | Forces score |
|---|---|---|---|---|---|---|
| Grab and push carriage | 40 | Static | Left | | 184 | 6.6 |
| Grab and push carriage and grab PDA during walking | 44 | Static | Right | | 184 | |
| Reach reel, grab (waiting for the PDA screening) and place in carriage | 29 | Dynamic (3) | Left | 1311 | | |
| Grab PDA during picking | 4 | Static | Right | | 276 | |

The final forces score is 6.6 points, which corresponds to the highest score between the two hands, which is the right-hand score in this case. This score was calculated based on a software used to apply EAWS method at case study.

The ergonomic evaluation of upper limbs contemplates the percentage of time adopting an awkward position of hand, forearm and elbow. In this case, reaching higher levels should be considered, when arms are at or above shoulder or head level. In case of $25^{th}$ female percentile, it occurs 20.5% of the time, while in case of $95^{th}$ male percentile, the postures represent 14% of the time. Moreover, the type of activity at or above shoulder height is relevant as well, which was considered unfavourable. This parameter adds no additional points to the final score, because the above-mentioned percentage is lower than 25%.

Additional factors were not considered in this analysis because of none of the risk factors were applicable for the operations under study, which does not add points to the final score of upper limbs.

The individual scores of each section of upper limbs analysis and the final score for upper limbs, which is the same to all scenarios and percentiles, are represented in Table 54.

Table 54. Upper limbs – total score for reels' picking operations

| Upper limbs section | Score |
|---|---|
| Duration | 7.2 |
| Forces | 6.6 |
| Posture (awkward position of hand, forearm and elbow/ activity at or above shoulder height) | 0 |
| Additional factors | 0 |
| Upper limbs score = (force score + posture score + additional factors score) × duration score | 47.52 |

#### 5.3.1.3.3 Final score

After analysing all the data described above for the whole-body and upper limbs, a final score is calculated, from which it is possible to draw some conclusions about the risk to which employees are exposed during reels picking operations. A score has been assigned to whole-body and upper limbs for each percentile and each scenario for reaching lower levels. The total score for whole-body is calculated as the sum of the allotted points for four sections: posture, manual materials handling, action forces and additional workload. On the other hand, the total score for upper limbs is provided by the evaluation of real actions, hand, arm and joint positions and the corresponding stresses of repetitive tasks. The risk of a possible health hazard is estimated considering the following categories depicted in Table 55.

Table 55. Points, risk area, meaning and colour

| Points | Risk area | Meaning | Colour |
|---|---|---|---|
| ≤25 | Low risk | Recommended: no corrective measures required. The risk of a disease or an injury is negligible or at an acceptably low level for the operation in question. | ● (green) |
| >25 - ≤50 | Possible risk | Not recommended: redesign or take actions to control the risk. A non-negligible risk of an injury or disease exists for the whole or a part of the operator population in question. | ● (yellow) |
| >50 | High risk | To be avoided: take actions to control the risk. The risk of an injury or disease is obvious and it is unacceptable to expose the operators in question to this risk. | ● (red) |

The final scores for the two different percentiles under study (25th female and 95th male) and for different scenarios are presented in Table 56. As mentioned before, the analysis considered two different scenarios for each percentile. The first scenario assumes that workers adopt a standing posture and bend the trunk to reach lower levels. On the other hand, the second scenario consist in the adoption of a standing posture and kneeling or crouching to reach lower levels. The two different scenarios only consider posture of trunk and lower limbs, being only applicable to the calculation of total score for whole-body.

Table 56. Total score for whole-body and upper limbs – Reels area in SMD warehouse

| Percentile | Part of the Body | Scenario (for lower levels) | Total Score |
|---|---|---|---|
| P25F | Whole-body | Standing (with bending) | 51.00 ● (red) |
| | | Standing and kneeling or crouching | 62.50 ● (red) |
| | Upper Limbs | | 47.52 ● (red) |
| P95M | Whole-body | Standing (with bending) | 44.10 ● (yellow) |
| | | Standing and kneeling or crouching | 55.60 ● (red) |
| | Upper Limbs | | 47.52 ● (red) |

After analysing the final scores, it was possible to conclude that almost every score represents a high risk for operators that perform reels picking operations and it is needed to take actions to control the risk.

Regarding to the evaluation of 25th female percentile, every part of body and every scenario represent a high risk. When this percentile adopt standing posture to perform picking operations and bend the trunk to reach lower levels, the final score for whole-body is very high (51.00 points), which can be justified by the unfavourable postures adopted during the workday, including arms above head and shoulders, picking in levels below knees and strong trunk bending.

On the other hand, when 25th female percentile adopts kneeling and crouching postures to reach lower levels, the final score for whole-body slightly worsens (62.50 points). Besides the unfavourable postures of arms above shoulders and head, trunk bending has been eliminated in this scenario. However, this method penalizes kneeling and crouching postures much more than bending postures. This is due to the fact that the right posture from an ergonomic point of view to reach lower levels is squatting (Figure 60), which is not adopted by workers during picking operations. Moreover, kneeling and crouching positions usually require trunk bending, which represents a high risk for operators.


Figure 60. Different postures to reach lower levels

With regard to 95th male percentile, when standing posture with bending to reach lower levels is adopted, the risk associated is moderated (44.10 points), which means that there is a risk and the process should be redesigned in order to avoid it. This final score can be justified by the high prevalence of lower levels, which requires frequent trunk bending postures. In comparison with the same scenario for 25th female percentile, the score has improved due to the fact that the individuals under study are higher, which results in a lower frequency of reaching higher levels, avoiding positioning arms above shoulder or head level.

In contrast, when 95th male percentile adopts kneeling and crouching postures to reach lower levels, the final score for whole-body increases (55.60 points), which represents a high risk for workers that perform these tasks. Once again, this method penalizes kneeling and crouching postures much more than bending postures because the correct posture to reach lower levels is squatting and adopting kneeling and crouching positions usually require trunk bending, which is not beneficial for operators. In comparison with the same scenario for 25th female percentile, the score has slightly improved due to the fact that the individuals under study are higher, and consequently, a lower frequency of reaching higher levels is required, avoiding positioning arms above shoulder or head level.

The evaluation of both percentiles under study is not favourable for upper limbs. The total score for both is 47.52 points, which means that there is a high risk for operators and measures have to be taken. The score is the same for both percentiles because this evaluation considers general information regardless the stature of workers, such as, duration of repetitive tasks, forces applied during task performance, unfavourable postures and other additional risk factors.

#### 5.3.1.4 Step 3.4: Identification of improvement potential and definition of mitigation measures

The negative scores that resulted from ergonomic evaluation through EAWS method can be justified by the high prevalence of extreme postures during reels picking operations. Extreme postures are characterized by postures that are required to reach higher levels, positioning arms above shoulder or head, and lower levels, above knees. That means that for 25th female percentile the shelves are higher than they should, especially the higher levels that require unfavourable postures of arms. On the other hand, for 95th male percentile, the lower levels are lower than they should, which requires a strong trunk bend and unfavourable kneeling and crouching postures.

In fact, reels picking operations in higher and lower levels are critical. If it were possible to eliminate extreme postures, positioning the shelves only at medium levels, the scores for the whole-body would be drastically reduced and a low risk would be associated to these tasks' performance.

Furthermore, carrying the PDA, that weights 400 grams, during the whole working day is a critical factor that highly increases the score and, consequently, the risk for upper limbs. An ergonomic analysis for upper limbs using EAWS was performed in order to assess the improvement potential if workers could perform the picking of reels without carrying this device for 460 minutes per day.

Thus, the individual scores of each section of upper limbs analysis and the final score for upper limbs when the use of PDA is eliminated are represented in Table 57. This score is transversal for every percentile under study and both scenarios for reaching lower levels.

Table 57. Upper limbs – total score for reels' picking operations without carrying PDA

| **Upper limbs section** | **Score** |
|---|---|
| Duration | 7.2 |
| Forces | 1.9 |
| Posture (awkward position of hand, forearm and elbow/ activity at or above shoulder height) | 0 |
| Additional factors | 0 |
| Upper limbs score =<br>(force score + posture score + additional factors score) × duration score | 13.68 |

Therefore, it is possible to conclude that the elimination of PDA significantly reduces the risk associated to upper limbs, since the previous score that considered the use this device was 47.52 (representing a high risk for workers) and the score calculated above is 13.68 points. This means that there is no corrective measures required, represented a low risk of a disease or an injury for operators. The comparison between the total score for upper limbs carrying and not carrying PDA, as well as the scores for whole body regarding both percentiles and both scenarios is presented in Table 58.

Table 58. Total score for whole body and upper limbs carrying and not carrying PDA – Reels area in SMD warehouse

| Percentile | Part of the Body | Scenario (for lower levels) | Total Score | |
|---|---|---|---|---|
| | | | **Carrying PDA** | **Not carrying PDA** |
| **P25F** | Whole Body | Standing (with bending) | 51.00 ● | |
| | | Standing and kneeling or crouching | 62.50 ● | |
| | Upper Limbs | | 47.52 ● | 13.68 ● |
| **P95M** | Whole Body | Standing (with bending) | 44.10 ● | |
| | | Standing and kneeling or crouching | 55.60 ● | |
| | Upper Limbs | | 47.52 ● | 13.68 ● |

Since the analysis carried out in the PCB area was similar to the quantitative ergonomic analysis in the reels area presented previously, the Table 59 shows the comparison between the total score for upper limbs carrying and not carrying PDA, as well as the scores for whole body regarding both percentiles and both scenarios. The obtained final scores regarding the current situation represent a possible risk for workers that perform PCB picking operations, thus, it is needed to take actions to control such risks in order to avoid a possible injury or disease associated to these tasks' performance.

Furthermore, the potential mitigation of ergonomic risk factors regarding upper limbs through the elimination of the use of PDA during the whole working day is also presented below. More details regarding to the quantitative ergonomic analysis carried out for picking operation within PCB are in SMD warehouse can be bound in Appendix III – Application in PCB area of phase 3 (ergonomic assessment and mitigation measures for picking operations) .

Table 59. Total score for whole body and upper limbs carrying and not carrying PDA – PCB area in SMD warehouse

| Percentile | Part of the Body | Scenario (for lower levels) | Total Score | |
|---|---|---|---|---|
| | | | **Carrying PDA** | **Not carrying PDA** |
| **P25F** | Whole Body | Standing (with bending) | 42.80 ● | |
| | | Standing and kneeling or crouching | 48.90 ● | |
| | Upper Limbs | | 43.92 ● | 16.56 ● |
| **P95M** | Whole Body | Standing (with bending) | 37.60 ● | |
| | | Standing and kneeling or crouching | 41.30 ● | |
| | Upper Limbs | | 43.92 ● | 16.56 ● |

Hence, similar to the reels area, the elimination of PDA within PCB picking operations can significantly reduce the risk associated to upper limbs, given that the previous score that considered the use of this device was 43.92 points. This represents a moderate risk for workers, and the score calculated above is 16.56 points, with no corrective measures required, since it represents a low risk for operators.

In short, the main ergonomic risk factors associated with the execution of picking tasks in SMD warehouse (reels and PCB areas), which represent a greater potential for improvement if they were eliminated or mitigated, are mainly related to the high prevalence of awkward postures to reach levels above head and shoulder height, as well as levels below the knee height.

Moreover, the high force demand and the repetitiveness of movements of the upper limbs during tasks performance represents a risk factor, since operators have to continuously handle heavy loads (3 kg for the heaviest reel and 6.2 kg for the heaviest PCB). Additionally, the use of PDA to scan barcodes in both areas throughout the day also represents a high risk for the upper limbs.

Therefore, the identified improvement potential for picking operations within SMD warehouse area, as well as the proposed mitigation measures using AR are presented in Table 60.

Table 60. Improvement potential in picking process in SMD warehouse and mitigation measures

| **Improvement potential** | **Mitigation measures using AR** |
|---|---|
| Use of PDA to read bar codes throughout the working day | • Use of a Wrist-Wearable Device or a ring bar code scanner<br>• Use of an HMD with barcode scanning functionality |
| Awkward postures | Use of a suitable exoskeleton that meets the task requirements and mitigates the associated ergonomic risk factors |
| Manual handling of heavy loads | |
| Repetitiveness of movements of the upper limbs | |

The use of a WWD equipped with barcode scanning functionality or a ring barcode scanner is a measure that can mitigate the risk to which the upper limbs are exposed due to the use of PDA, which weights 400 g, to scan barcodes throughout the working day (460 min). The use of this device will allow the decreasing of the ergonomic risk factors, such as injury and MSD development risks, through the augmentation of worker's physical capabilities, allowing them to scan barcodes without carrying a device during the whole day and perform their activities in a hands-free way.

Smart glasses and HMD cameras are usually equipped with barcode scanning functionality and could be used in order to enhance physical capabilities and mitigate risks associated to the prolonged use of PDA in workplaces. However, as stated in section 2.5.3.1, external scanners, such as WWD or ring barcode scanners provide a faster and more reliable and ergonomic solution, since the use of HMD or smart glasses involves some issues, especially when product are stored at a ground-level shelf and workers have to bend until the camera is able to scan the products.

Nevertheless, the selection of the most suitable model of WWD or HMD with barcode scanning functionalities to enhance physical capabilities and mitigate risks associated to the continued use of PDA in workplaces requires and extensive analysis, considering the existing equipment, characteristics and functionalities, as well as the task's nature and requirements. For this purpose, the selection of the most suitable model to perform picking operations and mitigate the associated ergonomic risk factors for upper limbs should be subjected to a multi-criteria analysis, considering these factors and ensuring the safety and comfort for workers that will these devices during the whole working day, according to the key characteristics defined in section 5.2.5.6.

Furthermore, the augmentation of physical capabilities intends to mitigate every risk regarding ergonomic conditions. As mentioned in section 5.2.5.4 (step 2.5), it is crucial to enhance physical capabilities of workers in order to eliminate awkward postures and reduce the physical loads, fatigue and risk of injury and MSD. The use of a suitable exoskeleton that meets the task requirements will allow the mitigation of ergonomic risks associated to the adoption of awkward postures during picking operations, enhancing worker's physical capabilities and allowing operators to lift and lower heavier loads, that would not be possible without the use of this equipment.

However, the selection of the most suitable exoskeleton to enhance physical capabilities in workplaces requires and extensive analysis, considering the characteristics of the equipment, ergonomic analysis, risk factors and the task's nature and requirements. For this purpose, the selection of the most suitable exoskeleton model to perform picking operations and mitigate the associated ergonomic risk factors should follow the key characteristics defined in Table 32, presented in section 5.2.5.6.

### 5.3.2 Application on lifting and lowering loads operations

The assessment of risk factors in incoming area carried out during step 2.3 and presented in section 5.2.3, has led to the conclusion that the most critical tasks regarding ergonomic risks are concentrated in incoming area, since these activities have the highest scores criticality for ergonomic risk factors due to the high prevalence of lifting and lowering loads activities. After several observations over the time, process mapping and a survey made to managers, supervisors and employees of incoming area, it was concluded that some of the most critical logistic operations were concentrated in the unloading dock area.

In this area, there are two critical processes that represent ergonomic risks to the operators, namely: (1) unloading boxes from docks; and (2) repalletization of materials. These two processes represent materials handling, what coincides with the conclusion made during the step 1.4 of occurrence analysis (section 5.1.4), where it was defined that material handling process was the most critical process with highest prevalence of MSD-related injuries.

In this section, the assessment carried out for both processes is presented, following the four main steps of ergonomic assessment phase defined at the beginning of section 5.3, namely: (1) analysis of the current situation; (2) identification of extreme postures; (3) application of ergonomic analysis method; and (4) identification of improvement potential. This ergonomic assessment comprises the evaluation of every posture adopted considering every level of loading and unloading.

#### 5.3.2.1 Step 3.1: Analysis of the current situation

As mentioned above, the unloading dock area comprises two critical processes that represent ergonomic risks to the operators. The first one regards to material arriving from air individual transports, which consists in loose boxes that are unloaded by the operators from the floor to higher levels. The second critical process regards to the repalletization process of pallets with raw material arriving from Asian suppliers, which do not meet company standards and are accommodated on non-standard pallets (Figure 61).

Figure 61. Material stored on non-standard pallets

Since company's standards require the use of Euro pallets, operators must transfer manually all the boxes to the correct pallet before storing them on the shelves of the raw material warehouse. Therefore, both processes require the repalletization of materials, so that they can be stored on the shelves of the raw material warehouse, complying with the company's standards.

During the unloading and repalletization processes, workers must manually handle materials from lower to higher levels and vice versa, which requires the adoption of awkward postures during lifting and lowering materials, with a high incidence, which may lead to the development of work-related MSD and injuries. There are several types of pallets, however, the typical pallet is composed by 32 handling units, divided by four different levels (nine handling units per level). Henceforth, this pallet configuration will be assumed for the ergonomic risk assessment. The dimensions of a typical handling unit are 350 mm x 270 mm x 200 mm (Figure 62).

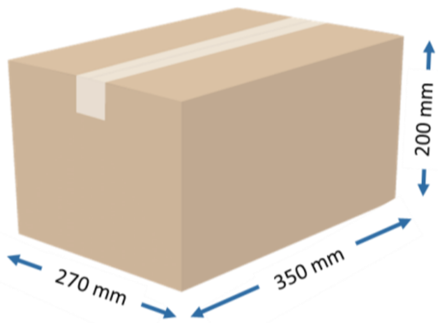


Figure 62. Typical dimensions of a handling unit

It is important to note that the units can have various weights and, after analysing the weights of all the material that have been received in incoming area that have arrived from air individual transports or in Asian pallets, it was concluded that the heaviest unit weights 36 kg and the lightest 2 kg. However, there is a wide range of weights for all handled materials. Thus, a statistical analysis was carried out, which allowed the determination of the average weight of the units handled during a working day: 12 kg.

Furthermore, a working day, considering repetitive tasks, has a total duration of 457 minutes (a working shift of 480 minutes, with 18 minutes of official breaks and 5 minutes for the daily meeting, which is a non-repetitive task) and, for this ergonomic analysis, it was assumed that an operator performs this task during the entire work shift, in order to study the worst-case scenario from an ergonomic point of view. Since the transfer of a handling unit from its point of origin to the destination pallet takes about eight seconds, it is possible to conclude that an operator is able to transfer a total of 3428 boxes for each working day (Table 61).

Table 61. Data for repalletization process (per working shift)

| | |
|---|---|
| **Duration of task** | 457 minutes |
| **Duration of each lift** | 8 seconds |
| **Number of transferred handling units during working day** | 3428 boxes |
| **Weight of heaviest handling unit** | 36 kg |
| **Average loaded weight per handling unit** | 12 kg |

#### 5.3.2.2 Step 3.2: Identification of extreme postures

The identification of extreme postures during repalletization operations has required the measurement of vertical distances for boxes in origin and destination pallets, in order to determine the reaching levels. The pallets were measured and the postures recorded or photographed. This allowed the evaluation of postures and the quantification of angular displacement during tasks performance.

It was important to analyse the reach level of every handling unit, in order to evaluate the posture adopted during picking at each level. These dimensions have been measured for origin and destination pallets (Table 62) during repalletization process performance, taking into account the vertical distance between worker's hands and the floor level when lifting and lowering materials.

Table 62. Reach level during repalletization process for origin and destination pallets

| Reach level | Origin Pallet | Destination Pallet |
|---|---|---|
| Level 1 | 330 mm | 360 mm |
| Level 2 | 540 mm | 570 mm |
| Level 3 | 720 mm | 760 mm |
| Level 4 | 950 mm | 980 mm |

The above-mentioned dimensions are very useful to identify the extreme postures during the performance of this process. Reaching the higher levels that require the positioning of the arms above head or shoulder height or the lower levels that leads to bending, crouching or kneeling postures represents the most critical postures in an ergonomic point of view (Figure 63). Hence, it is crucial to identify which selves' levels are above head and shoulders height as well as the ones that are below the knee's height to the percentiles under study (95th male and 25th female).

Figure 63. Unfavourable posture during repalletization process

In the Table 63, there are identified the levels that require the adoption of inappropriate postures during repalletization process, taking into account the four different levels of the origin and the destination pallets for both percentiles under study.

Table 63. Unfavourable postures during the repalletization for 95th male percentile and 25th female percentile

| | | **Origin Pallet (reach level)** | | | | **Destination Pallet (reach level)** | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Level** | | **1** | **2** | **3** | **4** | **1** | **2** | **3** | **4** |
| **P95M** | Above head level | | | | | | | | |
| | Above shoulder height | | | | | | | | |
| | Bellow knee height | x | x | | | x | x | | |
| **P25F** | Above head level | | | | | | | | |
| | Above shoulder height | | | | | | | | |
| | Bellow knee height | x | | | | x | | | |

The first and second levels are lower than knees height for both percentiles under study. Thus, reaching materials on these levels requires the adoption of unfavourable postures, such as, bending, crouching or kneeling. Reaching the second level is also critical for 95th male percentile, since it is lower than knees height. Regarding the remaining levels, both percentiles under study do not need to adopt unfavourable postures.

#### 5.3.2.3 Step 3.3: Application of quantitative ergonomic analysis method

This qualitative ergonomic analysis was supported by the revised NIOSH lifting equation method, described in section 2.4.3.1, since these processes are not cyclic and involve mainly manual materials handling. The main aim for the application of this method is to assess asymmetrical lifting and lowering tasks with both hands, considering biomechanical, physiological and psychophysical criteria and further determining the RWL for a specific manual lifting task, which is the load that nearly all healthy workers could lift over a substantial period of time. Furthermore, this method allows the calculation of LI, which provides a relative estimate of physical stress associated to a specific manual lifting or lowering task.

Since the origin and destination pallets are composed by four different levels, the NIOSH method will be divided into four analysed tasks, taking into account the combinations between the origin pallet and the destination pallet levels. Therefore, in order to perform the repalletization process, the operator starts by transferring nine handling units from the highest level of the origin pallet (fourth level) to the lowest level of the destination pallet (first level), which can be considerate the first task.

Afterwards, the second task consists in the transfer of the nine boxes located on the third level of the origin pallet are transferred to the second level of the destination pallet. In turn, the third task comprises the transfer of the boxes from the second level of the origin pallet will be placed on the third level of the destination pallet and, finally, the handling units located at the lowest level of the origin pallet (first level) will be transferred to the upper level (fourth level) of the destination pallet, which is the fourth task of repalletization process. These four tasks are depicted in Figure 64.

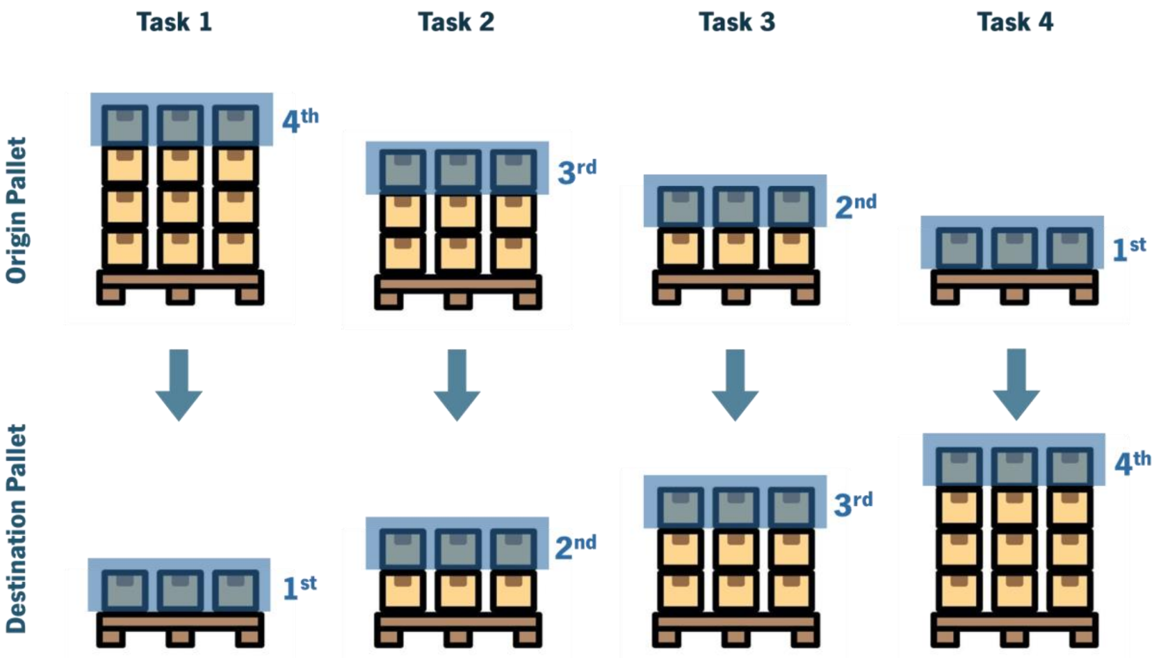


Figure 64. Four different tasks of repalletization process

Given that an operator lifts a total of 3428 handling units per shift (7.5 lifts per minute during 457 minutes – eight minutes for each lift), dividing this load by four different tasks, it means that each task accounts an average number of 857 lifted boxes per shift within each task, which represents an incidence of 1.88 lifts per minute for each task for a whole working day. However, it is important to take into account that each task is performed during a quarter of the total working time. Since this lifting job comprises multiple lifting activities, a multi-task job has been performed in order to combine the risk associated to every task and draw conclusion regarding the overall job.

The NIOSH equation consists in the multiplication of a Load Constant (LC) – 23 kg – by various multipliers of horizontal, vertical, distance, asymmetry, and frequency, whose values vary from task to task. The product of this equation is referred to as the RLW, that is, the recommended weight of a handling unit, for a task with specific characteristics that will be acceptable to 75% of female employees and for about 99% of male employees (Waters et al., 1993).

However, in order to determine the RWL, it is crucial to calculate six critical variables for each of four different operations. On the one hand, Horizontal Location (H) was measured from the mid-point of the line joining the inner ankle bones to a point projected on the floor directly below the mid-point of the hand grasps, being measured at both the origin and destination of the lift.

Instead, the Vertical Location (V) is the vertical height of the hands above floor and was measured from the floor to the mid-point between hand grasps (at the same height), being measured at both the origin and destination of the lift. Conversely, the absolute value of the difference of V at the origin and the corresponding V at the destination of the lift is the Vertical Travel Distance (D). The Lifting Frequency (F) is defined by the number of the average number of lifts per shift, while the Asymmetric Angle (A) is the angle between the movement and the neutral body position. Lastly, the Coupling Type (C) refers to the coupling or gripping method, which can be categorised as good, fair, or poor.

To carry out the ergonomic risk assessment of the repalletization process, two scenarios were considered for lower limbs regarding the postures adopted while reaching the lowest levels, in a similar way to what was studied in the picking process described in section 5.3.1. The first scenario consists in the adoption of a bending posture to reach lower levels, while the second refers to the adoption of a kneeling and crouching posture when reaching such levels. It is important to note that these two scenarios only represent differences when reaching the first and second levels of the pallets, as they are the lowest levels, probably below knee height.

The Table 64 presents the measured NIOSH variables and collected data for the first scenario, where logistic workers adopt bending postures to reach the first and second levels of the origin and destination pallets.

Table 64. Variables for different tasks – standing and bending scenario

| Task | H (cm) | | V (cm) | | D (cm) | F (lifts/shift) | A (º) | C |
|---|---|---|---|---|---|---|---|---|
| | Origin | Destination | Origin | Destination | | | | |
| **Task 1** | 40 | 46 | 95 | 36 | 59 | 857 | 0 | Fair |
| **Task 2** | 40 | 43 | 72 | 57 | 15 | 857 | 0 | Fair |
| **Task 3** | 44 | 40 | 54 | 76 | 22 | 857 | 0 | Fair |
| **Task 4** | 50 | 35 | 33 | 98 | 65 | 857 | 0 | Fair |

The variables above have resulted in the calculation of the corresponding multipliers, which, in turn, will be used to calculate the RWL for each task when workers adopt bending postures to reach lower levels, in order to determine the load that nearly all healthy workers could lift over a period of time.

The RWL has been calculated at both the origin and the destination of the lift for each task, in order to identify the most stressful location of the lift, which is presented in Table 65.

Table 65. Multipliers and RWL calculation – standing and bending scenario

| Multiplier | Task 1 | | Task 2 | | Task 3 | | Task 4 | |
|---|---|---|---|---|---|---|---|---|
| | Origin | Destination | Origin | Destination | Origin | Destination | Origin | Destination |
| **LC** | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 |
| **HM** | 0.63 | 0.54 | 0.63 | 0.58 | 0.57 | 0.63 | 0.50 | 0.71 |
| **VM** | 0.94 | 0.88 | 0.99 | 0.95 | 0.94 | 1.00 | 0.87 | 0.93 |
| **DM** | 0.9 | 0.9 | 1 | 1 | 1.00 | 1.00 | 0.89 | 0.89 |
| **FM** | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 |
| **AM** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **CM** | 1 | 0.95 | 0.95 | 0.95 | 0.95 | 1 | 0.95 | 1 |
| **RWL = LC × HM × VM × DM × FM × AM × CM** | | | | | | | | |
| **RWL** | 8.21 | **6.26** | 9.13 | **8.07** | **7.84** | 9.71 | **5.67** | 9.06 |

Given that the maximum loaded weight for this job is 36 kg and the average loaded weight is 12 kg, at this stage of assessment, it is possible to conclude that every task represents a significant risk for operators, since the RWL for every task is lower than these two values.

Therefore, the most stressful location refers to the lowest calculated RWL, which are highlighted above in bold, have been used to calculate the Lifting Index (LI) in order to estimate the relative magnitude of physical stress for each specific task, as well as, the MSD risk associated with the performance of each task. The calculation of LI for the four different tasks when workers adopt bending postures to reach lower levels is presented in Table 66.

Table 66. LI calculation – standing and bending scenario

| | Task 1 | Task 2 | Task 3 | Task 4 |
|---|---|---|---|---|
| **LI = Average Loaded Weight / RWL** | 1.92 | 1.49 | 1.53 | 2.12 |

The greater the LI, the smaller the segment of workers that are capable of safely perform such task. From the NIOSH perspective, lifting tasks with a LI higher than 1.0 represents an increased risk for lifting-related low back pain and development of work-related injuries. In this scenario, every task presents an associated LI higher than 1.0, which represents a significant risk for workers.

The multi-task assessment comprises the calculation of several variables, such as, the FIRWL STRWL, FILI and STLI for each task. After the calculation of these variables, the tasks have been ordered from the greatest STLI to the smallest STLI, putting the more difficult tasks first, as shown in Table 67.

Table 67. Multi-task assessment – standing and bending scenario

| STLI order | Task | FIRWL | STRWL | FILI | STLI |
|---|---|---|---|---|---|
| **1st** | Task 4 | 8.46 | 5.67 | 4.26 | 2.12 |
| **2nd** | Task 1 | 9.34 | 6.26 | 3.85 | 1.92 |
| **3rd** | Task 3 | 11.71 | 7.84 | 3.08 | 1.53 |
| **4th** | Task 2 | 12.04 | 8.07 | 2.99 | 1.49 |

The FIRWL calculated for each task represents the compressive force and muscle strength demands for a single repetitive task and determines the value of the load that nearly all workers can safely handle, regardless of the frequency of the lifts. On the other hand, the value of STRWL is the same calculation, but considering the frequency of loads. Both variables show that almost every task represents a significant risk for operators, since the maximum loaded weight for this job is 36 kg and the average loaded weight is 12 kg, that are higher that FIRWL and STRWL values.

The level of physical stress and MSD risk associated with the performance of each task is given by FILI values (regardless the frequency) and STLI values (considering the frequency). Both values for every task are higher than 1.0, which means that workers are at risk and ergonomic changes may be needed. Furthermore, FILI exceeds STLI in every task, which means that the risk is likely due to the maximum loaded weight (36 kg). The final step of multi-task assessment consists in the calculation of CLI for the overall job, which provides information about the collective demands of the job, combining the physical demands of every task. The calculation of CLI for this scenario, where the workers adopt bending postures to reach lower levels is presented in Equation 4.

$$CLI = STLI_1 + \sum \Delta LI$$
$$= 2.12 + \left(3.85 \times \left(\frac{1}{0.48} - \frac{1}{0.67}\right)\right) + \left(3.08 \times \left(\frac{1}{0.30} - \frac{1}{0.48}\right)\right) + \left(2.99 \times \left(\frac{1}{0.20} - \frac{1}{0.30}\right)\right)$$
$$CLI = 13.24$$

Equation 4. Calculation of CLI – standing and bending scenario

The CLI for this job considering the scenario where workers adopt bending postures to reach lower levels presents a very high value – 13.24 – which means that this job represents a high risk for operators regarding work-related injuries and development of MSD. Furthermore, this job accounts a cumulative daily load of 41136 kg and the worst case of FILI, which can be understood as the lumbar spine load for this job is 4.26, much higher than the acceptable limit for developing tasks without risk, which is 1.0.

As mentioned before, the ergonomic analysis of this lifting job contemplated two possible scenarios for the lower limbs. Henceforth, the analysis for the second scenario, where the workers adopt kneeling or crouching postures when reaching the lowest levels, will be described. Regarding this scenario, the data collected and the related measured NIOSH variables are presented in the Table 68.

Table 68. Variables for different tasks – kneeling or crouching scenario

| Task | H (cm) | | V (cm) | | D (cm) | F (lifts/shift) | A (º) | C |
|---|---|---|---|---|---|---|---|---|
| | Origin | Destination | Origin | Destination | | | | |
| **Task 1** | 40 | 43 | 95 | 36 | 59 | 857 | 0 | Fair |
| **Task 2** | 40 | 40 | 72 | 57 | 15 | 857 | 0 | Fair |
| **Task 3** | 40 | 40 | 54 | 76 | 22 | 857 | 0 | Fair |
| **Task 4** | 43 | 35 | 33 | 98 | 65 | 857 | 0 | Fair |

The NIOSH variables presented above have been used for the calculation of the corresponding multipliers that compose NIOSH equation, in order to calculate the RWL for each task when workers adopt kneeling or crouching postures to reach lower levels. The RWL refers to the load that nearly all healthy workers could lift over a period of time and has been calculated at both the origin and the destination of the lift for each task, so that it was possible to identify the most stressful location of the lift. These values are presented in Table 69.

Table 69. Multipliers and RWL calculation – kneeling or crouching scenario

| Multiplier | Task 1 | | Task 2 | | Task 3 | | Task 4 | |
|---|---|---|---|---|---|---|---|---|
| | Origin | Destination | Origin | Destination | Origin | Destination | Origin | Destination |
| **LC** | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 | 23.00 |
| **HM** | 0.63 | 0.58 | 0.63 | 0.63 | 0.63 | 0.63 | 0.58 | 0.71 |
| **VM** | 0.94 | 0.88 | 0.99 | 0.95 | 0.94 | 1.00 | 0.87 | 0.93 |
| **DM** | 0.9 | 0.9 | 1 | 1 | 1.00 | 1.00 | 0.89 | 0.89 |
| **FM** | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 |
| **AM** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **CM** | 1 | 0.95 | 0.95 | 0.95 | 0.95 | 1 | 0.95 | 1 |
| **RWL = LC × HM × VM × DM × FM × AM × CM** | | | | | | | | |
| **RWL** | 8.21 | **6.72** | 9.13 | **8.76** | **8.67** | 9.71 | **6.57** | 9.06 |

Similar to the previous studied scenario, every task of the job in this scenario represents a significant risk for operators, since the RWL for every task is lower than the value of the maximum loaded weight (36 kg) or even the average loaded weight (12 kg). Hence, the lowest calculated RWL values, which represent the most stressful location for each task, are highlighted above in bold. These values have been used to calculate the Lifting Index (LI) that represents the relative magnitude of physical stress for each specific task. Thus, the calculation of LI for the four tasks when workers adopt kneeling or crouching postures to reach lower levels, which is presented in Table 70.

Table 70. LI calculation – kneeling or crouching scenario

| | **Task 1** | **Task 2** | **Task 3** | **Task 4** |
|---|---|---|---|---|
| **LI = Average Loaded Weight / RWL** | 1.78 | 1.37 | 1.38 | 1.83 |

Similar to the previous scenario, in this case, every task presents a LI higher than 1.0, which means that all of them represent an increased risk for operators. However, in comparison with the previous scenario, the LI for each task slightly decreases, which means that workers have to deal with less physical stress when they adopt improved postures, such as kneeling instead of bending. Furthermore, the RWL increases in some extent, which means that workers are allowed to lift heavier weights without risk of developing a MSD or a work-related injury when they adopt improved postures from an ergonomic point of view.

The multi-task assessment and the calculation of the FIRWL STRWL, FILI and STLI for each task is presented in Table 71. Furthermore, after the calculation of these variables, the tasks have been ordered from the greatest STLI to the smallest STLI, putting the more difficult tasks first.

Table 71. Multi-task assessment – kneeling or crouching scenario

| **STLI order** | **Task** | **FIRWL** | **STRWL** | **FILI** | **STLI** |
|---|---|---|---|---|---|
| **1st** | Task 4 | 9.81 | 6.57 | 3.67 | 1.83 |
| **2nd** | Task 1 | 10.04 | 6.72 | 3.59 | 1.78 |
| **3rd** | Task 3 | 12.94 | 8.67 | 2.78 | 1.38 |
| **4th** | Task 2 | 13.08 | 8.76 | 2.75 | 1.37 |

The compressive force and muscle strength demand for a single repetitive task is given by the calculated FIRWL for each task, which was useful for determining the load that nearly all workers can safely handle, regardless of the frequency of the lifts. The same load, but considering the frequency of lifts, is given by the value of STRWL. The maximum loaded weight for this job (36 kg) and the average loaded weight (12 kg) are higher than FIRWL and STRWL values for almost every task, which represents a significant risk for operators.

On the other hand, the FILI values represent the level of physical stress and MSD risk associated with the performance, regardless the frequency of lifts, while STLI values consider this frequency. Both values for every task are higher than 1.0, which means that workers are at risk and ergonomic changes may be needed. Moreover, FILI values exceed STLI values in every task, which means that the risk is likely due to the maximum loaded weight (36 kg).

The multi-task assessment is completed with the calculation of CLI for the overall job, providing information about the combination the physical demands for every task, resulting in the collective demands for the overall job. The calculation of CLI for this scenario, where the workers adopt bending postures to reach lower levels is presented in Equation 6.

$$CLI = STLI_1 + \sum \Delta LI$$
$$= 1.83 + \left(3.59 \times \left(\frac{1}{0.48} - \frac{1}{0.67}\right)\right) + \left(2.78 \times \left(\frac{1}{0.30} - \frac{1}{0.48}\right)\right)$$
$$+ \left(2.75 \times \left(\frac{1}{0.20} - \frac{1}{0.30}\right)\right)$$
$$CLI = 12.04$$

Equation 5. Calculation of CLI – kneeling or crouching scenario

The value of collective demands of the overall job, given by the calculation of CLI, considering the scenario where workers adopt kneeling or crouching postures to reach lower levels is very high – 12.04 – which means that this job represents a high risk for operators regarding work-related injuries and development of MSD. However, the value of CLI slightly decreased in comparison with the previous scenario, due to the adoption of improved postures for lower limbs.

Furthermore, similar to the previous scenario, this job accounts a cumulative daily load of 41136 kg and the worst case of FILI, which can be understood as the lumbar spine load for this job is 3.67, which much higher than the acceptable limit for developing tasks without risk, however, slightly lower than the value obtained during the assessment of the previous scenario with bending postures to reach lower levels.

The NIOSH results are summarised in Table 72, showing the calculated CLI (or Lifting Index of multi-task assessment) and the lumbar spine load (worst case of FILI) for the both analysed scenarios.

Table 72. NIOSH results for lifting and lowering load operations within incoming area

| Scenario | Lifting Index (CLI) | Lumbar spine load |
|---|---|---|
| Standing and bending | 13.24 ● | 12.04 ● |
| Kneeling or crouching | 4.26 ● | 3.67 ● |

As mentioned before, the analyses for both scenarios result in values of CLI and FILI much higher than the acceptable limit for developing tasks without risk, which is 1.0, representing high risk for operators that perform operations that require lifting and lowering loads within incoming area.

#### 5.3.2.4 Step 3.4: Identification of improvement potential and definition of mitigation measures

In brief, the main ergonomic risk factors associated with the execution of lifting and lowering loads within incoming area are mainly related to the high force demand to perform tasks, since the average weight per handling unit is 12 kg and the heaviest handling unit weights 36 kg.

Moreover, the repetitiveness of movements and prevalence of awkward postures to reach materials far from hands are critical factors as well. Therefore, the identified improvement potential for lifting and lowering operation within incoming area, as well as the proposed mitigation measures using AR are presented in Table 73.

Table 73. Improvement potential in lifting and lowering loads process within incoming area and mitigation measures

| **Improvement potential** | **Mitigation measures using AR** |
|---|---|
| Manual handling of heavy loads | Use of a suitable exoskeleton that meets the task requirements and mitigates the associated ergonomic risk factors |
| Awkward postures | |
| Repetitiveness of movements of the upper limbs | |

As mentioned in 5.2.5.4, in step 2.4 of this methodology, it is crucial to enhance physical capabilities of workers in order to eliminate awkward postures and reduce the physical loads, fatigue and risk of injury and MSD.

Thus, the augmentation of physical capabilities intends to mitigate every risk regarding ergonomics and, similar to the mitigation measures proposed in sections 5.3.1.4 during the step 3.4 of ergonomic analysis of picking operations, the use of a suitable exoskeleton that meets the task requirements will allow the mitigation of ergonomic risks associated to the high force demand during lifting and lowering operations, enhancing worker's physical capabilities and allowing operators to lift and lower heavier loads, that would not be possible without the use of this equipment.

The selection of the most suitable exoskeleton model to perform lifting and lowering loads operations within incoming area and mitigate the associated ergonomic risks requires and extensive analysis, considering the key characteristics of the equipment, defined in section 5.2.5.6, as well as, the ergonomic analysis, risk factors and the task's nature and requirements.

## 5.4 Methodology overview

An overview about the proposed methodology for Risks Assessment for Ergonomics and Safety in Logistics (RAES-Log), as well as, the main phases, each step and the main outputs and results are presented in Table 74.

Table 74. Overview of methodology phases, steps and main outputs

| Phase | Step | Output |
|---|---|---|
| Phase 1. Occurrence analysis | Step 1.1. Identification of the most critical logistic areas | • Internal logistics (72% of occurrences; incidence rate of 30 for accidents and 75 for incidents)<br>• Incoming (22% of occurrences; incidence rate of 23 for accidents and 105 for incidents) |
| | Step 1.2. Identification of the most critical processes | • Materials handling (48% of accidents and 46% of incidents)<br>• Transportation (23% of accidents and 27% of incidents)<br>• Picking (20% of accidents and 20% of incidents) |
| | Step 1.3. Identification of the most common consequences | Part of body injured:<br>• Upper extremities<br>• Lower extremities<br>• Back, including spine and vertebra in the back<br>Type of injury:<br>• Wounds and superficial injuries<br>• Dislocations, sprains and strains |
| | Step 1.4. Conclusions and identification of improvement potential | • Critical logistic areas: used during phase 2<br>• Critical processes with highest prevalence of MSD-related injuries: used during phase 3 |
| Phase 2. OSH risk evaluation and mitigation measures | Step 2.1. Identification of hazards associated with each task performance | Hazards associated with each task performance within the two most critical logistic areas:<br>• Internal Logistics<br>• Incoming |
| | Step 2.2. Identification and categorisation of each OSH risk factor | Categories of OSH risk factors:<br>• Physical safety risk factors<br>• Ergonomic risk factors |
| | Step 2.3. Assessment of each risk based on their severity and frequency | • Parameterisation of risk evaluation criteria (frequency and severity)<br>• Categorisation of risks criticality based on obtained scores<br>• Definition of acceptability criteria |
| | Step 2.4. Identification of human senses and capabilities to be augmented | • Human senses: sight and hearing<br>• Capabilities: cognitive and physical |
| | Step 2.5. Definition of mitigation measures using AR | • Augmentation of sight sense: HMD, HHD and SAR<br>• Augmentation of hearing sense: AAR<br>• Augmentation of cognitive capabilities: HMD, HHD, SAR and AAR<br>• Augmentation of physical capabilities: WWD and exoskeletons |
| Phase 3. Ergonomic risk assessment and mitigation measures | Step 3.1. Analysis of the current situation | Activities with highest criticality for ergonomic risk factors (identified during step 2.3):<br>• Final and SMD assembly supermarkets tasks<br>• Incoming tasks<br>Critical processes with highest prevalence of MSD-related injuries (identified during steps 1.2 and 1.4):<br>• Picking operations within SMD warehouse area<br>• Lifting and lowering loads operations within incoming area |
| | Step 3.2. Identification of extreme postures | Unfavorable postures to reach materials:<br>• Above head level<br>• Above shoulder height<br>• Bellow knee height |
| | Step 3.3. Application of quantitative ergonomic analysis method | Quantification of ergonomic risk factors and risk of MSD:<br>• EAWS: ergonomic analyses of repetitive loads and cycling tasks<br>• NIOSH: tasks that require asymmetrical lifting and lowering tasks with both hands |
| | Step 3.4. Identification of improvement potential and definition of mitigation measures using AR | • Use of WWD equipped with barcode scanning functionality<br>• Use of suitable exoskeleton that meets each task requirements and augments worker's physical capabilities |

This summary shows the main outputs and conclusions drawn during the application of each step of the proposed methodology, as well as the proposed AR solutions to mitigate risks within logistic workplaces.

Moreover, in order to analyse the improvement potential associated with the implementation of these methodologies and study the worker's opinion and acceptance, an analysis involving logistic workers at case study has been carried out and presented in chapter 6. Furthermore, this analysis intended to validate the conclusions made during the three phases of RAES-Log methodology.

# 6 RESULTS ANALYSIS AND DISCUSSION

This chapter describes the analysis and discussion about the results revealed by the current case study. In order to study the worker's opinion and acceptance regarding the proposed AR solutions as a result of RAES-Log methodology development, a questionnaire was applied to logistic workers within the case study. Therefore, a discussion of the findings will be provided in the next sections, as results are stated and highlighted.

## 6.1 Identified improvements potential

It is crucial to assess the existing risks within workplaces, as well as the possible impact of AR technology implementation and its acceptance. For this purpose, a questionnaire has been designed and applied to assess the workers' perceptions about the implementation of such solutions within their workplaces.

The current study intends to analyse and assess the improvement potential associated to the implementation of the AR solutions presented in the previous chapter in order to mitigate risks and improve ergonomic conditions within workplaces.

The designed questionnaire was based on Nordic Musculoskeletal Questionnaire (NMQ), which has been developed by the Nordic Council of Ministers (Kuorinka et al., 1987) with the aim of developing and testing a standardized questionnaire methodology that allows the comparison between complaints regarding different parts of body (Crawford, 2007).

Therefore, the NMQ can be used as a questionnaire or as a structured interview (Crawford, 2007) and, in the context of this study, the NMQ has been used as a structured interview, following a systematic approach where logistic workers are asked the same predetermined questions in the same order. Moreover, each question is rated following a standardized scoring system.

The questionnaire was applied to workers from the most critical logistic areas, defined in step 1.1 of the proposed methodology (section 5.1.1): (1) incoming; and (2) internal logistics. Therefore, the workers from shipping have not been considered and the number of workers within these two logistic areas where the questionnaire has been applied is represented in Table 75.

Table 75. Number of workers within the most critical logistic areas

| Logistic area | Number of workers |
|---|---|
| Incoming | 38 |
| Internal logistics | 150 |
| Total | 188 |

Furthermore, within the above-mentioned critical areas, special attention has been given to the tasks with highest criticality regarding the OSH risk assessment carried out during step 2.3 (section 5.2.3). Thus, workers that perform logistic tasks that comprise risk factors categorised with medium, high or extreme criticality during this assessment have participated in the questionnaire in order to evaluate the mitigation measures proposed during step 2.5 (section 5.2.5). These critical tasks are presented in Table 76.

Table 76. Logistic tasks with highest criticality levels regarding OSH risk factors

| **Logistic area** | **Tasks** |
| --- | --- |
| Incoming | Incoming |
| Internal logistics | Warehousing |
| | Repacking |
| | Final and SMD assembly supermarkets |
| | Lines supply |

Moreover, during phase 3 of RAES-Log methodology (section 5.3), lifting and lowering loads operations within incoming area and picking operations within supermarkets have been analysed in order to assess the risk factors regarding ergonomic conditions. Thus, special attention has been given to workers that perform these two operations have been selected to participate in order to assess the AR solutions proposed to mitigate ergonomic risk factors in step 3.4 (sections 5.3.1.4 and 5.3.2.4)

In order to generalise and make inferences about a population from a sample, avoiding biases and errors, it is crucial to define an adequate sample size (Taherdoost, 2017). An online tool has been used to determine the sample size of this study (Raosoft, 2004).

Therefore, from a population of 188 workers within the two most critical logistic areas, a sample of 50 workers has been defined to make inference on the population. This calculation considers 10% of margin of error, 90% of confidence level and 50% of response distribution. The confidence level was slightly reduced compared to the initial 95%, while the margin of error was increased due to the restrictions regarding allocation of workers.

Hence, 50 workers were interviewed during their workday while performing their activities. The questions were asked in the form of interview and noted, while explanations were provided whenever necessary. However, the anonymity of the questionnaire can support employees to honestly express their views, problems and opinions.

The questionnaire summary, structure and used instruments are presented in Table 77. It starts with the characterisation of the population, asking the main sociodemographic characteristics and categorising workers by their logistic area and performed tasks (Category A).

Table 77. Summary of questionnaire structure, parameters assessed and used instruments

| Category | Parameters assessed | Used instruments |
|---|---|---|
| A. Workers' characterization | • Age<br>• Work experience<br>• Tasks performed | – |
| B. Musculoskeletal symptomatology | • Diagnosed MSD<br>• Work-related occurrences<br>• Classification of pain | Numerical pain scale (Jensen & Karoly, 2011) |
| C. Perception of exertion | • Assessment of physical exertion perceived by the workers;<br>• Identification of the most demanding tasks. | Category Ratio-10 (Borg, 1990) |
| D. Workers' opinion and acceptance | • Assessment of worker's opinions about the possible AR solutions to implement in workstations | Five-point Likert scale (Likert, 1932) |

Afterwards, the questionnaire addresses issues regarding work-related MSD regarding nine different anatomic regions (Category B), adapted from the NMQ developed by Mesquita et al. (2010), in order to classify the pain, using the numerical pain scale (Jensen & Karoly, 2011).

Furthermore, the Category C comprises questions regarding to worker's perception of exertion in physical work during their task's performance, using the Category Ratio-10 (Borg, 1990) to quantify subjective perceptions of physical overloads, such as effort and discomfort.

Finally, the Category D presents a list of statements used for an assessment about the acceptance of the proposed AR solutions, based on workers' opinion. For this purpose, the workers had to indicate their degree of agreement on a five-point Likert scale (Likert, 1932).

Therefore, this study pursues four specific objectives: (1) characterise the workers' sample with demographic data; (2) analyse wellbeing and discomfort of workers; (3) assess physical exertion perceived by the workers and identify the most demanding tasks: and (4) assess proposed AR solutions acceptance indicators based on the workers' opinion.

For this purpose, the questions and parameters assessed in each category will be detailed in the next sections. The full questionnaire is presented in Appendix IV – Questionnaire.

### 6.1.1 Category A – Workers' characterization

The first category of the questionnaire intended to characterize participants regarding their demographic variables, such as age and gender, as well as anthropometric data, such as their stature. Furthermore, participants provided information about the logistic area where they work, the tasks performed during the working day and their work experience in such tasks, as well as other tasks performed during the last 12 months.

### 6.1.2 Category B – Musculoskeletal symptomatology

The questions regarding musculoskeletal symptomatology are addressed in the second category with the aim of understanding the previous developed work-related MSD and assessing if the workers have ever had a work accident or incident. In the case of a positive answer to the previous question, the workers are asked about the period in which the occurrence took place, the logistical area and the tasks that were being performed at the time of the occurrence.

Also in this category, it was intended to evaluate the pain or discomfort felt by the participants in nine different regions of the body (Figure 65). For this purpose, the participants were asked if they felt any pain in each region in the last 12 months and 7 days. Furthermore, it was intended to assess if workers were conditioned in their normal life due to some problem in each region and if they consulted a health professional in the last 12 months.

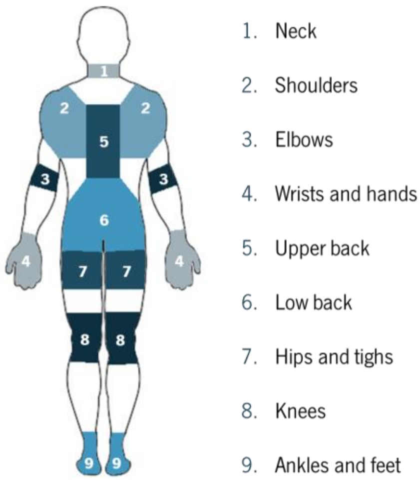


Figure 65. Body map with nine different anatomic regions
(Adapted from Mesquita et al. (2010))

Afterwards, based on the questions of the NMQ developed by Mesquita et al. (2010), workers were asked to classify their pain and discomfort regarding nine different anatomic regions using the numerical pain scale (Jensen & Karoly, 2011):

- 0: Painless;
- 1-3: Slight pain;
- 4-6: Moderate pain;
- 7-9: Intense pain;
- 10: Maximum pain.

Finally, workers are asked about the number of working days they missed due to pain or discomfort in the past 12 months and are invited to make a brief comment on what, in their opinion, triggered their problem.

### 6.1.3 Category C – Perception of exertion

The aim of the third category of this questionnaire is to understand the perception of exertion during tasks performance by workers. The self-reported physical exertion tasks were evaluated according to the Category Ratio-10 (Borg, 1990):

- 0: Nothing at all;
- 1: Very weak;
- 2: Weak;
- 3-4: Moderate;
- 5-6: Strong;
- 7-9: Very Strong
- 10: Extremely strong.

This is a scale used to quantify subjective perceptions of physical overloads, such as effort and discomfort, that is correlated to an effort that is well perceived by different individuals, being used as a reference physical effort for different workers or work conditions (Borg, 1990).

Therefore, the participants are asked about the most physically and cognitively demanding tasks performed at their workplace and, afterwards, used the above-mentioned scale to classify the following 20 different factors that can lead to discomfort or additional effort during tasks performance:

1. Manual handling of heavy loads;
2. Pushing or pulling heavy loads;
3. Utensils too heavy (e.g. PDA);
4. Repetitive movements;
5. Inappropriate trunk working postures;
6. Inappropriate upper limb working postures;
7. Inappropriate working postures of the lower limbs;
8. Workstations, shelves or material too high;
9. Workstations, shelves or material too low;
10. High distances covered;
11. Too much information to assimilate;
12. Hard to memorize work instructions;
13. Find the fastest route (for picking, put-away or lines supply);
14. Pay attention to all existing risks at the workplace;

15. Too much product information to check;
16. Quickly find product locations;
17. Know all the tasks to perform;
18. Detect errors or failures in processes;
19. Know the specifications of each product (e.g. box type, packaging, location, etc.);
20. Knowledge and compliance with all safety instructions.

#### 6.1.4 Category D – AR solutions: Workers' opinion and acceptance

This category comprises the presentation of the proposed AR solutions to mitigate risk factors within logistic workplaces. The main aim is to collect worker's global opinion and assess their acceptance regarding the possible implementation of these mitigation measures, changing their workplaces.

For this purpose, a list of seven statements, adapted from Colim et al. (2021), related to the possible changes at the workplaces was provided to the participants for each presented AR solution:

1. The equipment would make your tasks easier.
2. The equipment could lighten my physical/cognitive load.
3. The equipment could reduce my physical/cognitive effort.
4. The equipment could reduce my discomfort.
5. I would take less risk using the equipment.
6. My job would improve with this equipment.
7. I would use the equipment if the company made it available.

In order to assess the acceptance of the proposed AR solutions, based on workers' opinion, the participants had to indicate their degree of agreement on a five-point Likert scale (Likert, 1932):

- 0: No opinion;
- 1: Strongly disagree;
- 2: Disagree;
- 3: Neither agree nor disagree;
- 4: Agree;
- 5: Strongly agree.

In addition, an open response space was dedicated to each solution presented, in order to allow participants to comment with other information relevant to the study.

## 6.2 Analysis of obtained results

After the application of the questionnaire to logistic workers at the case study facilities, it was possible to draw some conclusions about the existing risks within workplaces, as well as the possible impact of AR technology implementation and its acceptance.

In this section, the obtained results of the questionnaire will be presented, divided into four categories that intend address the four main objectives: (1) characterise the workers' sample with demographic data; (2) analyse wellbeing and discomfort of workers; (3) assess physical exertion perceived by the workers and identify the most demanding tasks; and (4) assess proposed AR solutions acceptance indicators based on the workers' opinion.

### 6.2.1 Category A – Workers' characterization

Fifty logistic workers from different areas participated in this study, between 18 and 63 years old. The youngest employee was 18 years old and the oldest 63. The distribution of workers according to the age range is presented in Figure 66.

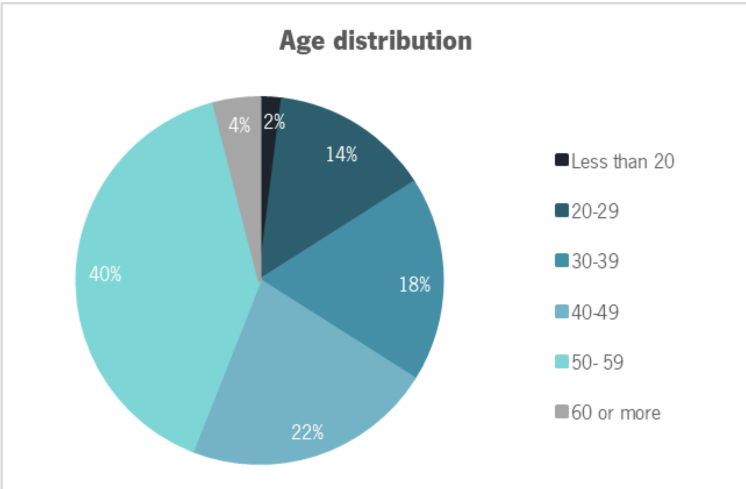


Figure 66. Age distribution of workers

The majority of workers are between 50 and 59 years old and, with an aging workforce, several challenges emerge. Therefore, it is crucial to minimise the physical strain and workload through the enhancement of ergonomic conditions and redesign of workplaces in order to improve well-being amongst all workers, reducing fatigue or discomfort.

With regard to the distribution of workers in the logistics areas according to their gender, the majority are women, totalling 52% of the participants (Figure 67). Moreover, the average height of all the workers that have participated in this questionnaire is 170 cm with a standard deviation of 11 cm. Furthermore, the maximum height is 195 cm, while the minimum is 147 cm.

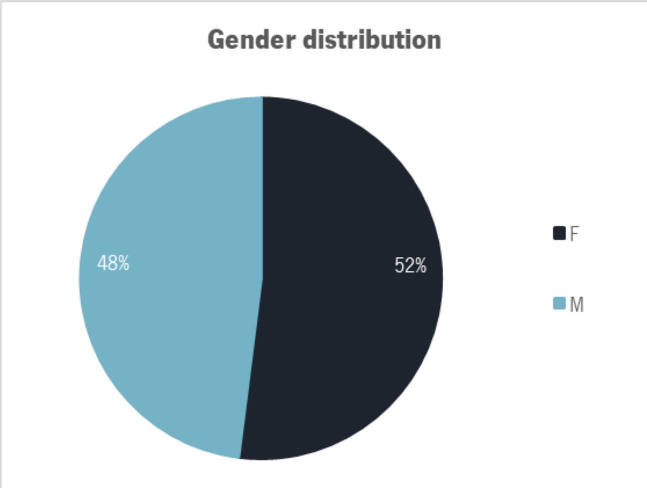


Figure 67. Gender distribution of workers

Around 18% of respondents perform tasks within incoming area, while the remaining 82% work in the different internal logistics areas. The warehousing activities account 16% of the responses, while repacking concerns 14% of the answers. Workers from final assembly and SMD supermarkets refer to a total of 52% of the respondents (Table 78).

Table 78. Distribution of workers according to logistic area

| Logistic area | | Number of respondents | Percentage |
|---|---|---|---|
| Incoming | | 9 | 18% |
| Internal logistics | Warehousing | 8 | 16% |
| | Repacking | 7 | 14% |
| | Final assembly supermarket and lines supply | 8 | 16% |
| | SMD supermarket and lines supply | 18 | 36% |

Concerning logistics tasks performed, as depicted in Figure 68, every respondent is responsible for executing manual materials handling, while 94% use transportation equipment and 90% perform picking or put-away tasks. Furthermore, 52% of the workers perform lines supply tasks and other 4% reported tasks such as battery charging and load preparation.

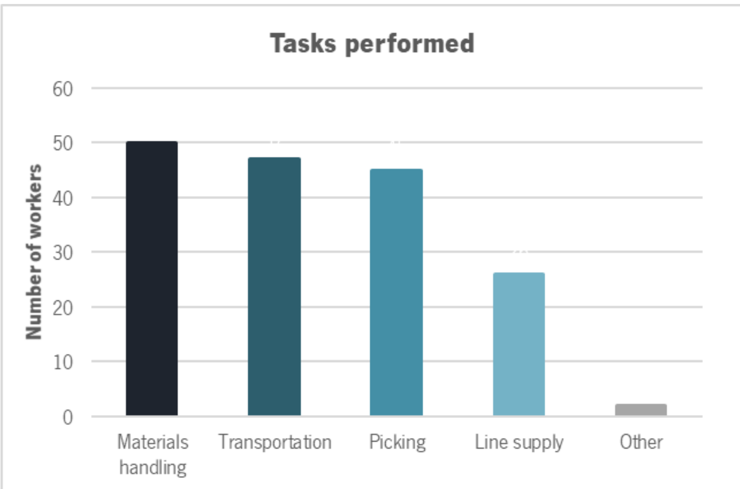


Figure 68. Tasks performed by workers

Regarding employees' work experience, it was possible to conclude that employees in the logistics areas have a high seniority in the execution of these tasks, with only 14% of respondents working in this area for less than 1 year and about 54% performing the same tasks for more than 10 years. Furthermore, 14% of the responses concern to team leaders or supervisors, while the remaining 86% are operational logistic workers.

### 6.2.2 Category B – Musculoskeletal symptomatology

Regarding to work-related MSD, the majority of the workers (56%) have reported, at least, one musculoskeletal problem, such as tendonitis, scoliosis, epicondylitis, dislocations, contractures and osteoarthritis (Figure 69).

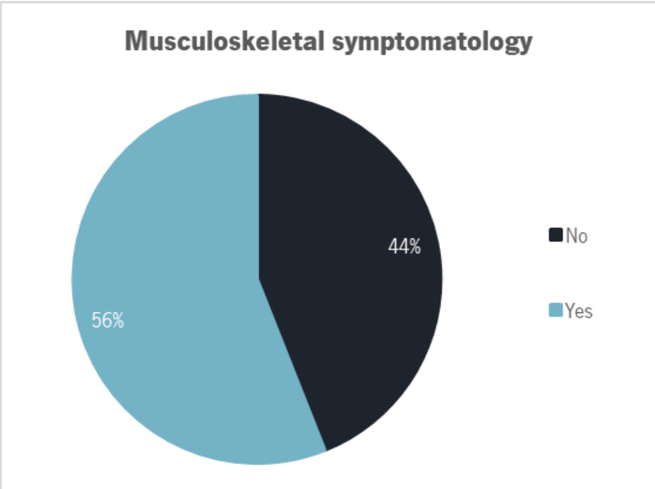


Figure 69. Number of workers reporting musculoskeletal symptomatology

This means that there is a high incidence of MSD within logistic workplaces related to the execution of the tasks. Therefore, it corroborates the analysis carried out during phase 1 (section 5.1) and phase 2 (section 5.2) of the RAES-Log methodology and it is imperative to eliminate or mitigate the risks of an ergonomic nature to which workers are exposed during the workday.

Furthermore, more than a quarter of respondents (13 people) have suffered a work-related occurrence during the last years. Regarding these reported occurrences, nine of them relate to accidents and four to incidents. Moreover, the majority of these occurrences (38.5%) have been reported during 2020 or later, which may indicate that there is a trend towards an increase in the number of occurrences over the last few years.

Therefore, it is not possible to relate this data with the conclusions made based on the occurrence analysis carried out during phase 1 of the proposed methodology (section 5.1), since there is a lack of data regarding occurrences during the last few years at the case study.

Regarding the logistic areas where the occurrences have been reported, the internal logistics areas account 69.3% of the total occurrences, being within the warehousing area that occurred the majority of these cases (3 accidents and 1 incident), as shown in Figure 70. Furthermore, these conclusions coincide with the occurrence analysis carried out during phase 1 of the proposed methodology (section 5.1).

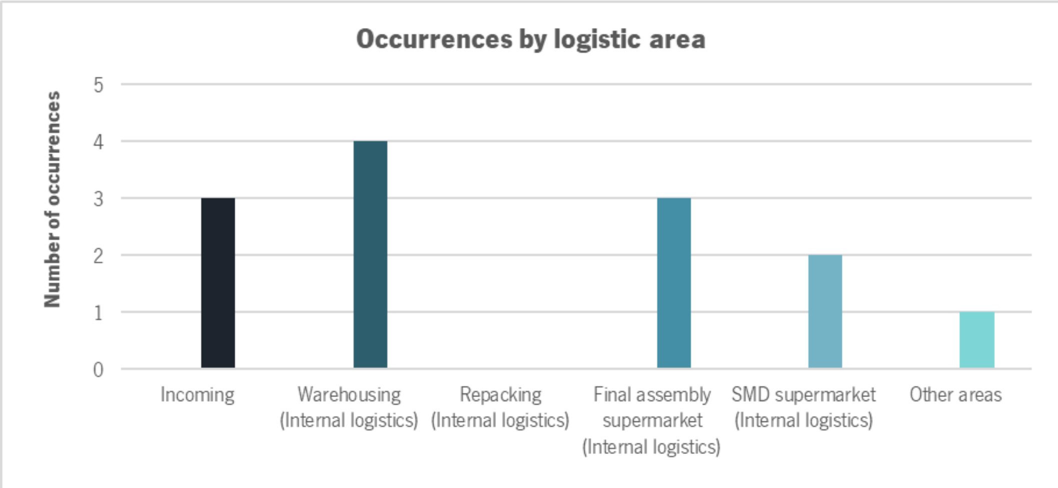


Figure 70. Number of occurrences by logistic area

Material handling has been the task performed during most of the occurrences reported by the respondents (62% of the occurrences), while picking and transportation activities account 46% and 39% of the work-related occurrences, respectively, as presented in Figure 71.

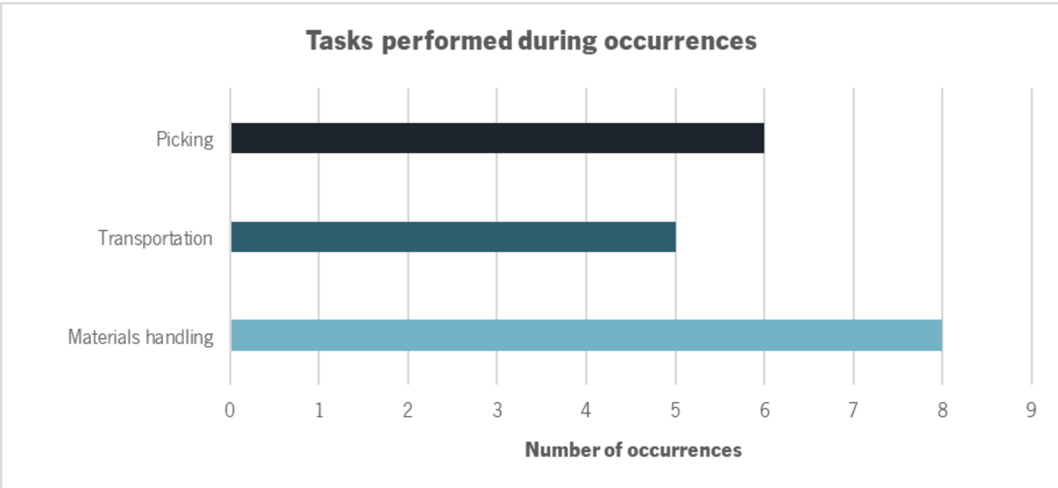


Figure 71. Tasks performed during occurrences

The results showed that a significant portion of the workers had pain or discomfort in the nine regions of the body during the last 12 months and the last seven days and the majority of the workers have not been conditioned in daily living due to these problems (Figure 72).

On the one hand, 33 workers described the shoulders and the lumbar region as the most critical regions, as well as the neck region (23 workers), reporting pain and discomfort during the last 12 months and, in most of the cases, persisting in the last seven days. On the other hand, the least critical body parts are ankles and feet (13 workers), chest region (12 workers), as well as hips and thighs (11 workers), with the lowest number of workers reporting pain during the last 12 months and persisting in the last seven days.

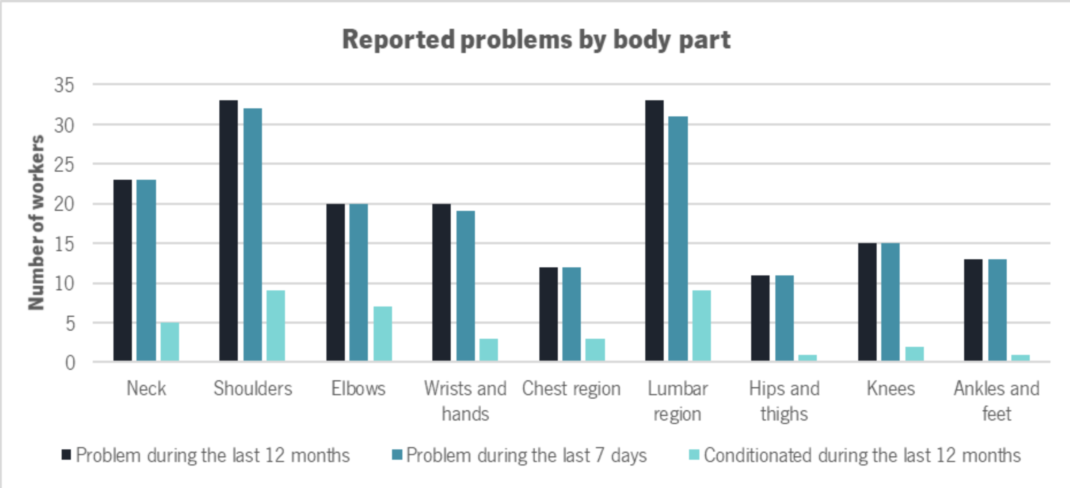


Figure 72. Reported problems by body part

Regarding the elbows, 20 workers refer pain or discomfort during the last 12 months and persisting in the last seven days, while 20 workers have reported pain in wrists and hands during the last 12 months, with 19 of them persist in the last seven days. Finally, 15 workers refer pain in knees region during the last 12 months and in the last seven days.

Workers have been asked to to classify their pain and discomfort in each different anatomic region using a numerical pain scale (Jensen & Karoly, 2011). Workers described the lumbar region as the major region complain, where 17 respondents reported intense pain and 15 reported moderate pain.

Furthermore, shoulders are a critical body part as well, since 14 workers classified their pain at this region as intense and 17 as moderate. Attention must be given to neck and elbows region, where 12 workers complain about intense pain, as well as seven and eight workers complaint about moderate pain in these body parts, respectively, as shown in Table 79.

Table 79. Number of workers reporting pain or discomfort according to pain scale and body part

| **Pain scale** | **Neck** | **Shoulders** | **Elbows** | **Wrists and hands** | **Chest region** | **Lumbar region** | **Hips and thighs** | **Knees** | **Ankles and feet** |
|---|---|---|---|---|---|---|---|---|---|
| Painless | 27 | 17 | 30 | 29 | 38 | 17 | 39 | 35 | 37 |
| Slight pain | 4 | 2 | 0 | 4 | 1 | 1 | 0 | 2 | 0 |
| Moderate pain | 7 | 17 | 8 | 11 | 5 | 15 | 6 | 5 | 6 |
| Intense pain | 12 | 14 | 12 | 6 | 6 | 17 | 5 | 8 | 7 |
| Maximum pain | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Therefore, the workers that reported pain and discomfort in different regions, have classified, in average, their pain as moderate in neck, shoulders, wrists and hands, hips and thighs and knees. However, body parts as elbows, chest and lumbar regions, as well as ankles and feet present higher levels of pain and discomfort, being classified by workers as intense.

The average level of pain and discomfort for each body part, as well as the standard deviation are depicted in Figure 73, where body parts classified with moderate pain are represented in light blue colour, while regions classified with intense pain are represented in dark blue colour.

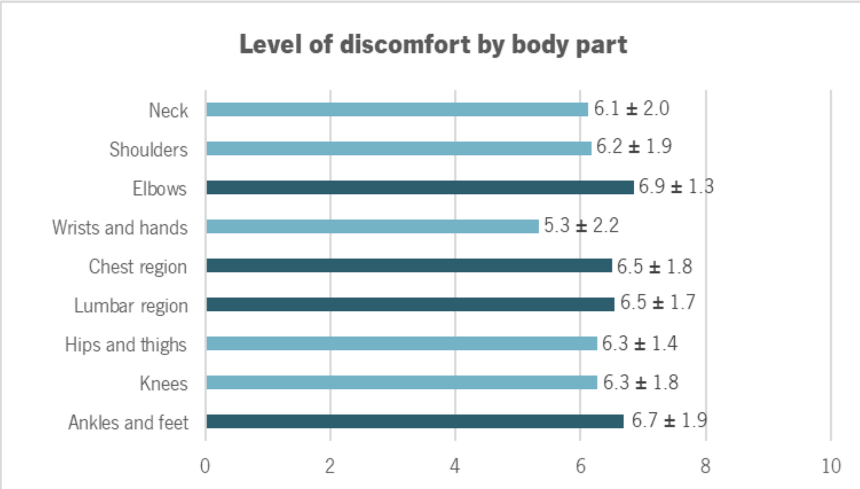


Figure 73. Level of discomfort by body part (mean values ± SD)

Finally, workers have been asked about the number of working days they missed due the above-mentioned situations of pain or discomfort in the past 12 months. Therefore, the majority of workers (34) have not missed any working day. However, these problems have resulted in a loss of between 10 and 30 working days for six respondents, as well as a loss of between 31 and 60 working days for the same number of workers during the last year (Figure 74).

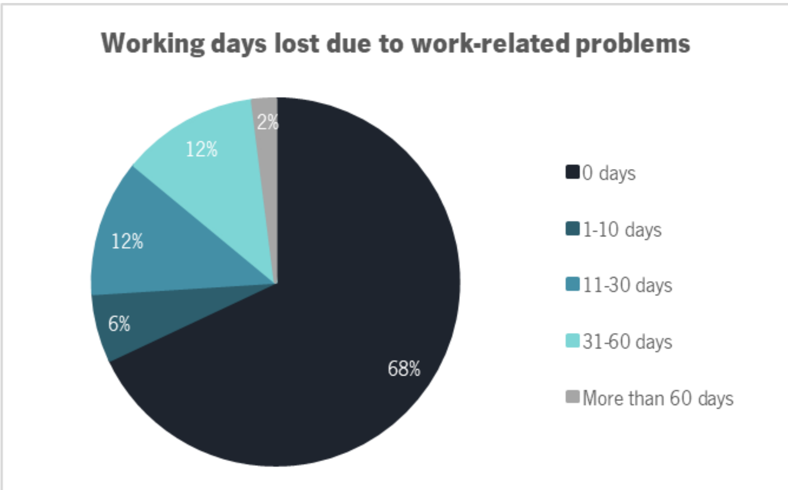


Figure 74. Working days lost due to work-related problems

### 6.2.3 Category C – Perception of exertion

The workers were asked about the most physically and cognitively demanding tasks performed at their workplace. Regarding the most physically demanding tasks, there is a high variation depending on the logistic area where the workers perform their tasks. The most common complaint and transversal to all logistic areas regards to the handling of heavy loads, issue that 78% of the respondents (39 workers) have reported (Figure 75).

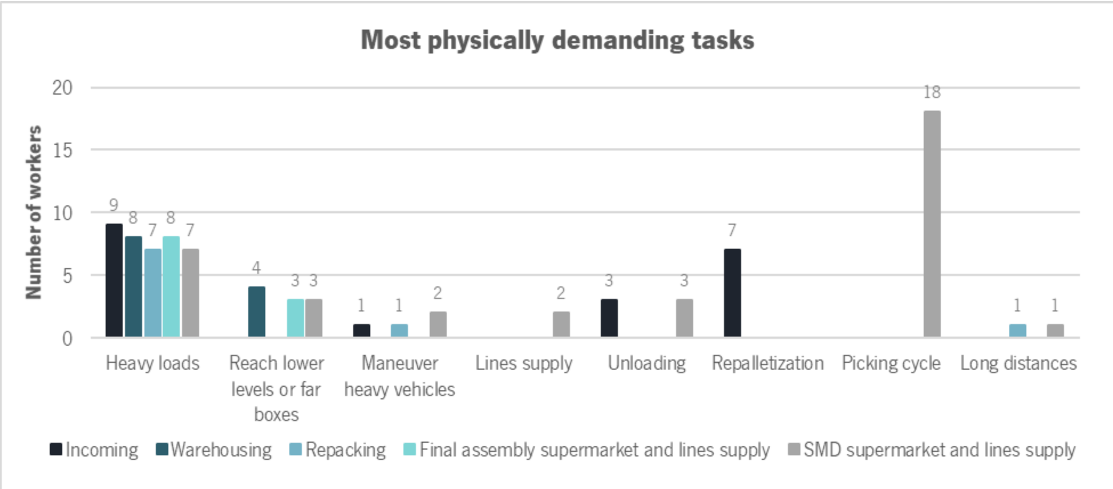


Figure 75. Most physically demanding tasks according to workers from different logistic areas

Regarding to incoming area, seven of the nine respondents mentioned the repalletization process as one of the most physically demanding tasks, which corroborates the risk analysis performed during phase 2 of the proposed methodology (section 5.2) and the ergonomic assessment carried out to this process within incoming area during phase 3 (section 5.3.2).

Furthermore, three workers from this area report physical difficulties during unloading boxes from docks, which also comprises materials handling tasks, the most critical process with highest prevalence of MSD-related injuries defined ring the step 1.4 of occurrence analysis (section 5.1.4).

Within the SMD supermarket area, where the picking operations of reels and PCB are performed to supply the SMD assembly area, 100% of the interviewed workers from this area reported the picking cycle as one of the most physically demanding tasks, which validates the conclusions obtained in step 1.4 of the proposed methodology (section 5.1.4) during occurrences analysis phase, where it was defined that picking process was one of the most critical processes with highest prevalence of MSD-related injuries.

Moreover, an ergonomic assessment based on EAWS method has been carried out regarding this process during phase 3 (section 5.3.1). Additionally, workers from this area also consider line supply tasks (two workers) and unloading process (3 workers) demanding from a physical point of view.

Additionally, reaching lower levels, in case of supermarkets, or reaching far boxes, in case of warehousing process, is an issue reported by a total of 10 workers. Additionally, one worker from incoming, one from repacking and two from SMD supermarket area consider critical the tasks that involve manoeuvring heavy vehicles, while a total of two workers (one from repacking and other from SMD supermarket) have difficulties walking long distances.

Also, in what concerns to cognitively demanding tasks, 23 workers reported a high level of stress and work pressure during tasks execution and two of them mentioned that it is difficult to memorize the warehouse aisles and the location of materials.

It is important to refer that these difficulties have been identified and considered during the proposal of mitigation measures during step 2.5 of the methodology (section 5.2.5). However, until now, there was no record of these complaints from the company's employees, which constitutes an opportunity for improvement. Considering that workers provide crucial information regarding aspects that need to be improved in their jobs, they should be more heard and consulted in the processes of changing their jobs.

Therefore, the participants were asked to use the Category Ratio-10 scale (Borg, 1990) to classify their perception of exertion during tasks performance regarding 20 different factors that can lead to discomfort or additional effort (Figure 76).

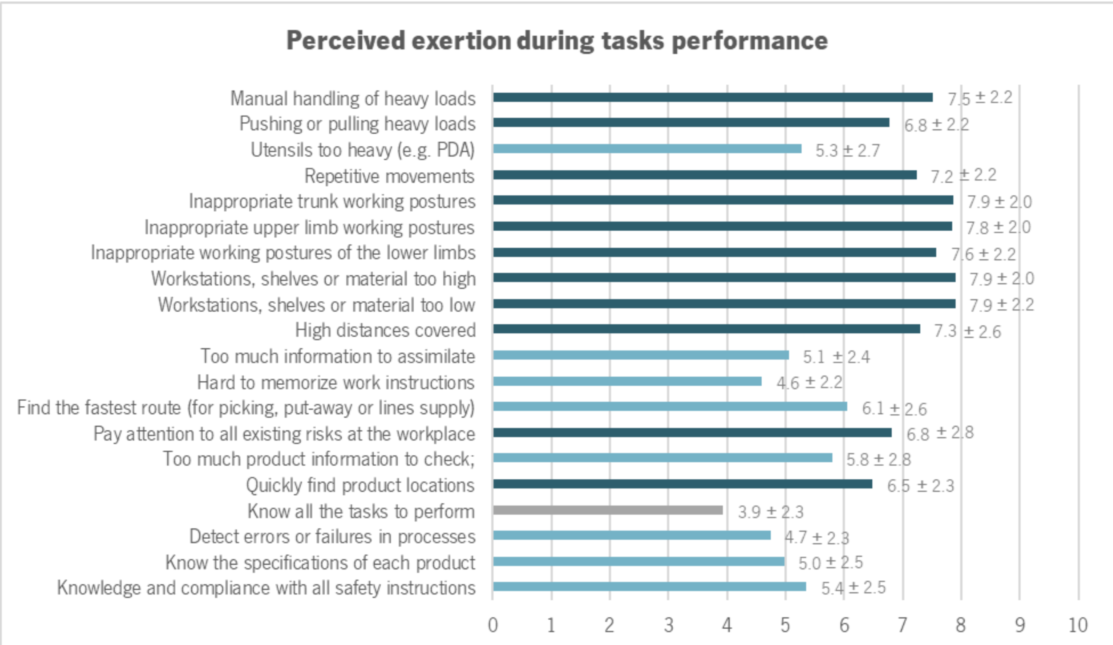

Figure 76. Perceived exertion from workers during tasks performance (mean values ± SD)

On the one hand, in average, workers consider that knowing all the tasks to perform requires a moderate cognitive effort (represented in grey colour). On the other hand, workers refer the higher perceive exertion levels for activities that require physical effort, such as manual handling or pushing of heavy loads, repetitive movements, inappropriate body postures, material store at higher or lower levels and high distances covered. Furthermore, from a cognitive point of view, they also find very difficult to pay attention to all existing risks at their workplaces, as well as finding the products and materials locations. Therefore, the activities classified by workers as requiring a very strong physical or cognitive effort are represented in dark blue colour.

Finally, the activities that require a strong effort, depicted in light blue colour, regard to the use of heavy utensils, such as the PDA, which can be replaced by AR solutions mentioned in step 2.5 (section 5.2.5) and analysed in step 3.4 for picking operations (section 5.3.1.4) in order to decrease the physical workload.

Moreover, the activities classified with this level of perceived exertion require mainly cognitive effort, regarding to information to assimilate, work instructions to memorize, find the fastest routes, know the product's information to check and the product's specification, detect errors and comply with all safety instructions.

Also, in what concerns to cognitively demanding tasks, 23 workers reported a high level of stress and work pressure during tasks execution and two of them mentioned that it is difficult to memorize the warehouse aisles and the location of materials.

Similar to the above-mentioned most demanding tasks, these complaints have been considered during the proposal of mitigation measures during step 2.5 of the methodology (section 5.2.5) and should be further considered and registered by the company, in order to support continuous improvements processes within workplaces.

### 6.2.4 Category D – AR solutions: Workers' opinion and acceptance

In order to evaluate the worker's opinion and acceptance regarding the proposed AR solutions and mitigation measures within their workplaces, a list of seven statements was provided and participants were asked to indicate their degree of agreement on a five-point Likert scale (Likert, 1932).

Therefore, the provided statements intended to evaluate the perception of workers regarding the possibility of reduce their physical or cognitive effort, as well as their opinion about the potential improvements and risks mitigation as a result of the proposed AR solutions implementation. Furthermore, workers were asked if they would use the equipment if the company made it available.

The augmentation of physical capabilities to mitigate the ergonomic risks through the implementation of exoskeletons is one of the mitigation measures proposed in section 5.2.5.4, during step 2.5 of the methodology, and analysed in step 3.4, after the ergonomic assessment of critical operations.

The opinions regarding exoskeletons are reported in Figure 77. The majority of workers (90%) expressed a positive judgement about this solution to augment their physical capabilities, agreeing or strongly agreeing with the statements about its potential in risk mitigation. Considering the used five-point Likert scale, the mean value for the total of 50 answers is 4.22 points, which means that there is a high level of worker's acceptance in what concerns to exoskeletons technology.

Nevertheless, two participants disagreed and showed concerns about the equipment's weight, comfort and the possibility of cable entangled in workstations, shelves or vehicles. Therefore, the majority believes that this solution will enhance their ergonomic conditions and reduce their difficulties and efforts, specially during heavy materials handling, which is one of the most common complaints within logistic workers and one of the main causes of work-related MSD development.

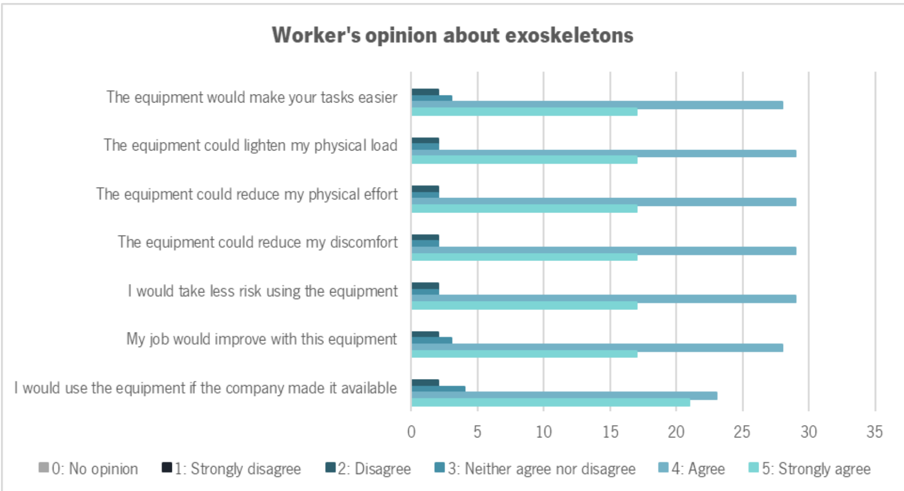


Figure 77. Answers distribution for the statements related to the impact of exoskeletons

As stated during the definition of mitigation measures, the step 2.5 of the proposed methodology (section 5.2.5.4) and further analysed during ergonomic assessment of picking operations, in step 3.4 (section 5.3.1.4), carrying heavy utensils during the whole workday can highly pledge the ergonomic conditions and workers well-being. This represents an additional physical workload with a high risk for the development of work-related MSD. Therefore, in order to mitigate the risks associated to the use of these devices, it was proposed the replacement of the existing PDA by lighter WWD equipped with barcode scanning functionalities.

This solution was proposed to the logistic workers during the questionnaire and a significant portion of participants (82%) showed a positive perception about these devices (Figure 78). Considering the five-point Likert scale, the mean value was 4.19 points, showing a high level of worker's acceptance regarding WWD technology.

However, the remaining workers (18%) disagree, have no opinion or neither agree or disagree because they believe that this solution will not benefit their workstation or logistic area, as they do not use this equipment during the whole working day. It is important to note that the most critical area regarding the use of PDA is the SMD supermarket (ergonomic assessment carried out in section 5.3.1.4), where this equipment is used during the whole working day, and 100% of participants within this area expressed a positive judgement about this AR solution, believing that WWD would reduce their physical load and decrease the risks to which they are exposed.

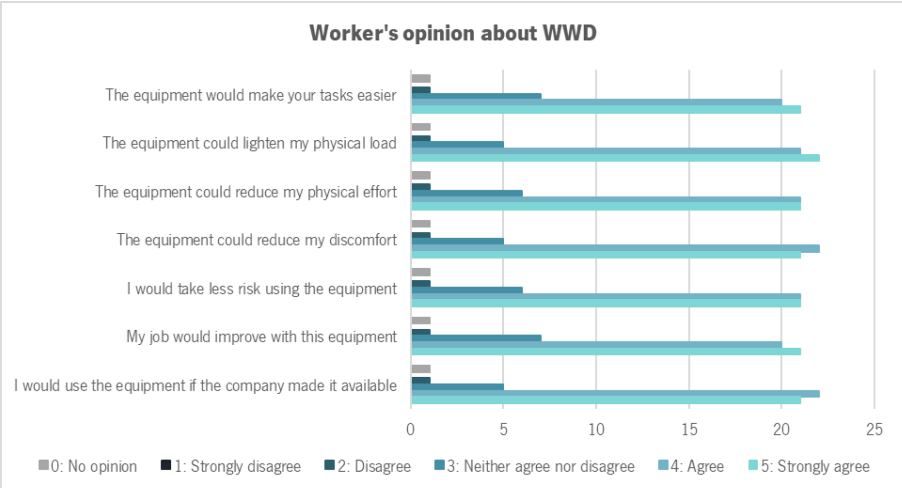


Figure 78. Answers distribution for the statements related to the impact of WWD

The use of wearable AAR devices to augment hearing sense (detailed in section 5.2.5.2) can enhance workers' safety conditions through the provision of relevant information over audio signals and warnings on incoming safety hazards, safety instructions and workplace hazard alerts. Furthermore, these devices can also provide relevant information in order to augment cognitive capabilities (detailed in section 5.2.5.3) and support the performance of logistic tasks.

The worker's opinions AAR or headsets are reported in Figure 79. A positive perception about this solution was expressed by 80% of the respondents, which represents a positive level of acceptance, with a mean value of 3.79 points, considering the five-point Likert scale. However, the majority of them believe that this solution would be more helpful regarding the augmentation of cognitive abilities to support tasks execution and not very effective regarding risks mitigation. Furthermore, 20% of workers do not believe that this solution is useful to mitigate risks within their workplace and express a concern about the possible discomfort during the usage of this equipment, as well as, the risk of distraction and interference with the normal execution of their tasks.

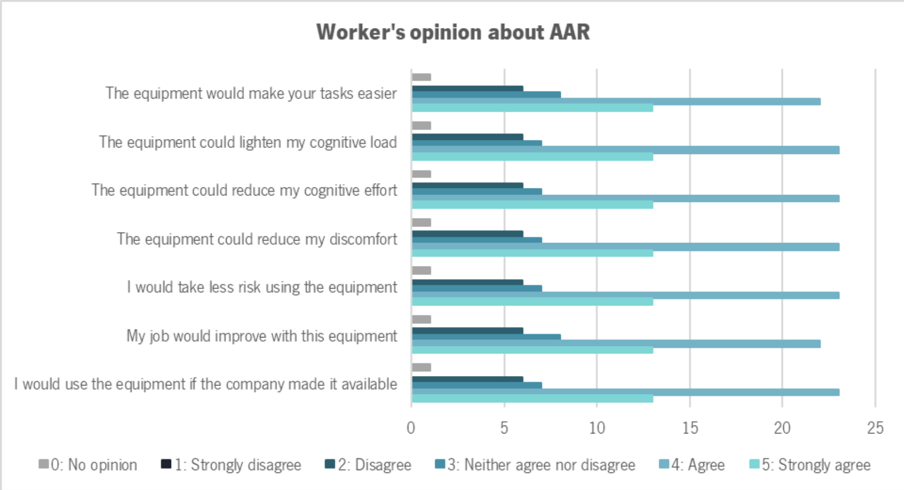


Figure 79. Answers distribution for the statements related to the impact of AAR

The augmentation of the natural human sight sense (presented in section 5.2.5.1) using AR solutions, such as HMD, HHD or SAR holds a huge potential regarding the enhancement of safety conditions within the workplaces, as well as the provision of relevant information to support tasks execution through the augmentation cognitive capabilities (presented in section 5.2.5.3).

An HMD model has been presented to workers during questionnaire in order to assess their acceptance regarding this technology and collect their opinions about the potential of this technology to mitigate risks in their workplaces. Positive perceptions about this solution have been expressed by 68% of the interviewed logistic workers, with a mean of 3.87 points considering the the five-point Likert scale. Nevertheless, 32% do not believe on the potential of this solution regarding risk mitigation or even cognitive support, expressing concerns about the discomfort during its usage, the risk of distraction and interference with the normal execution of their tasks (Figure 80).

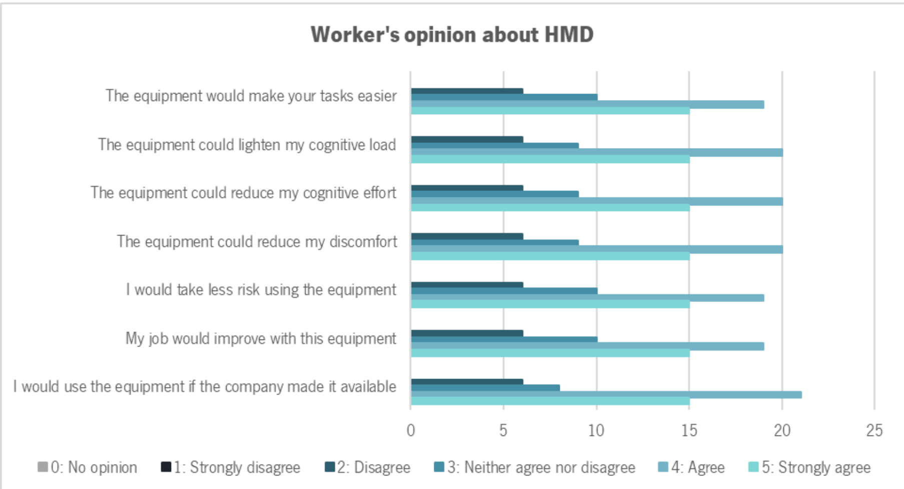


Figure 80. Answers distribution for the statements related to the impact of HMD

The global worker's opinion regarding proposed AR solution is expressed in Figure 81, where is possible to understand that, for all the solutions, the majority of workers showed a positive judgement about these technologies to mitigate risks within their workplaces.

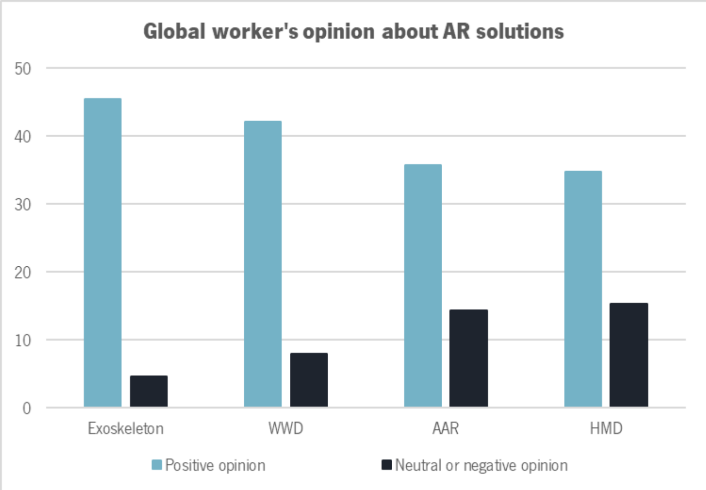


Figure 81. Global worker's opinion about the impact of proposed AR solutions

The highest acceptance level, which accounts the highest number of positive opinions, regards to exoskeleton technology. This fact can be explained based on the one of the most common complaints within logistic workers that regards the heavy materials handling. In fact, workers believe that this solution will enhance their ergonomic conditions and reduce the risk of work-related MSD development. The same concerns about physical workload relates to the high acceptance level of WWD, especially within SMD supermarket workers, that use a heavy PDA during the whole working day.

A lower level of acceptance is expressed by workers regarding solutions that enhance cognitive abilities and can reduce their mental workload, such as AAR and HMD. The main concerns pointed out by workers regard to discomfort during the usage of these equipment, as well as the risk of distraction during tasks performance.

### 6.2.5 Synthesis of results

The work was focused on the development of the methodology for Risk Assessment for Ergonomics and Safety in Logistics (RAES-Log), proposed in chapter 5, that allows the analysis and definition of AR implementation requirements within logistic workplaces to mitigate risks, as well as, the further study about the potential of enhancement of working conditions through the implementation of AR technology.

Therefore, the RAES-Log methodology intends to identify the critical logistic areas and processes within an organization, with the aim of assessing and evaluating the risks regarding safety and ergonomics during tasks execution in order to propose mitigation measures based on AR solutions.

Consequently, the definition of requirements for implementing AR within logistic workplaces includes the identification and assessment of safety and ergonomic risks and the further identification of the human senses and capabilities that should be augmented in order to improve working condition in lean workplaces. Afterwards, AR solutions are proposed in order to mitigate the identified risks and enhance working conditions and workers' well-being, while reducing the risk of developing work-related MSD and eliminating the existing risks within workplaces.

However, despite of this case study project being focused on the use of AR, this methodology can be applied to analyse implementation requirements for every Industry 4.0 disruptive technology that has the potential to mitigate risks regarding ergonomic conditions and physical safety in workplaces. Furthermore, this methodology can be used in any company that performs logistic tasks in order to enhance the working conditions through the implementation of technological solutions that can benefit both organisations and workers.

Furthermore, a study about the potential of enhancement of working conditions through the implementation of AR technology has been carried out in order to analyse the current situation regarding MSD and perceived exertion during tasks execution, as well as, the workers' opinion and acceptance about the proposed AR solutions that resulted from the implementation of RAES-LOG methodology at case study.

This study revealed that the prevalence of MSD among logistic workers is high and 56% of workers reported at least one musculoskeletal problem. The most prevalent regions of musculoskeletal complaints were in shoulders (66%), lumbar region (66%) and neck (46%), according to NMQ.

When asked about physical exertion, 78% of the workers have reported the handling of heavy loads, which is the most common complaint within logistic areas. Furthermore, the picking cycle process within SMD supermarket (36%), reaching lower levels and far materials (20%) and repalletization process within incoming area (14%) are considered high physically demanding tasks by the interviewed workers.

Regarding the perceived exertion from workers during tasks performance, the higher levels mainly refer to activities that require very strong physical effort, such as manual handling or pushing of heavy loads, repetitive movements, inappropriate body postures, material store at higher or lower levels and high distances covered. However, workers also refer a very strong cognitive effort to find the products and materials locations and to pay attention to all existing risks at their workplaces. Indeed, two of these above-mentioned activities have been classified with highest criticality for ergonomic risk within logistic workplaces, having been the subject of an ergonomic assessment during phase 3 of the methodology (section 5.3). As concluded at the end of this methodology, the application of AR solutions based on exoskeletons technology and WWD could reduce the physical workload and improve ergonomic conditions, decreasing the prevalence of work-related MSD.

Concerning the proposed AR solutions to mitigate risks within workplaces that resulted from the RAES-Log methodology implementation, the majority of workers expressed a positive judgement about them and their potential to enhance their working conditions and eliminate the existing risks. In fact, workers showed confidence in these technologies, especially for those that hold the potential to reduce physical workload and reduce the risk of work-related MSD development, such as exoskeleton technology (90%) and WWD (82%). In fact, workers trust in these technologies to enhance their ergonomic conditions and reduce the risk of work-related MSD development.

When asked about solutions that hold the potential to decrease their cognitive workload, such as AAR and HMD, workers also believe that AR solutions can relieve their mental effort during the workday, however, with a lower level of acceptance when compared with the proposed solutions to reduce their physical workload. Therefore, workers believe that AAR (80%) and HMD (68%) can relieve their mental effort during the workday, enhancing their working conditions.

On the one hand, the AR technology that accounts the highest acceptance level regards to exoskeleton technology, which can be explained by the fact that one of the most common complaints within logistic workers that regards the heavy materials handling and it is urgent to enhance their ergonomic conditions and reduce the risk of work-related MSD development.

On the other hand, solutions that enhance cognitive abilities and can reduce their mental workload account a lower number of positive opinions and the main concerns pointed out by workers regard to discomfort during the usage of these equipment, as well as the risk of distraction during tasks performance.

Hence, the global worker's opinion is positive for every proposed AR solution and the majority of workers showed curiosity and optimism about these technologies to mitigate risks within their workplaces. Nevertheless, it is crucial to highlight that the workers' involvement in this process was essential to anticipate and correct problems. The workers showed motivation and curiosity about the proposed AR solutions, actively participating in this study towards their workstation's transformation and providing relevant opinions concerning the possible changes and proposed solutions. Moreover, the anonymity of this study allowed the employees to honestly express their views about what is working well and what could be improved within their workstations, as well as their main concerns and complaints.

Being the workers the most valuable resource in every organization, it is crucial to consider their opinions when proposing changes to their workstations and working methods, in order to have a more efficient implementation and adaptation of changes to their needs. This approach leads to an increase in workers' satisfaction, while at the same time improving the information and requirements collection.

# 7 CONCLUSIONS

This final chapter presents an overview of the major findings of this thesis. Therefore, this work culminates with the presentation of the main and general conclusions, followed by the discussion on the research questions and related answers presented on section 1.3. and further analysed in chapter 3, during the definition of the research methodology.

Furthermore, the main achieved results and scientific and practical contributions are listed in the third section. In its turn, the main limitations of the developed work are presented in the fourth section, followed by the discussion about the opportunities for future work that could enhance the work presented in this thesis.

## 7.1 General conclusions

The fourth industrial revolution embraces a set of disruptive technologies, namely AR, that aim to bring together the digital and physical worlds, enabling new types of interaction between humans and machines within workplaces. This new industrial paradigm holds a set of opportunities to improve companies' productivity and efficiency, however, there is also an opportunity to study the creation of operators with augmented or enhanced physical, sensorial and cognitive capabilities.

Therefore, this work was focused on the creation of a symbiosis between Industry 4.0 and Industry 5.0 paradigms. The project addresses Industry 4.0 philosophies, through the study about the potentials of implementation of a disruptive technology, namely AR, and Industry 5.0 principles, driving the transition to human-centric, sustainable and resilient systems.

Operators should be the main focus on every production system and they are the main motivation of this work. For this reason, this project aimed to develop a methodology – RAES-Log – that allows the analysis and definition of AR implementation requirements within logistic workplaces in order to mitigate the existing risks and study the potential of enhancement of working conditions through the implementation of AR technology.

## 7.2 Scientific contribution and answers to research questions

Given the identified research gaps during the literature review (chapter 2) and the objectives described in the section 1.2, it was necessary to address the research questions that have arisen (reported in section 1.3).

The work was focused on the development of the methodology for risk assessment for ergonomics and safety in logistics (RAES-Log), proposed in chapter 5, that allows the analysis and definition of AR implementation requirements within logistic workplaces to mitigate risks, as well as, the further study about the potential of enhancement of working conditions through the implementation of AR technology.

This project addresses the Lean Thinking philosophy, which embraces every area from industry and services and helps organisations to continuously improve. Lean principles allow companies to face the current and future challenges, fostering their competitiveness and eliminating the symptoms of wastes. Therefore, this project focuses on three main domains of Lean Thinking: (1) Lean Ergonomics; (2) Lean Logistics; and (3) Lean Automation.

The first domain consists in the combination of lean, safety and ergonomic aspects within a workstation, addressing HF issues, while the second regards to the application of lean to supply chain and warehouse management and the last domain refers to the synergies between industry 4.0 and lean. Therefore, the main scientific contribution of this work regards to a novel approach that integrates these three above-mentioned lean domains.

It is known that the relationship between Lean Production and Industry 4.0 technologies, known as Lean Automation, has been widely discussed recently. Moreover, the industrial applications of AR and its use cases have been an extensively researched topic in the last few years. Nevertheless, the production and assembly areas have been widely discussed, while logistics remains an under-explored area concerning the application of disruptive technologies. This project intended to address this literature gap, contributing to this topic, known as Logistics 4.0, in order to understand how AR technology can benefit workers and processes from logistic areas.

Furthermore, the relationship between Industry 4.0 technologies and the enhancement of HF and HMI in workplaces remains an under-explored area, since the application of these cutting-edge technologies is generally associated with increasing the productivity and performance of the systems, neglecting working conditions and the operators. Therefore, and considering the operators and their well-being as the main focus of this work, while addressing Industry 5.0 principles, this project intended to understand how AR technology can be used to enhance user's experience and ergonomic conditions, while mitigating risks in logistic workplaces. For this purpose, it was crucial to understand the relationship between HMI and HF in industry 4.0 context, as well as its implications and requirements for its implementation, which was a gap in the literature.

Finally, ergonomic and safety issues are topics widely discussed within production area. However, these remain under-explored logistics areas, which is one of the most critical areas regarding OSH risks and hazards. Thus, this work addressed this topic and the relationship between logistics and HF, which is also a valuable scientific contribution.

Therefore, the accomplishment of this project addressed the Industry 4.0 and 5.0 paradigms, considering the implementation AR technology within logistic workplaces in order to improve the ergonomic conditions and create waste-free workplaces. Moreover, the proposed methodology promotes safe and secure working environments and well-being within the organizations, while ensuring healthy workplaces, as well as equality for all workers, regardless their capabilities or disabilities.

Additionally, this work aimed to respond to the research questions that have arisen, reported previously in section 1.3. The summary of the answers to the research questions is presented in Table 80.

Table 80. Answers to research questions

| Research Question | Answer |
|---|---|
| RQ 1 – How can AR enhance human capabilities and senses in lean workplaces? | • Display of safety information and warnings to augment human senses (sight and hearing) and cognitive capabilities;<br>• Use of WWD equipped with barcode scanning functionality and suitable exoskeleton that meets each task requirements and augments worker's physical capabilities |
| RQ 1.1 – How can AR enhance human capabilities and senses in order to mitigate risks? | Display of safety information and warnings to augment:<br>• Human senses (sight and hearing);<br>• Cognitive capabilities; |
| RQ 1.2 – How can AR enhance human capabilities and senses in order to improve ergonomic conditions? | Display of safety information and warnings to augment:<br>• Sight sense;<br>• Cognitive capabilities;<br>Use of WWD equipped with barcode scanning functionality and suitable exoskeleton that meets each task requirements and augments worker's physical capabilities |
| RQ 2 – Which AR solutions are more suitable for logistic processes? | Level of acceptance from logistic workers:<br>• Exoskeletons (90% of positive answers);<br>• WWD (82% of positive answers);<br>• AAR (80% of positive answers);<br>• HMD (68% of positive answers). |

## 7.3 Limitations

This work has been developed having one the major international flagships in the automotive electronics industry as the case study. Thus, in some situations, this company has strict organizational data policies, holding a huge of confidential business information.

Therefore, the collection of the required data can be seen as the major limitation of this thesis, since crucial data for the development of the project could not be obtained in some cases. Furthermore, the available data was, in some situations, incomplete or not registered in the correct order or with the correct date and containing errors related with manual interactions, which made the quantitative analysis processes more difficult. Hence, with this lack of data consistency, the obtained results may not be as accurate as expected.

Regarding the Logistics Department, where this research was held, the lack of metrics and updated KPI was remarkable, for instance, regarding the work-related occurrences within logistics areas, work-related MSD development and prevalence, as well as the absenteeism data. In fact, it was clear that, as with most industrial companies around the world, the logistic area is somewhat overlooked compared to manufacturing area. This fact is reflected in the lack of logistic KPI and the absence of ergonomic analysis in logistic workstations. Furthermore, the negligence regarding the risks to which workers are exposed is notable, within this area that is one of the most critical areas in industry regarding the occurrence of accidents and prevalence of work-related MSD.

As stated before, the fact that logistics is a less studied area regarding the above-mentioned factors, compared to manufacturing area, was the main motivation for choosing this area to develop this work within the case study.

However, regardless the mentioned difficulties, efforts were made to achieve the results already discussed. It is important to note that, despite of the lack of available data, this work also includes a qualitative analysis, which has been achieved through the collection of information during unstructured interviews with all the stakeholders, as well as questionnaires that promoted the involvement of every logistic worker in order to conceive solutions that are suitable for their needs.

Finally, the last limitation regards to the single case study analysis, as well as, its subjectivity and applicability and possibility of generalization to other companies. However, the first issue tried to be avoided through the in-depth study of the processes, which are transversal to most industries, and the detailed construction of a methodology that can be applied in various contexts, taking into account data that, despite being qualitative and with a certain degree of subjectivity, have been validated by various levels within the organisation, from management to direct operators.

Regarding the generalizability can be considered of little relevance, since the aim of this work was the particularization of logistic processes and the application of AR solutions to enhance ergonomics conditions and mitigation of risks. Moreover, the company to develop the case study was strategically selected in order to provide the richest insights about these processes and the potentials of the proposed solutions, often using extreme and worst cases in order to reveal more information about the situation studied. It is important to highlight that the selected company, in spite of all the issues found and the enormous potential for improvement regarding HF and working conditions, it is considered a good example, in terms of concern for employees and application of lean philosophy and practices.

Indeed, it is important to be careful with generalization to specific cases, taking into account the collected requirements and the suitability of the proposed RAES-LOG methodology in order to avoid overgeneralization or misunderstandings of the relationship between variables or processes.

While the conceived methodology has its pros and cons, a strong conviction remains that this tool comprises an accurate and solid solution that was possible to achieve, taking into account the available data and resources.

## 7.4 Opportunities for future research

It is possible to conclude that the methodology developed in the scope of this thesis has reached a satisfactory conclusion, meeting the established objectives. However, attending to the limitations of the survey developed in this research, there is still place for future research directions.

A suggestion to enhance this solution is to extend it to more companies, from different activity sectors and countries, in order to obtain results statistically significant. In addition, it is extremely important that companies keep an up-to-date record of occurrences at workplaces, as well as, the prevalence of MSD on workers and data on absenteeism, in order to guarantee the accuracy of the analysis.

Moreover, this methodology constitutes a solution that is difficult to implement, in case the user does not know the techniques used, as is the case of the ergonomic assessment methods, that require an extensive knowledge about the area. In order to overcome these difficulties, a possible solution is the integration of the RAES-Log methodology in a software tool, where users would follow the instructions about the data to be collected and the information on variables and parameters necessary to provide the tool. This way, it would be possible to evaluate the risks to which workers are exposed at workplaces and propose solutions based on technology to mitigate them, regardless of the technical knowledge of the users. This is a future opportunity for another expertise area (e.g., Informatics).

Regarding the choice of the most suitable model for each of the AR solutions, the application of the AHP tool was suggested in section 5.2.5.6. Both the application of AHP method and the collection of existing solutions on the market require specific knowledge and are intensive and time-consuming processes. Therefore, the integration of RAES-Log methodology in a software would facilitate this decision-making process, providing the most suitable models to the users, irrespective of their knowledge and experience.

Therefore, the main opportunity for future research directions regards to the integration of this methodology in order to understand its impact on improving KPI related to ergonomic and safety conditions, such as the lost time days, injury severity and prevalence of MSD. Moreover, it is crucial to determine how effective this methodology and MSD prevention process is in economic terms, through the determination of worker's compensation costs due to work-related MSD development. Additionally, the proposed AR solutions involve high investments in technology. Hence, it is important to evaluate and track the Return On Investment (ROI) over time, in order to understand whether it is worth reinvesting in these solutions to enhance ergonomic conditions, eliminate risks and prevent MSD within workplaces.

Furthermore, the operators and their well-being are the focus of this project and this methodology. For this purpose, it is crucial to promote workers' involvement in continuous improvement processes, including them and their opinions when changing their workplaces. Therefore, it is important to register their complaints and consult them in order to collect opportunities of improvement, since they are the ones who deal with their jobs on a daily basis, as well as the risks associated with carrying out their tasks

## REFERENCES


Acemoglu, D. (2002). Technical Change, Inequality, and the Labor Market. *Journal of Economic Literature*, *40*(1), 7–72.

ACGIH. (1995). Threshold limit values and biological exposure indices for 2001. *American Industrial Hygiene Association Journal*, *56*(5), 443–458.

Aerospace Manufacturing & Design, A. (2015). *Northrop Grumman delivers work instructions with light*. https://www.aerospacemanufacturinganddesign.com/article/northrop-grumman-work-instructions-light-092215/

Afonso, T., Alves, A. C., & Carneiro, P. (2021). Lean Thinking, Logistic and Ergonomics: Synergetic Triad to Prepare Shop Floor Work Systems to Face Pandemic Situations. *International Journal of Global Business and Competitiveness*, 1–15.

Al-Eidan, R. M., Al-Khalifa, H., & Al-Salman, A. M. (2018). A review of wrist-worn wearable: sensors, models, and challenges. *Journal of Sensors*, *2018*.

Almada-Lobo, F. (2016). The Industry 4.0 Revolution and the Future of Manufacturing Execution Systems (MES). *Journal of Innovation Management*, *3*(4), 16–21.

Alves, A. C., Dinis-Carvalho, J., & Sousa, R. M. (2012). Lean production as promoter of thinkers to achieve companies' agility. *The Learning Organization*, 19(3), 219-237.

Alves, A. C., Ferreira, A. C., Maia, L. C., Leão, C. P., & Carneiro, P. (2019). A symbiotic relationship between Lean Production and Ergonomics: insights from Industrial Engineering final year projects. *International Journal of Industrial Engineering and Management*, 10(4), 243.

Alves, A. C., Flumerfelt, S., & Kahlen, F.-J. (2016). *Lean education: An overview of current issues*. Springer.

Amaro, P., Alves, A. C., & Sousa, R. M. (2019). Lean thinking: a transversal and global management philosophy to achieve sustainability benefits. *Lean Engineering for Global Development*, 1–31.

Ansari, N. A., & Sheikh, M. J. (2014). Evaluation of work Posture by RULA and REBA: A Case Study. *IOSR Journal of Mechanical and Civil Engineering*, *11*(4), 18–23.

Arezes, P. M., Dinis-Carvalho, J., & Alves, A. C. (2015). Workplace ergonomics in lean production environments: A literature review. *Work*, *52*(1), 57–70.

Atzori, L., Iera, A., & Morabito, G. (2010). The Internet of Things: A Survey. *Computer Networks*, *54*(15), 2787–2805.

Ayoub, M. M., & Mital, A. (2020). *Manual materials handling: Design and injury control through ergonomics*. CRC Press.

Azadeh-Fard, N., Schuh, A., Rashedi, E., & Camelio, J. A. (2015). Risk assessment of occupational injuries using Accident Severity Grade. *Safety Science*, *76*, 160–167.

Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., & MacIntyre, B. (2001). Recent advances in augmented reality. *IEEE Computer Graphics and Applications*, *21*(6), 34–47.

Azuma, R. T. (1997). A Survey of Augmented Reality. Presence: Teleoperators and Virtual Environments. *Proceedings of the Workshop for Facial and Bodily Expressions for Control and Adaptation of Games (ECAG 2008)*, *1*, 355–385. https://doi.org/10.1162/pres.1997.6.4.355

Barreto, L., Amaral, A., & Pereira, T. (2017). Industry 4.0 implications in logistics: an overview. *Procedia Manufacturing*, *13*, 1245–1252.

Barroso, M. P., Arezes, P. M., da Costa, L. G., & Miguel, A. S. (2005). Anthropometric study of Portuguese workers. *International Journal of Industrial Ergonomics*, *35*(5), 401–410.

Baumann, H. (2012). *Order picking supported by mobile computing* (Doctoral dissertation, Universität Bremen).

Berlin, C., & Adams, C. (2017). *Production ergonomics: Designing work systems to support optimal human performance*. Ubiquity press.

Bigliardi, B., Casella, G., & Bottani, E. (2021). Industry 4.0 in the logistics field: A bibliometric analysis. *IET Collaborative Intelligent Manufacturing*, *3*(1), 4–12.

Bimber, O., & Raskar, R. (2005). Spatial augmented reality: Merging real and virtual worlds. In *Spatial Augmented Reality: Merging Real and Virtual Worlds*. https://doi.org/10.1201/b10624

Bittencourt, V. L., Alves, A. C., & Leão, C. P. (2021). Industry 4.0 triggered by Lean Thinking: insights from a systematic literature review. *International Journal of Production Research*, *59*(5), 1496–1510.

Borg, G. (1990). Psychophysical scaling with applications in physical work and the perception of exertion. *Scandinavian Journal of Work, Environment & Health*, 55–58.

Borgia, E. (2014). The Internet of Things Vision: Key Features, Applications and Open Issues. *Computer Communications*, *54*, 1–31.

Bottani, E., & Vignali, G. (2019). Augmented reality technology in the manufacturing industry: A review of the last decade. *IISE Transactions*, *51*(3), 284–310. https://doi.org/10.1080/24725854.2018.1493244

Bräuer, P., & Mazarakis, A. (2018). AR in order-picking–experimental evidence with Microsoft HoloLens. *Mensch Und Computer 2018-Workshopband*.

Bräuer, P., & Mazarakis, A. (2020). Visualization of turnover rate in a warehouse using augmented reality: a demo with the Microsoft Hololens. *Proceedings of the Conference on Mensch Und Computer*, 519–522.

Breque, M., De Nul, L., & Petridis, A. (2021). Industry 5.0: towards a sustainable, human-centric and resilient European industry. *Luxembourg, LU: European Commission, Directorate-General for Research and Innovation*.

Brito, M. F., Ramos, A. L., Carneiro, P., & Gonçalves, M. A. (2019). Ergonomic analysis in lean manufacturing and industry 4.0-A systematic review. In *Lean Engineering for Global Development*. https://doi.org/10.1007/978-3-030-13515-7_4

Brito, M. F., Ramos, A. L., Carneiro, P., & Gonçalves, M. A. (2020). A continuous improvement assessment tool, considering lean, safety and ergonomics. *International Journal of Lean Six Sigma*, *11*(5), 893–916. https://doi.org/10.1108/IJLSS-12-2017-0144

Brito, M. F., Ramos, A. L. F. A., Carneiro, P., Gonçalves, M. A., Ferreira, J. A. de V., & Frade, A. B. T. (2018). Improving the production performance and ergonomic aspects using lean and agile concepts. *The Open Cybernetics & Systemics Journal*, *12*(1).

Browning, T. R., & de Treville, S. (2021). *A lean view of lean*. Wiley Online Library.

BSI, B. S. I. (2004). *Occupational health and safety management systems—Guide*.

BSI, B. S. I. (2008). *Occupational Health and Safety Management Systems - Requirements*. British Standards Institution.

Burton, J., & WHO, W. H. O. (2010). *WHO Healthy workplace framework and model: Background and supporting literature and practices*. World Health Organization.

Cardoso, J., Voigt, K., & Winkler, M. (2008). Service Engineering for the Internet of Services. *International Conference on Enterprise Information Systems*, 15–27.

Carmigniani, J., Furht, B., Anisetti, M., Ceravolo, P., Damiani, E., & Ivkovic, M. (2011). Augmented reality technologies, systems and applications. *Multimedia Tools and Applications*, *51*(1), 341–377.

Carroll, J. B. (2009). Human cognitive abilities. In *Human cognitive abilities*. https://doi.org/10.1017/cbo9780511571312

CDC. (2020). *Work-Related Musculoskeletal Disorders & Ergonomics*. Centers for Disease Control and Prevention. https://www.cdc.gov/workplacehealthpromotion/health-strategies/musculoskeletal-disorders/index.html

Chatzimichali, A. P., Gijselaers, W. H., Segers, M. S. R., van den Bossche, P., van Emmerik, H., Smulders, F. E., Jonker, P. P., & Verlinden, J. C. (2011). Bridging the Multiple Reality Gap: Application of Augmented Reality in New Product Development. *Systems, Man, and Cybernetics (SMC), 2011 IEEE International Conference On*, 1914–1919.

Cimini, C., Lagorio, A., Pirola, F., & Pinto, R. (2019). Exploring human factors in Logistics 4.0: empirical evidence from a case study. *IFAC-PapersOnLine*, *52*(13), 2183–2188.

Cimini, C., Lagorio, A., Pirola, F., & Pinto, R. (2021). How human factors affect operators' task evolution in Logistics 4.0. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *31*(1), 98–117.

Cirulis, A., & Ginters, E. (2013). Augmented reality in logistics. *Procedia Computer Science*, *26*, 14–20.

Colim, A., Morgado, R., Carneiro, P., Costa, N., Faria, C., Sousa, N., Rocha, L. A., & Arezes, P. (2021). Lean Manufacturing and Ergonomics Integration: Defining Productivity and Wellbeing Indicators in a Human–Robot Workstation. *Sustainability*, *13*(4), 1931.

Comau. (2020). *MATE-XT Exoskeleton*. https://mate.comau.com/

Costa, L., & Arezes, P. (2005). Ergonomia e Biomecânica: Introdução à elevação manual de cargas. *Guimarães: Escola de Engenharia, Universidade Do Minho*.

Cowger, G. (2016). Half measures gets less than half results. *Mechanical Engineering -The Magazine of ASME*, *138*(1), 30–35.

Crawford, J. O. (2007). The Nordic musculoskeletal questionnaire. *Occupational Medicine*, *57*(4), 300–301.

Cusumano, M. A., Holweg, M., Howell, J., Netland, T., Shah, R., Shook, J., Ward, P., & Womack, J. (2021). Commentaries on "The Lenses of Lean." *Journal of Operations Management*.

Datalogic. (2021). *HandScanner*.

de Silva, P., & Liyanage, H. (2019). Augmented reality in warehouse operations: possibilities and dynamics in Sri Lankan context. *2019 Moratuwa Engineering Research Conference (MERCon)*, 261–266.

Defense, D. of. (1993). Military Standard-System Safety Program Requirements. *MILSTD-882C. Department of Defense*.

Deguchi, A., Hirai, C., Matsuoka, H., Nakano, T., Oshima, K., Tai, M., & Tani, S. (2020). What is society 5.0. *Society*, *5*, 1–23.

Digiesi, S., Facchini, F., Mossa, G., & Mummolo, G. (2018). Minimizing and balancing ergonomic risk of workers of an assembly line by job rotation: A MINLP Model. *Int. J. Ind. Eng. Manag*, *9*(3), 129–138.

Dombrowski, U., & Wagner, T. (2014). Mental Strain as Field of Action in the 4th Industrial Revolution. *Procedia CIRP*, *17*, 100–105.

Douwes, M., & Kraker, H. de. (2009). Hand Arm Risk assessment Method (HARM), a new practical tool. *17th World Congress on Ergonomics, August*, 9–14.

Dul, J., & Neumann, W. P. (2009). Ergonomics contributions to company strategies. *Applied Ergonomics*, *40*(4), 745–752.

Eisenhardt, K. M. (1989). Building theories from case study research. *Academy of Management Review*, *14*(4), 532–550.

Elbert, R., & Sarnow, T. (2019). Augmented reality in order picking—boon and bane of information (over-) availability. *International Conference on Intelligent Human Systems Integration*, 400–406.

Erol, S., Jäger, A., Hold, P., Ott, K., & Sihn, W. (2016). Tangible Industry 4.0: A Scenario-based Approach to Learning for the Future of Production. *Procedia CIRP*, *54*, 13–18.

Etiden. (2020). *Proglove Mark 2, BT, 2D, Sr., BT (BLE, 5.1)*. https://www.etiden.com/PT/m003-eu-proglove-1.html?gclid=Cj0KCQiAk4aOBhCTARIsAFWFP9Get_19IB-Io3EuteILkx6EF3YGerHbWM7uT_sv5Vfx5szNUWfyWE4aAn7-EALw_wcB

EU-OSHA, E. A. for S. and H. at W. (2007). *Safety and health at work is everyone's concern*.

EU-OSHA, E. A. for S. and H. at W. (2019). Work-related musculoskeletal disorders: prevalence, costs and demographics in the EU.

European Commission. (2010). Factories of the future PPP: strategic multi-annual roadmap. Publications Office. https://doi.org/doi/10.2777/98640

European Commission. (2021). Industry 5.0: towards a sustainable, human-centric and resilient European industry. Publications Office. https://doi.org/doi/10.2777/308407

Eurostat. (2013). *European Statistics on Accidents at Work (ESAW)*.

Eurostat. (2019a). *Accidents at work by days lost and NACE Rev. 2 activity*. HSW_N2_04. https://ec.europa.eu/eurostat/databrowser/view/HSW_N2_04__custom_1279639/default/table?lang=en

Eurostat. (2019b). *Accidents at work by NACE Rev. 2 activity and part of body injured*. HSW_N2_06. https://ec.europa.eu/eurostat/databrowser/view/HSW_N2_06__custom_1279938/default/table?lang=en

Eurostat. (2019c). *Accidents at work by NACE Rev. 2 activity and type of injury*. HSW_N2_07. https://ec.europa.eu/eurostat/databrowser/view/hsw_n2_07/default/table?lang=en

Eurostat. (2019d). *Fatal Accidents at work by NACE Rev. 2 activity*. HSW_N2_02. https://ec.europa.eu/eurostat/databrowser/view/HSW_N2_02__custom_1271613/default/table?lang=en

Eurostat. (2019e). *Non-fatal accidents at work by NACE Rev. 2 activity*. HSW_N2_01. https://ec.europa.eu/eurostat/databrowser/view/HSW_N2_01__custom_1271609/default/table?lang=en

Eurostat. (2019f). *Persons reporting a work-related health problem by sex, age and type of problem*. HSW_PB65. https://ec.europa.eu/eurostat/databrowser/view/HSW_PB5__custom_1282777/default/table?lang=en

Falcioni, J. G. (2016). *Rewritting the Rules of Product Development*. ASME TWO PARK AVE, NEW YORK, NY 10016-5990 USA.

Fan, L., & Deng, J. (2016). Application of lean logistics in engine plant. *2016 Manufacturing and Industrial Engineering Symposium: Innovative Applications for Industry, MIES 2016*. https://doi.org/10.1109/MIES.2016.7779984

Fang, W., Zheng, S., & Liu, Z. (2019). A Scalable and Long-Term Wearable Augmented Reality System for Order Picking. *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, 4–7.

Fantini, P., Pinzone, M., & Taisch, M. (2020). Placing the operator at the centre of Industry 4.0 design: Modelling and assessing human activities within cyber-physical systems. *Computers & Industrial Engineering*, *139*, 105058.

Fite-Georgel, P. (2011). Is there a reality in industrial augmented reality? *2011 10th Ieee International Symposium on Mixed and Augmented Reality*, 201–210.

Fjeld, M. (2003). Introduction: Augmented Reality - Usability and Collaborative Aspects. *International Journal of Human-Computer Interaction*, *16*(3), 387–393. https://doi.org/10.1207/S15327590IJHC1603_1

Flumerfelt, S., Kahlen, F.-J., Alves, A. C., & Siriban-Manalang, A.-B. (2015). *Lean engineering education: driving content and competence mastery*. American Society of Mechanical Engineers (ASME).

Foidl, H., & Felderer, M. (2016). Research Challenges of Industry 4.0 for Quality Management. In *Innovations in Enterprise Information Systems Management and Engineering* (pp. 121–137). Springer.

Fondazione Ergo-MTM Italia. (2020). *EAWS Practitioner Manual*.

Fondazione Ergo-MTM Italia. (2021). *EAWS - Ergonomic Assessment Worksheet*. EAWS. https://www.eaws.it/

Fraga-Lamas, P., Fernández-Caramés, T. M., Blanco-Novoa, Ó., & Vilar-Montesinos, M. A. (2018). A review on industrial augmented reality systems for the industry 4.0 shipyard. *Ieee Access*, *6*, 13358–13375.

Francalanza, E., Borg, J., & Constantinescu, C. (2017). A Knowledge-based Tool for Designing Cyber Physical Production Systems. *Computers in Industry*, *84*, 39–58. http://www.sciencedirect.com/science/article/pii/S0166361516301373

Friedrich, W., Jahn, D., & Schmidt, L. (2002). ARVIKA-Augmented Reality for Development, Production and Service. *ISMAR*, *2002*, 3–4.

Fritzsche, L. (2010). Ergonomics risk assessment with digital human models in car assembly: Simulation versus real life. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *20*(4), 287–299.

Fukuyama, M. (2018). Society 5.0: Aiming for a new human-centered society. *Japan Spotlight*, *1*, 47–50.

Furht, B. (2011). *Handbook of Augmented Reality*. Springer Science & Business Media.

Glova, J., Sabol, T., & Vajda, V. (2014). Business Models for the Internet of Things Environment. *Procedia Economics and Finance*, *15*, 1122–1129.

Gorecky, D., Schmitt, M., Loskyll, M., & Zühlke, D. (2014). Human-machine-interaction in the industry 4.0 era. *Proceedings - 2014 12th IEEE International Conference on Industrial Informatics, INDIN 2014*, 289–294. https://doi.org/10.1109/INDIN.2014.6945523

Grosse, E. H., Glock, C. H., Jaber, M. Y., & Neumann, W. P. (2015). Incorporating human factors in order picking planning models: framework and research opportunities. *International Journal of Production Research*, *53*(3), 695–717.

Hancock, P. A., & Diaz, D. D. (2002). Ergonomics as a foundation for a science of purpose. *Theoretical Issues in Ergonomics Science*, *3*(2), 115–123.

Hancock, P. A., Pepe, A. A., & Murphy, L. L. (2005). Hedonomics: The power of positive and pleasurable ergonomics. *Ergonomics in Design*, *13*(1), 8–14.

Hansen, S. M., & Jensen, P. L. (1993). *Arbeidsmilj. o og samfundsekonomi i Norden (Working environment and national economies in the Nordic Countries)*. Report.

Härmä, A., Jakka, J., Tikander, M., Karjalainen, M., Lokki, T., Hiipakka, J., & Lorho, G. (2004). Augmented reality audio for mobile and wearable appliances. *AES: Journal of the Audio Engineering Society*, *52*(6), 618–639. https://www.scopus.com/inward/record.uri?eid=2-s2.0-4344645826&partnerID=40&md5=0669099b83cc2cd049231f578de827ec

Hermann, M., Pentek, T., & Otto, B. (2016). Design Principles for Industrie 4.0 Scenarios. *Proceedings of the Annual Hawaii International Conference on System Sciences*, 3928–3937.

Hignett, S., & McAtamney, L. (2000). Rapid entire body assessment (REBA). *Applied Ergonomics*, *31*(2), 201–205.

Hopp, W. J., & Spearman, M. S. (2021). The lenses of lean: Visioning the science and practice of efficiency. *Journal of Operations Management*, *67*(5), 610–626.

Hou, L., Wang, X., Bernold, L., & Love, P. E. D. (2013). Using Animated Augmented Reality to Cognitively Guide Assembly. *Journal of Computing in Civil Engineering - ASCE*, *27*(5), 439–451. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000184

IEA, C. of the I. E. A. (2015). *What is ergonomics?* Federation of the European Ergonomics Societies. https://www.ergonomics-fees.eu/node/7

Ilanković, N., Živanić, D., & Zelić, A. (2020). Augmented Reality in Order-picking processes–Advantages and Disadvantages. *Nikola Ilanković-Dragan Živanić-Atila Zelić: Augmented*.

ILS, I. L. S. Ltd. (2017). *Vocollect A500 Mobile Device*. http://inter-solutions.co.uk/solutions/honeywell-vocollect-voice-solutions/vocollet-werable-mobile-devices/vocollect-a500-mobile-device.html

IMD. (2014). *Risk screening. The Ergonomic Assessment Work-Sheet (EAWS)*. IMD. http://mtm-international.org/risk-screening-the-ergonomic-assessment-work-sheet-eaws/

International Standard Organization. (2003). ISO 11228-1: Ergonomics-Manual handling-Part 1: Lifting and carrying. *International Standard Organization*.

Jensen, M. P., & Karoly, P. (2011). *Self-report scales and procedures for assessing pain in adults.*

Kaasinen, E., Schmalfuß, F., Özturk, C., Aromaa, S., Boubekeur, M., Heilala, J., Heikkilä, P., Kuula, T., Liinasuo, M., Mach, S., Mehta, R., Petäjä, E., & Walter, T. (2020). Empowering and engaging industrial workers with Operator 4.0 solutions. *Computers and Industrial Engineering*, *139*. https://doi.org/10.1016/j.cie.2019.01.052

Kagermann, H. (2015). Change Through Digitization - Value Creation in the Age of Industry 4.0. In *Management of Permanent Change* (pp. 23–45). Springer.

Kagermann, H., Wahlster, W., & Helbig, J. (2013a). *Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0*.

Kagermann, H., Wahlster, W., & Helbig, J. (2013b). *Securing the Future of German Manufacturing Industry: Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0*. http://forschungsunion.de/pdf/industrie_4_0_final_report.pdf

Karhu, O., Härkönen, R., Sorvali, P., & Vepsäläinen, P. (1981). Observing working postures in industry: Examples of OWAS application. *Applied Ergonomics*, *12*(1), 13–17.

Karwowski, W., & Zhang, W. (2021). The discipline of human factors and ergonomics. *Handbook of Human Factors and Ergonomics*, 1–37.

Kaspar, S., & Schneider, M. (2015). Lean and industry 4.0 in the field of intra logistics: Efficiency improvement by combination of the two approaches [Lean und Industrie 4.0 in der Intralogistik: Effizienzsteigerung durch Kombination der beiden Ansätze]. *Productivity Management*, *20*(5), 17–20. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84946398205&partnerID=40&md5=2d9b05cb6515f199dff91146ccdf697d

Keidanren, J. B. F. (2016). Toward realization of the New Economy and Society—Reform of the Economy and Society by the Deepening of “Society 5.0.” *April*, *19*, 2016.

Eriksson, K. (2018). *Augmented reality gives us super human abilities and a sixth sense*. https://www.ericsson.com/en/blog/2018/7/augmented-reality-gives-us-super-human-abilities-and-a-sixth-sense

Khoshnevis, M., & Lindberg, E. (2015). *Development of a Demonstrator in the Aerospace Industry for Visualization of 3D Work Instructions Mahan Khoshnevis*.

Kipper, G., & Rampolla, J. (2012). *Augmented Reality: an emerging technologies guide to AR*. Elsevier.

Kiss, F., & Poguntke, R. (2021). Augmented Senses: Evaluating Sensory Enhancement Applications. In *Technology-Augmented Perception and Cognition* (pp. 229–254). Springer.

Klussmann, A., Steinberg, U., Liebers, F., Gebhardt, H., & Rieger, M. A. (2010). The Key Indicator Method for Manual Handling Operations (KIM-MHO)-evaluation of a new method for the assessment of working conditions within a cross-sectional study. *BMC Musculoskeletal Disorders*, *11*(1), 1–8.

Kolberg, D., & Zühlke, D. (2015). Lean Automation Enabled by Industry 4.0 Technologies. *IFAC-PapersOnLine*, *48*(3), 1870–1875.

Kopetz, H. (2011). Real-Time Systems. In *Real-Time Systems: Design Principles for Distributed Embedded Applications* (pp. 307–323). Springer US. http://dx.doi.org/10.1007/978-1-4419-8237-7_13

Kosky, P., Balmer, R., Keat, W., & Wise, G. (2013). *Exploring engineering*. Academic Press: Boston, MA, USA.

Krafcik, J. F. (1988). Triumph of the lean production system. *Sloan Management Review*. https://doi.org/10.1108/01443570911005992

Krueger, M. W., & Wilson, S. (1985). VIDEOPLACE: A report from the Artificial Reality Laboratory. *Leonardo*, *18*(3), 145–151.

Kuorinka, I., Jonsson, B., Kilbom, A., Vinterberg, H., Biering-Sørensen, F., Andersson, G., & Jørgensen, K. (1987). Standardised Nordic questionnaires for the analysis of musculoskeletal symptoms. *Applied Ergonomics*, *18*(3), 233–237.

Kymäläinen, T., Koskinen, H., & Aromaa, S. (2016). Design and research for advanced human augmentation in the industrial work context. *12th International Conference on Intelligent Environments*, 608–614.

Kyriazis, D., & Varvarigou, T. (2013). Smart, Autonomous and Reliable Internet of Things. *Procedia Computer Science*, *21*, 442–448.

Lee, J., Bagheri, B., & Kao, H.-A. (2015). A Cyber-Physical Systems Architecture for Industry 4.0-based Manufacturing Systems. *Manufacturing Letters*, *3*, 18–23. http://www.sciencedirect.com/science/article/pii/S221384631400025X

Leigh, J., Macaskill, P., Kuosma, E., & Mandryk, J. (1999). Global burden of disease and injury due to occupational factors. *Epidemiology*, 626–631.

Leigh, S.-W., Agrawal, H., & Maes, P. (2018). Robotic Symbionts: Interweaving Human and Machine Actions. *IEEE Pervasive Computing*, *17*(2), 34–43. https://doi.org/10.1109/MPRV.2018.022511241

Liker, J. K. (2004). *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*. McGraw-Hill Education.

Likert, R. (1932). A technique for the measurement of attitudes. *Archives of Psychology*.

Lin, C. J., Caesaron, D., & Woldegiorgis, B. H. (2019). The Effects of Augmented Reality Interaction Techniques on Egocentric Distance Estimation Accuracy. *Applied Sciences*, *9*(21), 4652.

Livingston, M. A. (2005). Evaluating human factors in augmented reality systems. *IEEE Computer Graphics and Applications*, *25*(6), 6–9.

Lu, S. C.-Y., Shpitalni, M., & Gadh, R. (1999). Virtual and Augmented Reality Technologies for Product Realization. *CIRP Annals - Manufacturing Technology*, *48*(2), 471–495. http://www.sciencedirect.com/science/article/pii/S0007850607632296

Maia, L. C., Alves, A. C. & Leão, C. P. (2012). Does Lean Methodologies include ergonomic tools? *International Symposium on Occupational Safety and Hygiene (SHO2012)*

Malik, A. A., & Bilberg, A. (2017). FRAMEWORK TO IMPLEMENT COLLABORATIVE ROBOTS IN MANUAL ASSEMBLY: A LEAN AUTOMATION APPROACH. *Annals of DAAAM & Proceedings*, *28*.

Malik, A. A., & Bilberg, A. (2019). Human centered lean automation in assembly. *Procedia CIRP*, *81*, 659–664. https://doi.org/10.1016/j.procir.2019.03.172

Marsh McLennan. (2021). *Augmented Reality Is a Game-Changer. Can We Lower the Barrier to Entry?* https://www.brinknews.com/augmented-reality-is-a-game-changer-can-we-lower-the-barrier-to-entry/

Maslow, A. H. (2013). *Toward a psychology of being*. Simon and Schuster.

Mayo, E. (2004). *The human problems of an industrial civilization*. Routledge.

McAtamney, L., & Corlett, E. N. (1993). RULA: a survey method for the investigation of work-related upper limb disorders. *Applied Ergonomics*, *24*(2), 91–99.

Mesquita, C. C., Ribeiro, J. C., & Moreira, P. (2010). Portuguese version of the standardized Nordic musculoskeletal questionnaire: cross cultural and reliability. *Journal of Public Health*, *18*(5), 461–466.

Michalos, G., Karagiannis, P., Makris, S., Tokçalar, Ö., & Chryssolouris, G. (2016). Augmented Reality (AR) Applications for Supporting Human-robot Interactive Cooperation. *48th CIRP Conference on Manufacturing Systems - CIRP CMS 2015*, *41*, 370 – 375. https://doi.org/10.1016/j.procir.2015.12.005

Microsoft. (2020). *Business-ready solutions for HoloLens 2*. https://www.microsoft.com/en-gb/hololens/apps

Mills, J., & Birks, M. (2014). *Qualitative methodology: A practical guide*. Sage.

Miorandi, D., Sicari, S., de Pellegrini, F., & Chlamtac, I. (2012). Internet of Things: Vision, Applications and Research Challenges. *Ad Hoc Networks*, *10*(7), 1497–1516.

Mital, A., Nicholson, A. S., & Ayoub, M. M. (2017). *A guide to manual materials handling*. CRC Press.

Monden, Y. (1983). *Toyota Production System - An Integrated approach to Just-in-Time* (First Edit). Industrial Engineering and Management Press, Institute of Industrial Engineers.

Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., Sauer, O., Schuh, G., Sihn, W., & Ueda, K. (2016). Cyber-Physical Systems in Manufacturing. *CIRP Annals - Manufacturing Technology*, *65*(2), 621–641. http://www.sciencedirect.com/science/article/pii/S0007850616301974

Moore, J. S., & Vos, G. A. (2004). The strain index. In *Handbook of Human Factors and Ergonomics Methods* (pp. 109–114). CRC Press.

Mourtzis, D., Vlachou, E., & Milas, N. (2016). Industrial Big Data as a Result of IoT Adoption in Manufacturing. *Procedia CIRP*, *55*, 290–295. http://www.sciencedirect.com/science/article/pii/S2212827116307880

Mourtzis, D., Zogopoulos, V., & Vlachou, E. (2017). Augmented reality application to support remote maintenance as a service in the robotics industry. *Procedia CIRP*, *63*, 46–51.

Mueck, B., Höwer, M., Franke, W., & Dangelmaier, W. (2005). Augmented reality applications for warehouse logistics. In *Soft Computing as Transdisciplinary Science and Technology* (pp. 1053–1062). Springer.

Mühlhäuser, M. (2008). Constructing Ambient Intelligence. In M. Mühlhäuser, A. Ferscha, & E. Aitenbichler (Eds.), *AmI 2007 Workshops Darmstadt, Germany, November 7-10, 2007 Revised Papers* (pp. 158–164). Springer Berlin Heidelberg. http://dx.doi.org/10.1007/978-3-540-85379-4_20

Mura, M. D., Dini, G., & Failli, F. (2016). An Integrated Environment Based on Augmented Reality and Sensing Device for Manual Assembly Workstations. *48th CIRP Conference on MANUFACTURING SYSTEMS - CIRP CMS 2015*, *41*, 340 – 345. https://doi.org/10.1016/j.procir.2015.12.128

Murauer, N., Müller, F., Günther, S., Schön, D., Pflanz, N., & Funk, M. (2018). An analysis of language impact on augmented reality order picking training. *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*, 351–357.

Nakanishi, M., Ozeki, M., Akasaka, T., & Okada, Y. (2007). Human factor requirements for Applying Augmented reality to manuals in actual work situations. *2007 IEEE International Conference on Systems, Man and Cybernetics*, 2650–2655.

Nee, A. Y. C., Ong, S. K., Chryssolouris, G., & Mourtzis, D. (2012). Augmented reality applications in design and manufacturing. *CIRP Annals*, *61*(2), 657–679. https://doi.org/https://doi.org/10.1016/j.cirp.2012.05.010

Neugebauer, R., Hippmann, S., Leis, M., & Landherr, M. (2016). Industrie 4.0 - From the Perspective of Applied Research. *Procedia CIRP*, *57*, 2–7. http://www.sciencedirect.com/science/article/pii/S2212827116311556

Neumann, W. P., Winkelhaus, S., Grosse, E. H., & Glock, C. H. (2021). Industry 4.0 and the human factor–A systems framework and analysis methodology for successful development. *International Journal of Production Economics*, *233*, 107992.

New Atlas. (2018). *MATE is made to look out for your shoulders*. https://newatlas.com/comau-mate-exoskeleton/56625/

NRC, I. O. M. (2001). *Musculoskeletal Disorders and the Workplace. Low Back and Upper Extremities*. National Research Council/Institute of Medicine//National Academy Press.

Nunes, I. L. (2009). Ergonomic risk assessment methodologies for work-related musculoskeletal disorders: a patent overview. *Recent Patents on Biomedical Engineering (Discontinued)*, *2*(2), 121–132.

Nunes, I. L. (2013). Occupational safety and health risk assessment methodologies. *OSH Wiki Networking Knowledge, EU-OSHA—European Agency for Safety and Health at Work (Http://Oshwiki. Eu/Wiki/Occupational_safety_and_health_risk_assessment_ Methodologies)*.

Nunes, I. L. (2015). Integration of ergonomics and lean six sigma. A model proposal. *Procedia Manufacturing*, *3*, 890–897.

Nunes, I. L., & Bush, P. M. (2012). Work-related musculoskeletal disorders assessment and prevention. *Ergonomics-A Systems Approach*, 1–30.

Nunes, I. L., & Machado, V. C. (2007). Merging ergonomic principles into lean manufacturing. *IIE Annual Conference. Proceedings*, 836.

Nunes, M. L., Pereira, A. C., & Alves, A. C. (2017). Smart products development approaches for Industry 4.0. *Procedia Manufacturing*, *13*(Supplement C), 1215–1222. https://doi.org/https://doi.org/10.1016/j.promfg.2017.09.035

Oborne, D. J. (1987). Ergonomics at work. *New York: Joh Wiley & Sons, Inc.*

Occhipinti, E. (1998). OCRA: a concise index for the assessment of exposure to repetitive movements of the upper limbs. *Ergonomics*, *41*(9), 1290–1311.

Ohno, T. (1988). Toyota production system: beyond large-scale production. In *Produtivity Press* (Vol. 15, Issue 2). CRC Press, 1988. https://doi.org/10.1108/eb054703

Parviz, B. A. (2009). Augmented reality in a contact lens. *IEEE Spectrum, Sep*, *1*.

Pereira, A., Abreu, M. F., Silva, D., Alves, A. C., Oliveira, J. A., Lopes, I., & Figueiredo, M. C. (2016). Reconfigurable Standardized Work in a Lean Company – A Case Study. *Procedia CIRP*, *52*, 239–244. https://doi.org/10.1016/j.procir.2016.07.019

Pereira, A. C., Arezes, P., Alves, A. C., & Duarte, F. J. (2019). An enhanced human-machine interface enabled by augmented reality – A new approach for human augmentation. *Proceedings of the XIX International Conference on Occupational Risk Prevention*, 178–187.

Pereira, A. C., Dinis-Carvalho, J., Alves, A. C., & Arezes, P. (2019). How Industry 4.0 can enhance Lean practices. *FME Transactions*, *47*(4), 810–822.

Pereira, A. C., & Romero, F. (2017). A review of the meanings and the implications of the Industry 4.0 concept. *Procedia Manufacturing*, *13*(Supplement C), 1206–1214. https://doi.org/https://doi.org/10.1016/j.promfg.2017.09.032

Pereira, A., Lee, G. A., Almeida, E., & Billinghurst, M. (2016). A study in virtual navigation cues for forklift operators. *2016 XVIII Symposium on Virtual and Augmented Reality (SVR)*, 95–99.

Persson, J.-G. (2016). Current Trends in Product Development. *Procedia CIRP*, *50*, 378–383. http://www.sciencedirect.com/science/article/pii/S2212827116305881

Piedrahita, H. (2006). Costs of work-related musculoskeletal disorders (MSDs) in developing countries: Colombia case. *International Journal of Occupational Safety and Ergonomics*, *12*(4), 379–386.

Plavšic, M., Duschl, M., Tönnis, M., Bubb, H., & Klinker, G. (2009). Ergonomic Design and Evaluation of Augmented Reality Based Cautionary Warnings for Driving Assistance in Urban Environments. *Proceedings of Intl. Ergonomics Assoc*.

Porter, M. E., & Heppelmann, J. E. (2015). How Smart, Connected Products are Transforming Companies. *Harvard Business Review*, *93*(10), 96–114.

Porter, M. E., & Heppelmann, J. E. (2017). Why every organization needs an augmented reality strategy. *HBR'S 10 MUST*, *85*.

Posada, J., Toro, C., Barandiaran, I., Oyarzun, D., Stricker, D., de Amicis, R., Pinto, E. B., Eisert, P., Döllner, J., & Vallarino, I. (2015). Visual Computing as a Key Enabling Technology for Industrie 4.0 and Industrial Internet. *IEEE Computer Graphics and Applications*, *35*(2), 26–40.

Potvin, J. R., Ciriello, V. M., Snook, S. H., Maynard, W. S., & Brogmus, G. E. (2021). The Liberty Mutual manual materials handling (LM-MMH) equations. *Ergonomics*, 1–17.

Qin, J., Liu, Y., & Grosvenor, R. (2016). A Categorical Framework of Manufacturing for Industry 4.0 and Beyond. *Procedia CIRP*, *52*, 173–178.

Radziwon, A., Bilberg, A., Bogers, M., & Madsen, E. S. (2014). The Smart Factory: Exploring Adaptive and Flexible Manufacturing Solutions. *Procedia Engineering*, *69*, 1184–1190.

Rajesh, R., Babu, R. V, & Ramachandran, S. (2013). Ergonomics Redesign of Material Handling Work System in Manufacturing Plant. *International Journal of Innovative Research in Science Engineering and Technology*, *2*.

Raji, R. S. (1994). Smart Networks For Control. *IEEE Spectrum*, *31*(6), 49–55.

Raosoft. (2004). *Sample size calculator*. Raosoft, Inc. http://www.raosoft.com/samplesize.html

Rehab Concepts Physical Therapy. (2021). *Body Mechanics Lifting Technique*. https://rehabconceptspt.com/bone-health-series-part-four-of-four-posture-and-safe-movement/body-mechanics-lifting-technique/

Reif, R., & Günthner, W. A. (2009). Pick-by-vision: augmented reality supported order picking. *The Visual Computer*, *25*(5), 461–467.

Reif, R., & Walch, D. (2008). Augmented & Virtual Reality applications in the field of logistics. *The Visual Computer*, *24*(11), 987–994.

Rekimoto, J. (1997). Navicam: A magnifying glass approach to augmented reality. *Presence: Teleoperators & Virtual Environments*, *6*(4), 399–412.

Remenyi, D., Williams, B., Money, A., & Swartz, E. (1998). *Doing research in business and management: an introduction to process and method*. Sage.

Roblek, V., Meško, M., & Krapež, A. (2016). A Complex View of Industry 4.0. *SAGE Open*, *6*(2), 1–11.

Rodrigues, M. A., Arezes, P. M., & Leão, C. P. (2015). Defining risk acceptance criteria in occupational settings: A case study in the furniture industrial sector. *Safety Science*, *80*, 288–295.

Romero, D., Bernus, P., Noran, O., Stahre, J., & Berglund, Å. F. (2016). The operator 4.0: Human cyber-physical systems & adaptive automation towards human-automation symbiosis work systems. *IFIP Advances in Information and Communication Technology*, *488*, 677–686. https://doi.org/10.1007/978-3-319-51133-7_80

Romero, D., Flores, M., Herrera, M., & Resendez, H. (2019). Five management pillars for digital transformation integrating the lean thinking philosophy. *2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, 1–8.

Romero, D., Stahre, J., & Taisch, M. (2020). The Operator 4.0: Towards socially sustainable factories of the future. *Computers and Industrial Engineering*, *139*. https://doi.org/10.1016/j.cie.2019.106128

Romero, D., Stahre, J., Wuest, T., Noran, O., Bernus, P., Fast-Berglund, Å., & Gorecky, D. (2016). Towards an operator 4.0 typology: A human-centric perspective on the fourth industrial revolution technologies. *CIE 2016: 46th International Conferences on Computers and Industrial Engineering*. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85013852895&partnerID=40&md5=60458c9a89e1710f0588a5e11c711c0d

Ropp, T. D., Thomas, E., Lee, E., Broyles, A., Paul, L., C, A., & Nicol, J. (2013). *Creating hybrid air vehicle technical work instructions using Augmented Reality and 2D Barcode visualization technologies*.

Ruppert, T., Jaskó, S., Holczinger, T., & Abonyi, J. (2018). Enabling Technologies for Operator 4.0: A Survey. *Applied Sciences*, *8*(9), 1650.

Sääski, J., Salonen, T., Liinasuo, M., Pakkanen, J., Vanhatalo, M., & Riitahuhta, A. (2008). Augmented Reality Efficiency in Manufacturing Industry: a Case Study. Proceedings of NordDesign 2008 Conference, 99–109.

Saaty, T. L. (2004). Decision making—the analytic hierarchy and network processes (AHP/ANP). Journal of Systems Science and Systems Engineering, 13(1), 1–35.

Sanidas, E., & Shin, W. (2017). Lean production system and economic development across the world today. *Int J Econ Manage Sci*, *6*(06).

Sarodnick, F., & Brau, H. (2006). Methoden der usability evaluation. *Verlag Hans Huber*.

Saunders, M., Lewis, P., & Thornhill, A. (2009). Research Methods for Business Students. In *Research methods for business students* (Fifth edit). Financial Times Prentice Hall. https://doi.org/10.1007/s13398-014-0173-7.2

Schaub, K., Caragnano, G., Britzke, B., & Bruder, R. (2013). The European assembly worksheet. *Theoretical Issues in Ergonomics Science*, *14*(6), 616–639.

Schaub, K., Kugler, M., Bierwirth, M., Sinn-Behrendt, A., & Bruder, R. (2012). Prevention of MSD by means of ergonomic risk assessment (tools) in all phases of the vehicle development process. *Work*, *41*(Supplement 1), 4409–4412.

Schaub, K., Mühlstedt, J., Illmann, B., Bauer, S., Fritzsche, L., Wagner, T., Bullinger-Hoffmann, A. C., & Bruder, R. (2012). Ergonomic assessment of automotive assembly tasks with digital human modelling and the 'ergonomics assessment worksheet'(EAWS). *International Journal of Human Factors Modelling and Simulation*, *3*(3–4), 398–426.

Schmidt, R., Möhring, M., Härting, R.-C., Reichstein, C., Neumaier, P., & Jozinović, P. (2015). Industry 4.0 - Potentials for Creating Smart Products: Empirical Research Results. *International Conference on Business Information Systems*, 16–27.

Schuh, G., Potente, T., Wesch-Potente, C., & Hauptvogel, A. (2013). *Sustainable Increase of Overhead Productivity due to Cyber-Physical Systems*.

Schwerdtfeger, B., Reif, R., Günthner, W. A., & Klinker, G. (2011). Pick-by-vision: there is something to pick at the end of the augmented tunnel. *Virtual Reality*, *15*(2–3), 213–223.

Shariatzadeh, N., Lundholm, T., Lindberg, L., & Sivard, G. (2016). Integration of Digital Factory with Smart Factory Based on Internet of Things. *Procedia CIRP*, *50*, 512–517. http://www.sciencedirect.com/science/article/pii/S2212827116305066

Shiroishi, Y., Uchiyama, K., & Suzuki, N. (2018). Society 5.0: For human security and well-being. *Computer*, *51*(7), 91–95.

Sinha, N., & Matharu, M. (2019). A comprehensive insight into Lean management: Literature review and trends. *Journal of Industrial Engineering and Management*, *12*(2), 302–317.

Siriborvornratanakul, T. (2018). Enhancing user experiences of mobile-based augmented reality via spatial augmented reality: Designs and architectures of projector-camera devices. *Advances in Multimedia*, *2018*. https://doi.org/10.1155/2018/8194726

Snook, S. H., & Ciriello, V. M. (1991). The design of manual handling tasks: revised tables of maximum acceptable weights and forces. *Ergonomics*, *34*(9), 1197–1213.

Soliman, M., Saurin, T. A., & Anzanello, M. J. (2018). The impacts of lean production on the complexity of socio-technical systems. *International Journal of Production Economics*, *197*, 342–357.

Spear, S. J. (2004). Learning to lead at Toyota. *Harvard Business Review*, *82*(5), 78–91.

Stadnicka, D., & Antonelli, D. (2019). Human-robot collaborative work cell implementation through lean thinking. *INTERNATIONAL JOURNAL OF COMPUTER INTEGRATED MANUFACTURING*, *32*(6), 580–595. https://doi.org/10.1080/0951192X.2019.1599437

Risk management - AS/NZS 4360-2004, (2004).

Starner, T. E. (2002). Wearable computers: No longer science fiction. *IEEE Pervasive Computing*, *1*(1), 86–88.

Stein, R., Ferrero, S., Hetfield, M., Quinn, A., & Krichever, M. (1998). Development of a commercially successful wearable data collection system. *Digest of Papers. Second International Symposium on Wearable Computers (Cat. No. 98EX215)*, 18–24.

StickyLock. (2019). *AR Technology Set to Revolutionise the Manufacturing Industry*. https://immersive-technology.com/augmentedreality/ar-technology-set-to-revolutionise-the-manufacturing-industry/

Stoltz, M.-H., Giannikas, V., McFarlane, D., Strachan, J., Um, J., & Srinivasan, R. (2017). Augmented Reality in Warehouse Operations: Opportunities and Barriers. *IFAC-PapersOnLine*, *50*(1), 12979–12984. https://doi.org/10.1016/j.ifacol.2017.08.1807

Strandhagen, J. O., Vallandingham, L. R., Fragapane, G., Strandhagen, J. W., Stangeland, A. B. H., & Sharma, N. (2017). Logistics 4.0 and emerging sustainable business models. *Advances in Manufacturing*, *5*(4), 359–369.

Suárez-Warden, F., Mendívil, E. G., Rodríguez, C. A., & Garcia-Lumbreras, S. (2015). Assembly Operations Aided by Augmented Reality: An Endeavour toward a Comparative Analysis. *2015 International Conference on Virtual and Augmented Reality in Education*, *75*, 281–290. https://doi.org/10.1016/j.procs.2015.12.249

Sugimori, Y., Kusunoki, K., Cho, F., & Uchikawa, S. (1977). Toyota production system and Kanban system Materialization of just-in-time and respect-for-human system. *International Journal of Production Research*, *15*(6), 553–564. https://doi.org/10.1080/00207547708943149

Sun, L., Zhang, Y., Shang, K., & Wu, A. (2019). Investigation on musculoskeletal disorders of the workers in automobile production logistics. *Proceeding of the 24th International Conference on Industrial Engineering and Engineering Management 2018*, 491–498.

Sutherland, I. E. (1968). A head-mounted three dimensional display. *Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I*, 757–764.

Syberfeldt, A., Danielsson, O., & Gustavsson, P. (2017). Augmented reality smart glasses in the smart factory: Product evaluation guidelines and review of available products. *Ieee Access*, *5*, 9118–9130.

Syberfeldt, A., Danielsson, O., Holm, M., & Wang, L. (2015). Visual assembling guidance using augmented reality. *Procedia Manufacturing*, *1*, 98–109.

Syberfeldt, A., Danielsson, O., Holm, M., & Wang, L. (2016). Dynamic operator instructions based on augmented reality and rule-based expert systems. *Procedia CIRP*, *41*, 346–351.

Sylla, N., Bonnet, V., Colledani, F., & Fraisse, P. (2014). Ergonomic contribution of ABLE exoskeleton in automotive industry. *International Journal of Industrial Ergonomics*, *44*(4), 475–481. https://doi.org/10.1016/j.ergon.2014.03.008

Tachi, S. (2013). From 3D to VR and further to telexistence. *Proceedings of 23rd International Conference on Artificial Reality and Telexistence, ICAT 2013*, 1–10. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84894503380&partnerID=40&md5=e2cb1020e396386316e091c8821a682f

Taherdoost, H. (2017). Determining sample size; how to calculate survey sample size. *International Journal of Economics and Management Systems*, *2*.

Tesfay, W. B., Aleksy, M., Andersson, K., & Lehtola, M. (2013). Mobile computing application for industrial field service engineering: A case for ABB service engineers. *Proceedings - Conference on Local Computer Networks, LCN*, 188–193. https://doi.org/10.1109/LCNW.2013.6758518

Thomas, C., Panagiotopoulos, T., Kotipalli, P., Haynes, M., & Starner, T. (2018). RF-pick: comparing order picking using a HUD with wearable RFID verification to traditional pick methods. *Proceedings of the 2018 ACM International Symposium on Wearable Computers*, 168–175.

Thomas, D., & Holmquist, L. E. (2020). WristAR: A Wrist-Mounted Augmented Reality Interface. *19th International Conference on Mobile and Ubiquitous Multimedia*, 312–314.

Thomas P. Caudell, & David W. Mizell. (1992). Augmented reality: An application of heads-up display technology to manual manufacturing processes. *Hawaii International Conference on System Sciences*, 659–669.

Toomingas, A. (1998). *Methods for evaluating work-related musculoskeletal neck and upper-extremity disorders in epidemiological studies*.

Tunzelmann, N. von. (2003). Historical Coevolution of Governance and Technology in the Industrial Revolutions. *Structural Change and Economic Dynamics*, *14*(4), 365–384. http://www.sciencedirect.com/science/article/pii/S0954349X03000298

UN, U. N. (2019). *The Sustainable Development Goals Report 2019*. United Nations.

Verlinden, J., & Horváth, I. (2009). Analyzing Opportunities for Using Interactive Augmented Prototyping in Design Practice. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *23*(03), 289–303.

Vicente, S., Alves, A. C., Carvalho, M. S., & Costa, N. (2016). *Improving Safety and Health in a Lean Logistic project: a case study in an automotive electronic components company*.

vom Stein, A. M., & Günthner, W. A. (2016). Using Smart Glasses for the Inclusion of Hearing-Impaired Warehouse Workers into Their Working Environment. *International Conference on HCI in Business, Government, and Organizations*, 358–368.

Wallace, W. L. (1971). *The Logic of Science in Sociology*. ROUTLEDGE JOURNALS, TAYLOR & FRANCIS LTD.

Wang, W., Wang, F., Song, W., & Su, S. (2020). Application of augmented reality (AR) technologies in inhouse logistics. *E3S Web of Conferences*, *145*, 02018.

Wang, X., Ong, S. K., & Nee, A. Y. C. (2016). A comprehensive survey of augmented reality assembly research. *Advances in Manufacturing*, *4*(1). https://doi.org/10.1007/s40436-015-0131-4

Waters, T. R., Lu, M.-L., & Occhipinti, E. (2007). New procedure for assessing sequential manual lifting jobs using the revised NIOSH lifting equation. *Ergonomics*, *50*(11), 1761–1770.

Waters, T. R., Putz-Anderson, V., Garg, A., & Fine, L. J. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics*, *36*(7), 749–776.

Weber, A. (2014). Visual work instructions and the paperless factory. *Assembly Magazine*, *57*(3). http://www.scopus.com/inward/record.url?eid=2-s2.0-84897678650&partnerID=tZOtx3y1

Weyer, S., Schmitt, M., Ohmer, M., & Gorecky, D. (2015). Towards Industry 4.0 - Standardization as the Crucial Challenge for Highly Modular, Multi-vendor Production Systems. *IFAC-PapersOnLine*, *48*(3), 579–584. http://dx.doi.org/10.1016/j.ifacol.2015.06.143

Whitefoot, K. S., & Donofrio, N. M. (2015). *Making Value for America: Embracing the Future of Manufacturing, Technology, and Work. (Eds.) Foundational Best Practices for Making Value for America, National Academy of Engineering.*

Woltering, T., Sardoux Klasen, A., & Feldmann, C. (2020). *Augmented Reality in the Packing Process A Model for Analyzing Economic Efficiency*.

Womack, J. P. (1996). *Lean thinking : banish waste and create wealth in your corporation*. New York, NY : Simon & Schuster, [1996] ©1996. https://search.library.wisc.edu/catalog/999813748702121

Womack, J. P. ;, Jones, D. T. ;, & Roos, D. (1991). *The Machine That Changed the World: The Story of Lean Production*. Rawson Associates.

Wong, J. J. S., & Mir-Nasiri, N. (2012). Design and development of a human-machine interactive-force controlled powered upper-limb exoskeleton for human augmentation and physical rehabilitation. *2012 IEEE-EMBS Conference on Biomedical Engineering and Sciences, IECBES 2012*, 465–470. https://doi.org/10.1109/IECBES.2012.6498089

Yeo, H.-S., Koike, H., & Quigley, A. (2019). Augmented learning for sports using wearable head-worn and wrist-worn devices. *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 1578–1580.

Yin, R. K. (2009). *Case Study Research: Design and Methods*. SAGE Publications.

Yin, R. K. (2011). *Applications of case study research*. sage.

Yin, R. K. (2018). *Case Study Research and Applications: Design and Methods*. SAGE Publications.

Yuan, M. L., Ong, S. K., & Nee, A. Y. C. (2008). Augmented reality for assembly guidance using a virtual interactive tool. *International Journal of Production Research*, *46*(7), 1745–1767. https://doi.org/10.1080/00207540600972935

Zhou, K., Liu, T., & Zhou, L. (2016). Industry 4.0: Towards Future Industrial Opportunities and Challenges. *International Conference on Fuzzy Systems and Knowledge Discovery*, 2147–2152.

Zuehlke, D. (2010). SmartFactory - Towards a Factory-of-things. *Annual Reviews in Control*, *34*(1), 129–138.

## APPENDIX I – DETERMINATION OF THE FEMALE PERCENTILE FOR A STATURE OF 1520 MM

In order to determine the female percentile that corresponds to the stature of 1520 mm, it is necessary to determine the mean and standard deviation vales for female statures. Based on anthropometric measures for adult Portuguese population (Barroso et al., 2005), the mean stature for females is 1565 mm with a standard deviation of 66 mm. The calculation is presented in Equation 6.

$$Stature\ F\ (1565; 66)$$

$$P_x = \mu + Z_x \times \delta$$

$$1520 = 1565 + Z_x \times 66$$

$$Z_x = \frac{1520 - 1565}{66} = -0{,}68 \rightarrow p \approx 25\%$$

$Where$:

$\mu = Mean$

$Z_x = standard\ normal\ random\ variable$

$P_x = Stature\ (x)$

$\delta = Standard\ deviation$

$p = Probability\ that\ a\ standard\ normal\ random\ variable\ will\ be\ less\ than\ x$

Equation 6. Determination of the female percentile for a stature of 1520 mm

Thus, it is possible to conclude that 25% of the Portuguese female population have a stature smaller than 1520 mm, with means that this measurement corresponds to 25$^{th}$ female percentile.

# APPENDIX II – CALCULATION OF ANTHROPOMETRIC DIMENSIONS FOR 25TH FEMALE PERCENTILE

The Portuguese anthropometric database only comprises information about dimensions of 1st, 5th, 95th and 99th male and female percentiles. Thus, it was necessary to determine the dimensions for 25th female, such as, knee and shoulders height. This calculation has been possible through a linear interpolation based on values for 5th and 95th female percentiles (Table 81).

Table 81. Dimension of 5th and 95th female percentiles

| Percentiles | Stature | Shoulder height | Knee height |
|---|---|---|---|
| P5F | 1456 mm | 1203 mm | 435 mm |
| P95F | 1674 mm | 1387 mm | 525 mm |

The height of shoulders for 25th female percentile is calculated in Equation 7:

$$P_1(x) = y_0 + \frac{y_1 - y_0}{x_1 - x_0}(x - x_0)$$

$$P_1(1520) = 1203 + \frac{1387 - 1203}{1674 - 1456}(1520 - 1456) = 1257mm$$

Equation 7. Calculation of shoulders height for 25th female percentile

The height of knees for 25th female percentile is calculated in Equation 8.

$$P_1(x) = y_0 + \frac{y_1 - y_0}{x_1 - x_0}(x - x_0)$$

$$P_1(1520) = 435 + \frac{525 - 435}{1674 - 1456}(1520 - 1456) = 461mm$$

Equation 8. Calculation of knees height for 25th female percentile

The dimensions of stature, shoulders and knees height of 25th female percentile is presented in Table 82.

Table 82. Dimension of 25th female percentile

| Percentiles | Stature | Shoulder height | Knee height |
|---|---|---|---|
| P25F | 1520 mm | 1257 mm | 461 mm |

## Appendix III – Application in PCB area of phase 3 (ergonomic assessment and mitigation measures for picking operations)

The picking of PCB occurs on PCB area, where the materials are stored in 6-level shelves. During this ergonomic analysis, every posture adopted to reach every level of shelves was considered.

### Step 3.1: Analysis of the current situation

Similar to the ergonomic analysis that was carried out on reels area, described in section 5.3.1, the dimension of the shelves on PCB area was studied in order to identify critical postures associated to reaching levels above head or shoulders height, as well as levels below knees height. Thus, the Figure 82 represents the stature, shoulder and knee height values for the 95th male and 25th female percentiles, as well as the PCB 6-level shelves.

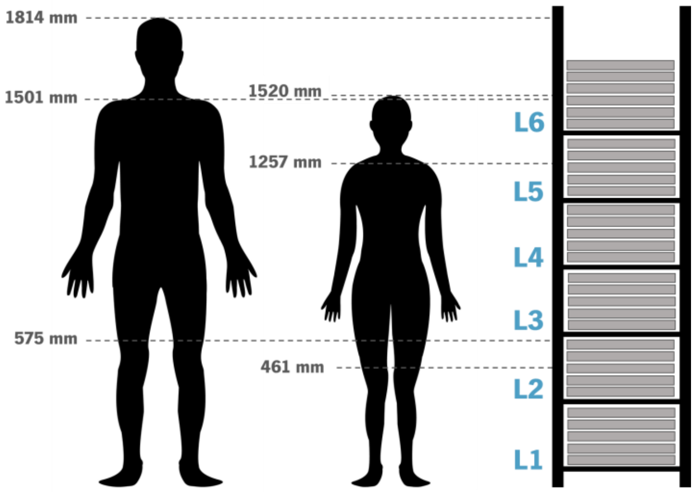


Figure 82. Representation of PCB shelves levels with stature and shoulder height of 95th male percentile and 25th female percentile

Once more, the dimension considered for each level is the reach level, which corresponds to the average value between the minimum and maximum heights of each shelf level. Furthermore, the PCB were weighed (Figure 83) in order to understand the ergonomic risk associated to picking operations. There is a wide range of PCB, the heaviest weighting 6.2 kg, a medium PCB weighing 5.4 kg and the lightest around 3kg.

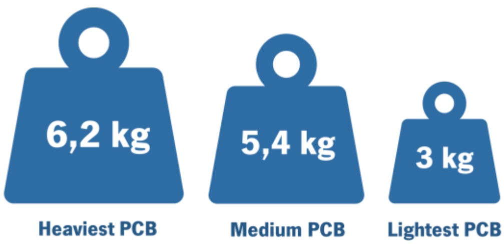


Figure 83. PCB weight

Like the picking of reels, a cycle of PCB picking also lasts 20 minutes, with 23 cycles per day (460 minutes of workday). As mentioned in section 5.3.1.1 (step 3.1 regarding reels' picking operations ergonomic analysis), a statistical study was carried out covering a period of six months (between October 1st, 2020 and March 31th, 2021), being concluded that the average number of PCB picked in each cycle is 5. This means that, considering this average number and considering the worst-case scenario from an ergonomic point of view (collecting only the heaviest PCB), the total weight of all materials collected can be 31 kg.

The PCB are carried in a carriage that weights 68 kg when empty, which has to be added to the weight of PCB calculated above. Therefore, it can be considered that in a worst-case scenario, the operator will have to push a total of 99 kg during the PCB picking route, which represents a total travelled distance of 135 m (Table 83).

Table 83. Data for PCB picking process (per route cycle)

| | |
|---|---|
| **Duration** | 20 minutes |
| **Average number of PCB picked** | 5 PCB |
| **Total weight of PCB (worst-case scenario)** | 31 kg |
| **Weight of PCB carriage (empty)** | 68 kg |
| **Total weight (PCB and carriage)** | 99 kg |
| **Travelled distance** | 135 m |

Like the ergonomic analysis carried out in reels area (section 5.3.1), it was important to take into account that the operators carry the PDA throughout the whole workday, which represents an additional daily load in the right hand of 400 grams for 460 minutes.

The percentage of time spent standing and walking in alternation while pushing the PCB carriage along the way is 40% of the time in each 20-minute cycle is dedicated to the picking process, like in the reels area. During the remaining 60% of the time, workers are collecting the PCB from the shelves and adopting several postures, such as, upright, bending, kneeling or even with arms above head or shoulder level. Consequently, it is possible to conclude that during the workday (460 minutes), the operator pushes the carriage that weight a total of 99 kg for 184 minutes.

### Step 3.2: Identification of extreme postures

The identification of extreme postures during PCB picking operations is very similar to the analysis carried out in reels area (section 5.3.1). Likewise, the shelves were modelled and the postures recorded or photographed. This allowed the evaluation of postures and the quantification of angular displacement of limbs during tasks performance.

Reaching the higher levels that require the positioning of the arms above head or shoulder height or the lower levels that leads to bending, crouching or kneeling postures represents the most critical postures in a ergonomic point of view. Hence, it is crucial to identify which selves' levels are above head and shoulders height as well as the ones that are below the knee's height to the percentiles under study (95th male and 25th female).

PCB are stored SMD warehouse, located in the internal logistics area, in a 6-level shelf, whose dimensions are represented in Figure 84.

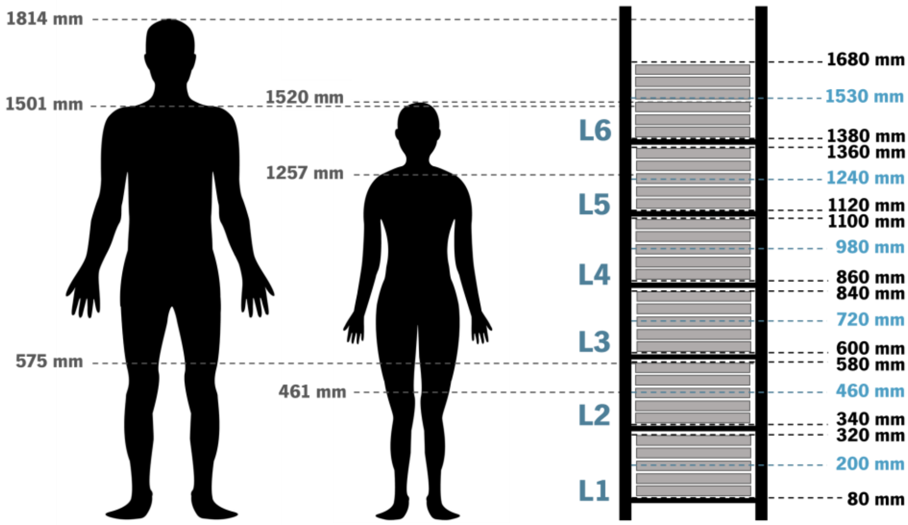


Figure 84. Dimensions of 6-level PCB shelves in comparison with stature and shoulder height of 95th male percentile and 25th female percentile

In the Table 84, there are identified the levels that require the adoption of inappropriate postures during the picking of PCB on 6-level shelves. The first and second levels are lower than knees height for both percentiles under study.

Table 84. Unfavourable postures during the picking of PCB on shelves for 95th male percentile and 25th female percentile

| **PCB 6-Level Shelves** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Shelf level** | | **L1** | **L2** | **L3** | **L4** | **L5** | **L6** |
| **P95M** | Above head level | | | | | | |
| | Above shoulder height | | | | | | x |
| | Bellow knee height | x | x | | | | |
| **P25F** | Above head level | | | | | | x |
| | Above shoulder height | | | | | | |
| | Bellow knee height | x | x | | | | |

Thus, reaching materials on these levels requires the adoption of bending, crouching or kneeling postures. Reaching the sixth level is critical for 95th male percentile, since it is higher than shoulder height and for 25th female percentile because it is above head level. Hence, both percentiles under study adopt unfavourable postures when they reach the highest level.

## Step 3.3: Application of quantitative ergonomic analysis method

Like the reels area, the ergonomic analysis in PCB area was supported by EAWS method, due to repetitive loads and cycling tasks. This method was performed for the two percentiles under study ($25^{th}$ female and $95^{th}$ male), comprising two main domains to evaluate: whole body and upper limbs.

### Analysis of whole-body

Two possible scenarios for lower limbs when reaching the lowest levels were contemplated during ergonomic analysis of whole body: the adoption of a bending posture and the adoption of a kneeling and crouching posture.

Similar to reels area, the first factors to take into account when evaluating the whole body is the total percentage of the total time operators spend adopting each posture. As stated before, 40% of the time is spent upright standing and walking in alternation while pushing the carriage of PCB. During the remaining 60% of the time, operators can adopt different postures to reach the materials in shelves and some of them can represent a high risk. Therefore, it is crucial to assess the amount of time spent adopting unfavourable postures in order to avoid them.

This amount of time is expressed in percentage. These percentage where calculated based on assumption that the probability of picking is the same for all levels. Based on this, once PCB are stored in 6-level shelves, the probability of picking each level is 16.667%.

Every posture adopted during the picking in every level was photographed, in order to evaluate the angular displacement of limbs and identify extreme postures, such as, bending or kneeling and position of arms above shoulders or head height. Given that the time spent on picking materials is 60% of the total time, the postures adopted reaching each level is identified and the probability of occurrence picking on each level is multiplied by 60%.

It is possible to identify in Table 85 the amount of time that $25^{th}$ female percentile spend adopting each posture in a scenario where operators are standing and adopting bending postures to reach lower levels, as well as the respective scores for EAWS method.

The $25^{th}$ female percentile is adopting unfavourable postures of arms during 10% of the time, which represents 46 minutes per working day. Unfavourable postures are those who require arms above shoulder or head level. Moreover, operators in this percentile spent 138 minutes (30% of the time) adopting bending positions, which represent a high risk, especially those with and angular displacement of trunk higher than 60°. The adoption of these postures in this scenario makes a total of 35.8 points.

Table 85. Postures of 25th female percentile – standing and bending

| Shelf type | Shelf Level | Probability of picking each level | Standing | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Bend, strongly forward >60º | Bend, slightly forward 20º -60º | Upright, no standing aid | Upright, with standing aid | Upright standing and walking in alternation | Upright, arms at or above shoulder height | Upright, arms above head level |
| 6-level | 1 | 16.667% | 10% | 0% | 0% | 0% | 40% | 0% | 0% |
| | 2 | 16.667% | 10% | 0% | 0% | 0% | | 0% | 0% |
| | 3 | 16.667% | 0% | 10% | 0% | 0% | | 0% | 0% |
| | 4 | 16.667% | 0% | 0% | 10% | 0% | | 0% | 0% |
| | 5 | 16.667% | 0% | 0% | 10% | 0% | | 0% | 0% |
| | 6 | 16.667% | 0% | 0% | 0% | 0% | | 0% | 10% |
| | Total: | 100% | 20% | 10% | 20% | 0% | 40% | 0% | 10% |
| | | Score for each posture: | 15.9 | 4.3 | 2.9 | 0 | 1 | 0 | 11.7 |
| | | Total postures score: | 35.8 points | | | | | | |

In order to avoid most of bending positions, it is possible to replace them by kneeling and crouching positions to reach lower levels. The Table 86 presents the percentage of time spent adopting each posture in a scenario where operators are standing and adopting kneeling or crouching postures to reach lower levels for 25th female percentile.

Table 86. Postures of 25th female percentile – standing and kneeling or crouching

| Shelf type | Shelf Level | Probability of picking each level | Standing | | | | | | | Kneeling or crouching | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Bend, strongly forward >60º | Bend, slightly forward 20º -60º | Upright, no standing aid | Upright, with standing aid | Upright standing and walking in alternation | Upright, arms at or above shoulder height | Upright, arms above head level | Bent forward | Upright | Elbow at / above shoulder level (90º) |
| 6-Level | 1 | 16.667% | 0% | 0% | 0% | 0% | 40% | 0% | 0% | 10% | 0% | 0% |
| | 2 | 16.667% | 0% | 0% | 0% | 0% | | 0% | 0% | 10% | 0% | 0% |
| | 3 | 16.667% | 0% | 0% | 0% | 0% | | 0% | 0% | 0% | 10% | 0% |
| | 4 | 16.667% | 0% | 0% | 10% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 5 | 16.667% | 0% | 0% | 10% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 6 | 16.667% | 0% | 0% | 0% | 0% | | 0% | 10% | 0% | 0% | 0% |
| | Total: | 100% | 0% | 0% | 20% | 0% | 40% | 0% | 10% | 20% | 10% | 0% |
| | | Score for each posture: | 0 | 0 | 2.9 | 0 | 1 | 0 | 11.7 | 18.8 | 6.3 | 0 |
| | | Total postures score: | 40.7 points | | | | | | | | | |

In this scenario, the time spent adopting unfavourable postures of arms by operators of 25th female percentile is the same (10%), however, bending postures were eliminated. Nevertheless, kneeling and crouching postures are adopted during a considerable amount of time (138 minutes – 30% of the total working time) and it is important to take into account that the biggest percentage regards to a bending position while kneeling (20% – 92 minutes), which is highly unfavourable regarding ergonomics. The final score for postures section in this scenario makes a total of 40.7 points, which represents a higher score for this percentile, when compared with the previous scenario, where the workers adopted standing and bending postures instead of kneeling and crouching.

This analysis of both scenarios was replicated for 95th male percentile. The Table 87 presents the amount of time spent adopting each posture in a scenario where operators are standing and adopting bending postures to reach lower levels for 95th male percentile, as well as the final scores for postures section.

Table 87. Postures of 95th male percentile – standing and bending

| **Shelf type** | **Shelf Level** | **Probability of picking each level** | **Standing** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | **Bend, strongly forward >60º** | **Bend, slightly forward 20º -60º** | **Upright, no standing aid** | **Upright, with standing aid** | **Upright standing and walking in alternation** | **Upright, arms at or above shoulder height** | **Upright, arms above head level** |
| 6-level | 1 | 16.667% | 10% | 0% | 0% | 0% | 40% | 0% | 0% |
| | 2 | 16.667% | 10% | 0% | 0% | 0% | | 0% | 0% |
| | 3 | 16.667% | 0% | 10% | 0% | 0% | | 0% | 0% |
| | 4 | 16.667% | 0% | 0% | 10% | 0% | | 0% | 0% |
| | 5 | 16.667% | 0% | 0% | 10% | 0% | | 0% | 0% |
| | 6 | 16.667% | 0% | 0% | 0% | 0% | | 10% | 0% |
| | Total: | 100% | 20% | 10% | 20% | 0% | 40% | 10% | 0% |
| | | Score for each posture: | 15.9 | 4.3 | 2.9 | 0 | 1 | 7.3 | 0 |
| | | Total postures score: | 31.4 points | | | | | | |

Operators of 95th male percentile are adopting bending positions during 30% of time (around 138 minutes per day). Furthermore, this percentile is positioning their arms above shoulder level during 10% (46 minutes), which improved in comparison with 25th female percentile that positions their arms above head level, because 95th male percentile workers are higher and do not have many difficulties in reaching higher levels. In total, this scenario and the adopted postures by this percentile during picking process make a total of 31.4 points.

Instead, the Table 88 presents the percentage of time spent adopting each posture and related scores in a scenario where operators are standing and adopting kneeling or crouching postures to reach lower levels for 95th male percentile.

In this case, operators of 95th male percentile spend the same amount of time with unfavourable postures of arms, however, bending postures improved and are adopted only during 10% of the working time (46 minutes) and it is not with a strong angular displacement. Nevertheless, kneeling and crouching postures are adopted during a considerable amount of time (92 minutes – 20% of the total working time) and it is important to take into account that this percentage regards to a bending position, which is highly unfavourable regarding ergonomics. The adoption of these postures during the workday scores a total of 34.3 points for this percentile in the scenario where workers adopt crouching and kneeling postures to reach lower levels and, similarly to $25^{th}$ female percentile, this scenario results in a worse score than the previous scenario, where the workers adopt bending postures to reach such levels.

Table 88. Postures of $95^{th}$ male percentile – standing and kneeling or crouching

| Shelf type | Shelf Level | Probability of picking each level | Standing | | | | | | | Kneeling or crouching | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Bend, strongly forward >60º | Bend, slightly forward 20º -60º | Upright, no standing aid | Upright, with standing aid | Upright standing and walking in alternation | Upright, arms at or above shoulder height | Upright, arms above head level | Bent forward | Upright | Elbow at / above shoulder level (90º) |
| 6-Level | 1 | 16.667% | 0% | 0% | 0% | 0% | | 0% | 0% | 10% | 0% | 0% |
| | 2 | 16.667% | 0% | 0% | 0% | 0% | | 0% | 0% | 10% | 0% | 0% |
| | 3 | 16.667% | 0% | 10% | 0% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 4 | 16.667% | 0% | 0% | 10% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 5 | 16.667% | 0% | 0% | 10% | 0% | | 0% | 0% | 0% | 0% | 0% |
| | 6 | 16.667% | 0% | 0% | 0% | 0% | | 10% | 0% | 0% | 0% | 0% |
| Total: | | 100% | 0% | 10% | 20% | 0% | 40% | 10% | 0% | 20% | 0% | 0% |
| Score for each posture: | | | 0 | 4.3 | 2.9 | 0 | 1 | 7.3 | 0 | 18.8 | 0 | 0 |
| Total postures score: | | | 34.3 points | | | | | | | | | |

The final scores for postures section considering each scenario for each percentile during PCB's picking process are summarised in Table 89.

Table 89. Postures – total score for different scenarios during PCB's picking

| Scenarios | Postures score |
|---|---|
| $25^{th}$ female percentile – standing and bending | 35.8 |
| $25^{th}$ female percentile – standing and kneeling or crouching | 40.7 |
| $95^{th}$ male percentile – standing and bending | 31.4 |
| $95^{th}$ male percentile – standing and kneeling or crouching | 34.3 |

After determining the percentage of time adopting each posture, the next step of EAWS method consists in considering the actions forces, which comprise the finger forces and the whole-body forces with no load. Though, action forces are not applicable to this analysis, adding no points to whole-body final score of EAWS method.

Furthermore, the next step that regards to manual materials handling section. In this case, it is important to take into account repositioning operations, which regards to tasks with a duration of less than 5 seconds and a distance of less than 5 meters. Additionally, pushing and pulling operations (different analysis for less or more than 5 meters) are also very relevant for the analysis of manual materials handling.

Similar to reels' picking process, holding, carrying and pushing and pulling (<=5m) operations are not applicable to PCB's picking process analysis. Therefore, only the repositioning operations and pushing and pulling (>5m) activities will be studied in EAWS method, in order to calculate the scores associated to the performance of these actions during the workday for this process.

Regarding the calculation of the final score for repositioning operations in EAWS method, it is crucial to analyse the different postures and positions that workers adopt when loading weights, assigning an individual score to this parameter. Thus, the amount of time spent adopting each posture in each scenario calculated previously is essential to calculate this individual score.

As mentioned in section 5.3.1.3.1 during the description of the analysis carried out in reels area, each possible posture and position of loading is categorised into four categories, with a score associated: 1 point for upright positions with load at the body; 2 points for slightly trunk bending with load at or close to the body; 4 points for bending postures; and 8 points for kneeling and crouching positions. For this purpose, a weighted calculation is attributed to every scenario, multiplying each percentage of time spend adopting each posture by the score associated to the category of postures and positions of load where it is categorised. Hereafter, all weighted values for each scenario are added, resulting in an individual score for postures and positions of load, which, in turn, will be used to calculate the repositioning score.

During repositioning operations, workers can handle a load weight of 6.2 kg (which represents an individual score of 1.8 points for females and 1.2 points for males), at the worst scenario, with an average frequency of 5 PCB per picking cycle (scored with 1 point).

The information regarding repositioning operations during manual materials handling, as well as the weighted calculation of postures and positions, and the scores for repositioning operations are summarised in Table 90 for 25$^{th}$ female percentile when adopting standing and bending postures to reach lower levels during the picking of PCB, resulting in a total score for repositioning operations of 4.6 points.

Table 90. Manual materials handling (repositioning operations) for 25$^{th}$ female percentile – standing and bending scenario in PCB's picking

| Characteristics | Parameters | Score |
|---|---|---|
| Load weight when repositioning | 6.2 kg | 1.8 |
| Posture and position of load | 2 points × 60% (upright) = 1.2<br>4 points × 40% (bending and arms above shoulder or head) = 1.6 | 2.8 |
| Frequency of handling of loads | 5 PCB | 1 |
| | Repositioning score = (load score + posture score) × frequency score | 4.6 |

In case of 25th female percentile adopting standing and kneeling postures to reach lower levels, the final score for repositioning operations makes a total of 5.8 points and the individual scores are summarised in Table 91.

Table 91. Manual materials handling (repositioning operations) for 25th female percentile – standing and kneeling scenario in PCB's picking

| Characteristics | Parameters | Score |
|---|---|---|
| Load weight when repositioning | 6.2 kg | 1.8 |
| Posture and position of load | 2 points × 60% (upright) = 1.2<br>4 points × 10% (bending and arms above shoulder or head) = 0.4<br>8 points × 30% (kneeling or crouching) = 2.4 | 4 |
| Frequency of handling of loads | 5 PCB | 1 |
| | Repositioning score = (load score + posture score) × frequency score | 5.8 |

Alternatively, regarding workers from 95th male percentile, the information and parameters that concern to repositioning operations during manual materials handling are presented in Table 92, considering standing and bending postures adopted to reach lower levels, scoring a total of 4 points.

Table 92. Manual materials handling (repositioning operations) for 95th male percentile – standing and bending scenario in PCB's picking

| Characteristics | Parameters | Score |
|---|---|---|
| Load weight when repositioning | 6.2 kg | 1.2 |
| Posture and position of load | 2 points × 60% (upright) = 1.2<br>4 points × 40% (bending and arms above shoulder or head) = 1.6 | 2.8 |
| Frequency of handling of loads | 5 PCB | 1 |
| | Repositioning score = (load score + posture score) × frequency score | 4 |

The last scenario for the calculation of repositioning operations' score regards to 95th male percentile, when the workers adopt standing and kneeling postures to reach lower levels. Making a total score of 4.8 points, the information and parameters that regard this scenario are presented in Table 93.

Table 93. Manual materials handling (repositioning operations) for 95th male percentile – standing and kneeling scenario in PCB's picking

| Characteristics | Parameters | Score |
|---|---|---|
| Load weight when repositioning | 6.2 kg | 1.2 |
| Posture and position of load | 2 points × 60% (upright) = 1.2<br>4 points × 20% (bending and arms above shoulder or head) = 0.8<br>8 points × 20% (kneeling or crouching) = 1.6 | 3.6 |
| Frequency of handling of loads | 5 PCB | 1 |
| | Repositioning score = (load score + posture score) × frequency score | 4.8 |

The time spent pushing the carriage along the way during each 20-minute cycle represents pushing and pulling (>5m) operations. This type of operations is relevant for the ergonomic analysis of whole-body through EAWS method. It is crucial to take into account that the total load weight of the PCB carriage is 99 kg, pushing a trolley with two steering rollers and 2 fixed rollers with small resistance to rolling. The distance is 135 meters and workers adopt postures that require trunk upright and load at the body. This information is summarised in Table 94. Workers from 25th female percentile score a total of 2.4 points, while workers from 95th male percentile make a total of 2.2 points regarding pushing and pulling operations for distances longer than 5 meters.

Table 94. Manual materials handling – pushing and pulling (>5m) operations in PCB's picking

| Characteristics | Parameters | Score | |
|---|---|---|---|
| Load weight when pushing and pulling | 99 kg | F | 1.4 |
| Means of transport | Trolley with fixed rollers (0-2 steering and 2-4 fixed rollers) | M | 1.2 |
| Posture and position of load | • Upper body upright and not twisted,<br>• Load at the body | 1 | |
| Working Conditions by pushing and pulling | Small resistance to rolling | 0 | |
| Distance | 135 m | 1 | |
| Pushing and pulling (>5m) score = (load score + posture score + workplace conditions score) × distance score | | F | 2.4 |
| | | M | 2.2 |

The scores of all operations that concern to manual materials handling section are added in order to calculate the final score for such section. In this case, the score for repositioning and the score for pushing and pulling (>5m) operations must be considered.

Therefore, the final scores for manual materials handling considering each scenario for each percentile under study are presented in Table 95.

Table 95. Manual materials handling – total score for different scenarios in PCB's picking

| Scenarios | Repositioning score | Pushing and pulling (>5m) score | Manual materials handling score |
|---|---|---|---|
| 25th female percentile – standing and bending | 4.6 | 2.4 | 7 |
| 25th female percentile – standing and kneeling or crouching | 5.8 | 2.4 | 8.2 |
| 95th male percentile – standing and bending | 4 | 2.2 | 6.2 |
| 95th male percentile – standing and kneeling or crouching | 4.8 | 2.2 | 7 |

Lastly, additional workloads consider joint positions of wrist, countershocks, impulses, vibrations, adverse effects by working on moving objects, accessibility factors or another physical workload. None of these factors are applicable to this analysis.

The Table 96 summarises the final scores regarding whole-body analysis for all scenarios during PCB picking, depicting the different sections previously analysed and their individual scores that were added together, giving rise to the final scores for whole-body.

Table 96. Whole-body – total score for different scenarios in PCB's picking

| Scenarios | Postures score | Action forces score | Manual materials handling score | Additional workloads score | Whole-body score |
|---|---|---|---|---|---|
| 25th female percentile – standing and bending | 35.8 | 0 | 7 | 0 | **42.8** |
| 25th female percentile – standing and kneeling or crouching | 40.7 | 0 | 8.2 | 0 | **48.9** |
| 95th male percentile – standing and bending | 31.4 | 0 | 6.2 | 0 | **37.6** |
| 95th male percentile – standing and kneeling or crouching | 34.3 | 0 | 7 | 0 | **41.3** |

### Analysis of upper limbs

The ergonomic analysis for upper limbs is transversal to both percentiles and both scenarios, analysing de duration of tasks, force, posture of upper limbs and additional factors for repetitive tasks.

The total duration of a workday is 480 minutes, though, it comprises a total of 15 minutes for official breaks and 5 minutes for the daily meeting. Therefore, the actual duration of picking tasks is 460 minutes in total. Similar to reels area, each PCB picking cycle lasts 20 minutes, which means that each operator performs a total of 23 picking cycles during the workday. These parameters regarding workload duration for repetitive tasks score a total of 7.7 points in EAWS method for upper limbs, which corresponds to the value of the net duration of repetitive tasks expressed in hours (460 min = 7.7 h). Furthermore, there are two recovery periods longer than eight minutes along the workday, scoring an additional 0.5 point that will be subtracted from the previous score, and work interruptions are possible anytime during the whole day, which adds no points to the final score. Thus, the total score for duration section is 7.2 points. This information and related scores are depicted in Table 97.

Table 97. Duration of repetitive tasks, recovery times and work organisation for PCB's picking operations

| Parameters | | Values | Score |
|---|---|---|---|
| Duration of repetitive tasks | Duration of task (min) | 480 | 7.7 |
| | Official breaks (min) | 15 | |
| | Additional breaks (min) | 0 | |
| | Non-repetitive tasks (min) | 5 | |
| | Net duration of repetitive tasks (min) | 460 | |
| | Number of cycles | 23 | |
| | Net cycle time (seg) | 1200 | |
| | Measured cycle time (seg) | 1200 | |
| | Deviation of the net cycle time from the measured cycle time (%) | 0 | |
| Recovery | Number of recovery periods > 8 minutes | 2 | 0.5 |
| Work organisation | Work interruptions | Possible anytime | 0 |
| Duration score = Duration of repetitive tasks score + work organisation score – recovery breaks score | | | 7.2 |

One more important section of EAWS method to take into account when calculating the final score for upper limbs regards to the forces applied by upper limbs during tasks performance.

Every time a worker picks a PCB up from the shelves, there are three dynamic real actions (reach, grab and place) assumed to be left-handed. At the worst case, the worker lifts a load of 6.2kg, which is the heaviest reel, with a force applied of 61N, calculated according to Newton's second law (Kosky et al., 2013), where the constant mass of the reel (6.2kg) is multiplied by its acceleration, which is given by the value of gravitational acceleration ($9.8m/s^2$). A dynamic physical work includes all tasks that involve a movement or contraction of the force-exerting muscles. This action is not quantified in time of duration but in number of real actions. Once it comprises three real actions and the average number of picked PCB is 5 per cycle with a total of 23 cycle throughout the workday, it is considered a total of 345 real actions (3 real actions x 5 PCB per cycle x 23 cycles).

During the picking operations of PCB, operators are grabbing and pushing the carriage with both hands during 40% of the time, which represents a total of 184 minutes. This posture is considered static because a muscular strength is necessary to hold the carriage but there is no movement of upper limbs, being longer than four seconds. The force applied is 33N, which was measured by a dynamometer.

At the same time that a PCB is reached, grabbed and placed in the carriage by left hand, the operator uses the right hand to screen the code on reel, carrying the PDA, which is a static action and represents an actual force of 4N (calculated according to the above-mentioned Newton's second law) applied during the whole day (460 minutes), however, 60% of the working time (276 min) regards to this static action during picking, while the remaining 40% (184 min) concerns carrying the PDA while the carriage is being pushed through the SMD warehouse. For that reason, these 4N were added to the force applied by the right hand during the carriage pushing process, totalling a force of 37N during 184 minutes.

The information about forces applied during PCB's picking and the resulting scores for upper limbs are depicted in Table 98.

Table 98. Forces applied by upper limbs during PCB's picking

| Description | Actual force (N) | Real action | Hand | Number (n) | Duration (min) | Forces score |
|---|---|---|---|---|---|---|
| Grab and push carriage | 33 | Static | Left | | 184 | 6.1 |
| Grab and push carriage and grab PDA during walking | 37 | Static | Right | | 184 | |
| Reach reel, grab (waiting for the PDA screening) and place in carriage | 61 | Dynamic (3) | Left | 345 | | |
| Grab PDA during picking | 4 | Static | Right | | 276 | |

The final forces score calculated with the software is 6.1 points, which corresponds to the highest score between the two hands, which is the right-hand score in this case.

Furthermore, the ergonomic evaluation of upper limbs contemplates the percentage of time adopting an awkward position of hand, forearm and elbow. In this case, reaching higher levels should be considered, when arms are at or above shoulder or head level. For both percentiles under study, this kind of postures occurs 10% of the total working time, being considered unfavourable postures. However, percentages below 25% add no points to the final score of upper limbs.

Finally, additional factors were not considered in this analysis because of none of the risk factors were applicable for the operations under study.

The individual scores of each section of upper limbs ergonomic analysis and the final score for upper limbs, which is the same to all scenarios and percentiles, are represented in Table 99.

Table 99. Upper limbs – total score for PCB's picking operations

| **Upper limbs section** | **Score** |
|---|---|
| Duration | 7.2 |
| Forces | 6.1 |
| Posture (awkward position of hand, forearm and elbow/ activity at or above shoulder height) | 0 |
| Additional factors | 0 |
| Upper limbs score = (force score + posture score + additional factors score) × duration score | 43.92 |

### Final score

After analysing all the data described above for the whole-body and upper limbs, a final score is calculated, from which it is possible to draw some conclusions about the risk to which employees are exposed during PCB picking operations. A score has been assigned to whole-body and upper limbs for each percentile and each scenario for reaching lower levels. The total score for whole-body is calculated as the sum of the obtained scores for four sections: posture, manual materials handling, action forces and additional workload. On the other hand, the total score for upper limbs is provided by the evaluation of real actions, hand, arm and joint positions and the corresponding stresses of repetitive tasks. The risk of a possible health hazard is estimated considering the three categories depicted in the section 0, following a traffic light scheme, where the green colour represents a low risk (score lower or equal to 25 points), the yellow colour signifies a possible risk (score between 25 and 50 points) and, finally, the red colours regards to a high risk (score higher than 50 points).

The final scores for the two different percentiles under study ($25^{th}$ female and $95^{th}$ male) and for different scenarios for reaching lower levels of shelves are presented in Table 100. As mentioned before, the analysis considered two different scenarios for each percentile. The first scenario assumes that workers adopt a standing posture and bend the trunk to reach lower levels. On the other hand, the second scenario consists in the adoption of a standing posture and kneeling or crouching to reach lower levels. The two different scenarios only consider posture of trunk and lower limbs, being only applicable to the calculation of total score for whole-body.

Table 100. Total score for whole body and upper limbs – PCB area in SMD warehouse

| **Percentile** | **Part of the Body** | **Scenario (for lower levels)** | **Total Score** |
|---|---|---|---|
| P25F | Whole Body | Standing (with bending) | 42.80 ● |
| | | Standing and kneeling or crouching | 48.90 ● |
| | Upper Limbs | | 43.92 ● |
| P95M | Whole Body | Standing (with bending) | 37.60 ● |
| | | Standing and kneeling or crouching | 41.30 ● |
| | Upper Limbs | | 43.92 ● |

The obtained final scores represent a possible risk for workers that perform PCB picking operations, thus, it is needed to take actions to control such risks in order to avoid a possible injury or disease associated to these tasks performance.

Regarding to the evaluation of 25th female percentile, every part of body and every scenario represent a possible risk, which is not recommended. When this percentile adopts standing posture to perform picking operations and bend the trunk to reach lower levels, the final score for whole-body is 42.80 points, which can be justified by the unfavourable postures adopted during the workday, including arms above head and shoulders, picking in levels below knees and strong trunk bending.

On the other hand, when 25th female percentile adopts kneeling and crouching postures to reach lower levels, the final score for whole-body is worse than the previous scenario, with 48.90 points. Besides the unfavourable postures of arms above shoulders and head, trunk bending has been eliminated in this scenario. However, as explained in section 5.3.1.3.3, this method penalizes kneeling and crouching postures much more than bending postures, due to the fact that the right posture from an ergonomic point of view to reach lower levels is squatting, which is not adopted by workers during picking operations. Moreover, kneeling and crouching positions usually require trunk bending, which also represents a risk for operators.

With regard to 95th male percentile, when standing posture with bending to reach lower levels is adopted, the risk associated is moderated (39.60 points), which means that there is a risk and the process should be redesigned in order to avoid it. This final score can be justified by the high prevalence of lower levels, which requires frequent trunk bending postures. In comparison with the same scenario for 25th female percentile, the score has improved due to the fact that the individuals under study are higher, which results in a lower frequency of reaching higher levels, avoiding positioning arms above head level in this case.

In contrast, when 95th male percentile adopts kneeling and crouching postures to reach lower levels, the final score for whole-body increases (41.30 points), which represents a moderate risk for workers that perform these tasks. Once again, this method penalizes kneeling and crouching postures much more than bending postures because the correct posture to reach lower levels is squatting and adopting kneeling and crouching positions usually require trunk bending, which is not beneficial for operators. In comparison with the same scenario for 25th female percentile, the score has slightly improved due to the fact that the individuals under study are higher, and consequently, a lower frequency of reaching higher levels is required, avoiding positioning arms above head level.

The evaluation of both percentiles under study is not favourable for upper limbs. The total score for both is 43.92 points, which means that there is a moderate risk for operators and workstations have to be redesigned in order to control those risks. The score is the same for both percentiles because this evaluation considers general information regardless the stature of workers, such as, duration of repetitive tasks, forces applied during task performance, unfavourable postures and other additional risk factors.

### Step 3.4: Identification of improvement potential and definition of mitigation measures

The scores that resulted from ergonomic evaluation through EAWS method are not favourable and can be justified by the high prevalence of extreme postures during reels picking operations, which can be understood as postures adopted to reach higher levels, positioning arms above shoulder or head, and lower levels, above knees. That means that for 25th female percentile the shelves are higher than they should, and the higher levels require unfavourable postures of arms. On the other hand, for 95th male percentile, the lower levels are lower than they should, which requires a strong trunk bend and unfavourable kneeling and crouching postures.

In fact, PCB picking operations in higher and lower levels are critical. If it were possible to eliminate extreme postures, positioning the shelves only at medium levels, the scores for the whole-body would be drastically reduced and a low ergonomic risk would be associated to these tasks' performance.

Furthermore, similar to reels picking process described in the previous section, carrying the PDA, that weights 400 grams, during the whole working day is a critical factor that highly increases the score and represents a significant risk for upper limbs. An ergonomic analysis for upper limbs using EAWS was performed in order to assess the improvement potential if workers could perform the picking of reels without carrying this device for 460 minutes per day. Thus, the individual scores of each section of upper limbs analysis and the final score for upper limbs when the use of PDA is eliminated are represented in Table 101. This score is transversal for every percentile under study and both scenarios for reaching lower levels.

Table 101. Upper limbs – total score for reels' picking operations without carrying PDA

| Upper limbs section | Score |
|---|---|
| Duration | 7.2 |
| Forces | 2.3 |
| Posture (awkward position of hand, forearm and elbow/ activity at or above shoulder height) | 0 |
| Additional factors | 0 |
| Upper limbs score = (force score + posture score + additional factors score) × duration score | 16.56 |

Therefore, it is possible to conclude that the elimination of PDA significantly reduces the risk associated to upper limbs, since the previous score that considered the use this device was 48.96 points (representing a moderate risk for workers) and the score calculated above is 16.56 points, which means that there is no corrective measures required, represented a low risk of a disease or an injury for operators. The comparison between the total score for upper limbs carrying and not carrying PDA, as well as the scores for whole body regarding both percentiles and both scenarios is presented in Table 102.

Table 102. Total score for whole body and upper limbs carrying and not carrying PDA – PCB area in SMD warehouse

<table>
<tr><th rowspan="2">Percentile</th><th rowspan="2">Part of the Body</th><th rowspan="2">Scenario<br>(for lower levels)</th><th colspan="2">Total Score</th></tr>
<tr><th>Carrying PDA</th><th>Not carrying PDA</th></tr>
<tr><td rowspan="3">P25F</td><td rowspan="2">Whole Body</td><td>Standing (with bending)</td><td colspan="2">42.80</td></tr>
<tr><td>Standing and kneeling or crouching</td><td colspan="2">48.90</td></tr>
<tr><td colspan="2">Upper Limbs</td><td>43.92</td><td>16.56</td></tr>
<tr><td rowspan="3">P95M</td><td rowspan="2">Whole Body</td><td>Standing (with bending)</td><td colspan="2">37.60</td></tr>
<tr><td>Standing and kneeling or crouching</td><td colspan="2">41.30</td></tr>
<tr><td colspan="2">Upper Limbs</td><td>43.91</td><td>16.56</td></tr>
</table>

Similar to the conclusions drawn during the step 3.4 regarding the analysis of reels area (section 5.3.1.4), the main ergonomic risk factors associated with the execution of PCB picking tasks in SMD warehouse are mainly associated to the high prevalence of awkward postures to reach levels above head and shoulder height, as well as levels below the knee height. Moreover, the high force demand and the repetitiveness of movements of the upper limbs are critical factors and operators have to continuously handle heavy loads (the heaviest PCB weights 6.2 kg). Additionally, the use of PDA to read bar codes throughout the day also represents a high risk for the upper limbs. Hence, the identified improvement potential for PCB picking tasks within SMD warehouse area, as well as the proposed mitigation measures using AR are presented in section 5.3.1.4, since these measures are similar for both areas of SMD warehouse, where the picking operations are performed.

## Appendix IV – Questionnaire

### A. Worker's characterization

1. Age:
   - ○ less than 20
   - ○ 20-29
   - ○ 30-39
   - ○ 40-49
   - ○ 50- 59
   - ○ 60 or more
2. Gender:
   - ○ M
   - ○ F
3. Height (cm): _____
4. Logistic area:
   - ☐ Incoming
   - ☐ Internal logistics for final assembly
   - ☐ Internal logistics for SMD assembly
5. Tasks performed:
   - ☐ Manual materials handling
   - ☐ Transportation
   - ☐ Picking
   - ☐ Lines supply
   - ☐ Other: ___________________
6. Seniority in the current activity: ___________________
7. If you answered less than 1 year to the previous question:
   a. Indicate your previous place of work:
      - ☐ Incoming
      - ☐ Internal logistics for final assembly
      - ☐ Internal logistics for SMD assembly
      - ☐ Shipping
      - ☐ Another department from the same company
      - ☐ Another company

   b. Indicate the tasks performed previously:
      - ☐ Manual materials handling
      - ☐ Transportation
      - ☐ Picking
      - ☐ Lines supply
      - ☐ Other: ___________________

## B. Musculoskeletal symptomatology

1. Do you have previously diagnosed musculoskeletal injuries related to the tasks you perform?
   ○ Yes. Which? ______________________________
   ○ No
2. Have you ever had an accident or incident at work?
   ○ Yes
   ○ No
3. If you answered yes to the previous question:
   a. Indicate the type of occurrence:
      ☐ Accident
      ☐ Incident
   b. Indicate the year of occurrence:
      ☐ 2020 or later
      ☐ 2016-2019
      ☐ 2015 or before
   c. Indicate the area of occurrence:
      ☐ Incoming
      ☐ Internal logistics for final assembly
      ☐ Internal logistics for SMD assembly
      ☐ Shipping
      ☐ Other: __________________
   d. Indicate the tasks performed during the occurrence:
      ☐ Manual materials handling
      ☐ Transportation
      ☐ Picking
      ☐ Lines supply
      ☐ Other: __________________
4. To answer the following questions, consider the body regions, as shown in Figure 85:


1. Neck
2. Shoulders
3. Elbows
4. Wrists and hands
5. Upper back
6. Low back
7. Hips and tighs
8. Knees
9. Ankles and feet

Figure 85. Body map

a. Considering the last 12 months, have you had any problems in the following regions?

| | Yes | No |
|---|---|---|
| Neck | ○ | ○ |
| Shoulders | ○ | ○ |
| Elbows | ○ | ○ |
| Wrists and hands | ○ | ○ |
| Chest region | ○ | ○ |
| Lumbar region | ○ | ○ |
| Hips and thighs | ○ | ○ |
| Knees | ○ | ○ |
| Ankles and feet | ○ | ○ |

b. Considering the last 12 months, have you been conditioned in your normal life due to any problems in the following regions?

| | Yes | No |
|---|---|---|
| Neck | ○ | ○ |
| Shoulders | ○ | ○ |
| Elbows | ○ | ○ |
| Wrists and hands | ○ | ○ |
| Chest region | ○ | ○ |
| Lumbar region | ○ | ○ |
| Hips and thighs | ○ | ○ |
| Knees | ○ | ○ |
| Ankles and feet | ○ | ○ |

c. Considering the last 7 days, have you had any problems in the following regions?

| | Yes | No |
|---|---|---|
| Neck | ○ | ○ |
| Shoulders | ○ | ○ |
| Elbows | ○ | ○ |
| Wrists and hands | ○ | ○ |
| Chest region | ○ | ○ |
| Lumbar region | ○ | ○ |
| Hips and thighs | ○ | ○ |
| Knees | ○ | ○ |
| Ankles and feet | ○ | ○ |

d. Considering your discomfort resulting from a problem in the following regions, select a value from 0 to 10, with 0 representing no pain and 10 referring to maximum pain.

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Neck | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Shoulders | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Elbows | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Wrists and hands | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Chest region | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Lumbar region | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Hips and thighs | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Knees | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Ankles and feet | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

5. If you answered yes to any of the above questions, please indicate:

a. In the past 12 months, how many days of work have you lost due to pain or discomfort? _________

b. If you find it convenient, make a brief comment on the reasons that, in your opinion, triggered your problem: ________________________________________________________________
________________________________________________________________________________

## C. Perception of Exertion

1. Which tasks performed at your workplace do you consider the most physically demanding?

________________________________________

________________________________________

2. Which tasks performed at your workplace do you consider the most mentally and cognitively demanding?

________________________________________

________________________________________

3. Considering your effort (physical or cognitive) in performing the tasks, select a value from 0 to 10, where 0 represents the absence of effort and 10 refers to the maximum effort.

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | N/A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Manual handling of heavy loads | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Pushing or pulling heavy loads | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Utensils too heavy (e.g. PDA) | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Repetitive movements | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Inappropriate trunk working postures | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Inappropriate upper limb working postures | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Inappropriate working postures of the lower limbs | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Workstations, shelves or material too high | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Workstations, shelves or material too low; | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| High distances covered; | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Too much information to assimilate; | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Hard to memorize work instructions; | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Find the fastest route (for picking, put-away or lines supply); | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Pay attention to all existing risks at the workplace; | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Too much product information to check; | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Quickly find product locations; | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Know all the tasks to perform; | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Detect errors or failures in processes; | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Know the specifications of each product (e.g. box type, packaging, location, etc.); | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Knowledge and compliance with all safety instructions | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Other: ____________________ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

## D. AR solutions: workers' opinion and acceptance

Considering your opinion regarding the AR solutions and the statements presented below, select a value from 0 to 5, where 0 represents "No opinion", 1 "Strongly disagree", 2 "Disagree", 3 "Neither agree nor disagree", 4 "Agree" and 5 "Strongly agree".

1. This equipment is an exoskeleton (Figure 86). This model, in particular, weighs 3 kg and allows the lifting of loads up to 10 times heavier without effort, helping to prevent musculoskeletal injuries.


Figure 86. Example of an exoskeleton
(Reproduced from: New Atlas (2018))

| | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| The equipment would make my tasks easier | ○ | ○ | ○ | ○ | ○ | ○ |
| The equipment could lighten my physical load | ○ | ○ | ○ | ○ | ○ | ○ |
| The equipment could reduce my physical effort | ○ | ○ | ○ | ○ | ○ | ○ |
| The equipment could reduce my discomfort | ○ | ○ | ○ | ○ | ○ | ○ |
| I would take less risk using the equipment | ○ | ○ | ○ | ○ | ○ | ○ |
| My job would improve with this equipment | ○ | ○ | ○ | ○ | ○ | ○ |
| I would use the equipment if the company made it available | ○ | ○ | ○ | ○ | ○ | ○ |

Comments: ______________________________________________

2. These devices are portable barcode scanners (Figure 87). They weigh about 40 grams and would replace the PDA, which weighs 400 grams.

Figure 87. Example of WWD
(Reproduced from: Etiden (2020) and Datalogic (2021))

| | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| The equipment would make my tasks easier | ○ | ○ | ○ | ○ | ○ | ○ |
| The equipment could lighten my physical load | ○ | ○ | ○ | ○ | ○ | ○ |
| The equipment could reduce my physical effort | ○ | ○ | ○ | ○ | ○ | ○ |
| The equipment could reduce my discomfort | ○ | ○ | ○ | ○ | ○ | ○ |
| I would take less risk using the equipment | ○ | ○ | ○ | ○ | ○ | ○ |
| My job would improve with this equipment | ○ | ○ | ○ | ○ | ○ | ○ |
| I would use the equipment if the company made it available | ○ | ○ | ○ | ○ | ○ | ○ |

Comments: ______________________________________________

3. This equipment is a wireless headset (Figure 88). It weighs about 180 grams and provides information on imminent safety hazards, material locations, work instructions, safety instructions, fastest routes, tasks to be performed, workplace hazard alerts and other relevant information about the products and tasks.

Figure 88. Example of AAR
(Reproduced from: ILS (2017))

| | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| The equipment would make my tasks easier | ○ | ○ | ○ | ○ | ○ | ○ |
| The equipment could lighten my cognitive load | ○ | ○ | ○ | ○ | ○ | ○ |
| The equipment could reduce my cognitive effort | ○ | ○ | ○ | ○ | ○ | ○ |
| The equipment could reduce my discomfort | ○ | ○ | ○ | ○ | ○ | ○ |
| I would take less risk using the equipment | ○ | ○ | ○ | ○ | ○ | ○ |
| My job would improve with this equipment | ○ | ○ | ○ | ○ | ○ | ○ |
| I would use the equipment if the company made it available | ○ | ○ | ○ | ○ | ○ | ○ |

Comments: ______________________________________________

4. This equipment is AR glasses (Figure 89). It weighs around 560 grams and provides access to information about work instructions, fastest routes, tasks to be performed, safety instructions, workplace hazard alerts and other relevant information about products and tasks.

Figure 89. Example of HMD
(Reproduced from: Microsoft (2020))

| | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| The equipment would make my tasks easier | ○ | ○ | ○ | ○ | ○ | ○ |
| The equipment could lighten my cognitive load | ○ | ○ | ○ | ○ | ○ | ○ |
| The equipment could reduce my cognitive effort | ○ | ○ | ○ | ○ | ○ | ○ |
| The equipment could reduce my discomfort | ○ | ○ | ○ | ○ | ○ | ○ |
| I would take less risk using the equipment | ○ | ○ | ○ | ○ | ○ | ○ |
| My job would improve with this equipment | ○ | ○ | ○ | ○ | ○ | ○ |
| I would use the equipment if the company made it available | ○ | ○ | ○ | ○ | ○ | ○ |

Comments: ______________________________________________