applied sciences

MDPI

Article

Augmented Reality in a Lean Workplace at Smart Factories: A Case Study

Ana C. Pereira [1,*], Anabela C. Alves and Pedro Arezes

ALGORITMI Research Centre/LASI, University of Minho, Campus of Azurém, 4800-058 Guimarães, Portugal; anabela@dps.uminho.pt (A.C.A.); parezes@dps.uminho.pt (P.A.)
* Correspondence: ana.pereira@dps.uminho.pt

Abstract: The last few years have seen a massive transformation of the global industrial landscape, thanks to the emergence of Industry 4.0 and the disruptive technologies it enables, such as Augmented Reality (AR). This paper presents the result of a project with the primary focus on enhancing the operators' working conditions and the further definition of the most suitable AR for each material handling and motion process. To achieve this, a methodology called Risk Assessment for Ergonomics and Safety in Logistics (RAES-Log) was developed in order to analyse and define AR implementation requirements, in order to mitigate existing risks and improve ergonomic conditions. Utilizing a human-centric approach consistent with Lean Thinking and Industry 5.0 vision, the main aim was to reduce human effort during task performance. Furthermore, the potential for creating waste-free and more efficient workspaces was explored, as well as the possibility of Human Augmentation (HA) to enhance workers' capabilities and senses. The workers' opinions and acceptance of the proposed AR solutions resulting from the RAES-Log methodology in a case study were collected and analysed. The overall feedback was positive and it is expected a lower prevalence of work-related Musculoskeletal Disorders (MSD), less lost time days, and lower injury severity, as well as increased process efficiency, operator motivation, well-being and engagement in continuous improvement processes.

Keywords: augmented reality; human augmentation; Industry 4.0; Industry 5.0; lean thinking; human factors; ergonomics; musculoskeletal disorders; occupational safety and health; human-centric systems

check for updates

Citation: Pereira, A.C.; Alves, A.C.; Arezes, P. Augmented Reality in a Lean Workplace at Smart Factories: A Case Study. *Appl. Sci.* **2023**, *13*, 9120. https://doi.org/10.3390/app13169120

Academic Editors: Dimitris Mourtzis and Christos Bouras

Received: 3 April 2023
Revised: 27 July 2023
Accepted: 27 July 2023
Published: 10 August 2023

1. Introduction

The fourth industrial revolution, or Industry 4.0, has captured the attention of academics and organizations due to the significant changes in technology and manufacturing processes in recent years [1]. It is being compared with the previous three industrial revolutions that occurred in the last centuries [2] and can be described as a complex technological system that is focused on the creation of smart products and processes, using smart machines and transforming conventional manufacturing systems into smart factories [3].

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 on the industry, markets, economy, products, and business models and completely changing the current workplace and the work environment [4,5].

Augmented Reality (AR) is one of the disruptive technologies that are also emerging with Industry 4.0, combining the physical world with computer-generated visuals, offering an intuitive interaction experience. It provides real-time interaction between virtual and physical objects, improving work performance and efficiency in manufacturing environments [6–8], enabling the combination of digital knowledge into the user's physical world in many other areas, such as healthcare, education, retail, Information Technology and entertainment [9,10].

Moving toward the Industry 4.0 paradigm and implementing emerging disruptive technologies such as AR will enable new types of interactions between humans and machines, transforming the current industrial workforce and workplace and leading to deep impacts on worker tasks and demands in the work environment [11,12].

To mitigate these impacts, AR tools must be developed with functionalities that allow a user-friendly collaboration between humans and technology, improving performance and awareness in a non-intrusive way to meet industrial requirements, and making people more efficient and effective in their tasks [13]. At the same time, it is important that humans develop such tasks without overburdening or stress or, even, accidents due to workplace unevenness that are considered, normally, symptoms of waste, i.e., all activities that do not add value from the client's point of view [14].

The main goal of Lean Production is "doing more with less" [14], where less means less human effort, fewer stocks, fewer resources, less space, and less product development time. Lean Production solutions represents a huge potential for current industrial landscape that integrated with automation, Lean Automation, brings several opportunities for the smart factories context [15].

Nevertheless, less attention has been paid to logistic activities in warehouses or supermarkets, particularly, in the manual handling operations, such as loading and unloading of parts on shelves. This continues to be a highly manual activity in many companies, which increases the ergonomics risks and contributes to the development of MSD.

The project described in this paper aimed to evaluate how Industry 4.0 technologies are affecting the HF and workplaces at smart factories, particularly in logistics activities, through the implementation of AR in a 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 Human Augmentation (HA) in logistics activities. HA relies on the use of technologies such as AR to enhance human senses, augmenting their capabilities and cognition.

Thus, the project also aimed to address Industry 5.0 principles, solving emerging societal needs through the introduction of industrial developments, and driving the transition to human-centric, sustainable and resilient systems [16]. By utilizing flexible and adaptable technologies, the Industry 5.0 paradigm promotes the agility and resiliency of systems [17].

The implementation of new technologies must be aligned with workers' physical and safety conditions. These technologies should promote creativity, responsibility, resilience, and critical thinking [18], promoting the creation of waste-free workplaces supported by Lean Thinking.

2. Literature Review

2.1. Lean Thinking

Lean Production is an organizational approach that resulted from the Toyota Production System (TPS), which main goal is "doing more with less", where less means less human effort, fewer stocks, fewer resources, less space, and less product development time [14,19]. Additionally, it tries to enable greater production flexibility, while meeting quality standards and deadlines.

This organizational approach aims to increase productivity and reduce costs by eliminating waste [14], which are all the activities that do not add value to the products from a client's point of view. Ohno [14] classified the wastes into seven categories: (1) overproduction; (2) over processing; (3) transportation; (4) defects; (5) motion; (6) inventory; and (7) waiting. Later on, Liker [20] identified an extra waste, i.e., untapped human potential.

However, 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 [21]. Hence, it can be said that Human Factors (HF) and ergonomics have an impact on a company's business strategy and competitiveness [22]. Most of the industrial projects implementing lean principles do not always address the ergonomics factors [23], although ergonomics and HF should be included in the lean process from the outset, which is not seen in a lot of organizations that fail to understand the potential of combining and carrying out ergonomic concepts in parallel with lean techniques [24].

Most the organisation are 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 [21,25], however, the right combination with lean and ergonomic design concepts will reduce errors, improve productivity and simultaneously improve the working conditions while reducing risk factors that can lead to the development of injuries or MSD [25,26].

It is important to ensure that people develop their tasks without waste (*muda*, in Japanese) and symptoms of waste. Beyond *muda*, there are the *mura* and *muri* that are considered the symptoms of *muda*. For instance, within an ergonomic context, *mura* are the consequences of wastes that result in workplace unevenness or irregularities, such as applying a force that increases the risk of strains and injuries that causes higher fatigue, which leads to reduced work pace and productivity. Muri is the overburden or stress caused by repetitive tasks or weight lifting or, even, accidents that could occur in the workplace due to other symptoms of waste, such as unevenness or irregularity, i.e., *mura*. Together these three Japanese words are called 3M [20]. Ergonomic design focuses on the creation of efficient and appropriate body postures, reducing the amount of strength required to perform a task, avoiding incorrect postures, repetitive tasks and motions throughout the work shift [21].

After decades, enhancing Lean Production solutions represent a huge potential for the current industrial landscape and the cutting-edge technologies enabled by Industry 4.0 paradigm bring several opportunities under the smart factories context to improve organisations competitiveness and working conditions [15].

2.2. Industry 4.0 and Industry 5.0

In recent years, the industrial landscape has been dramatically altered due to technological advancements and new manufacturing processes. This has sparked conversations between academics and organisations around a new concept called Industry 4.0, also referred to as the Fourth Industrial Revolution. This has allowed companies to benefit from emerging technologies that integrate digital and physical systems and enable more efficient, automated, and interconnected production [4,27].

Industry 4.0 is being compared with the previous three industrial revolutions that occurred in the last centuries. After steam power, electricity and the advent of computers, the emerging fourth industrial revolution will bring together the digital and physical worlds, embracing successive innovations and disruptive developments, mostly regarding digital technology and manufacturing [2].

Industry 4.0 has been highly discussed and studied, with a considerable impact on the industrial landscape by introducing disruptive changes with the advent of smart and future factories. This concept is a broad term encompassing the future of industrial developments, such as Cyber-Physical Systems, the Internet of Things, the Internet of Systems, Robotics, Big Data, Cloud Manufacturing, and AR, which will revolutionize both products and processes. Companies that make use of these technologies will increase their efficiency and productivity, transforming the current work environment and workplaces and bringing new ways of operating [5].

After a decade of discussion surrounding Industry 4.0, visionaries are now predicting the next revolution—Industry 5.0. During this time, Industry 4.0 has concentrated more on digitalisation and the use of disruptive technologies for greater efficiency and flexibility. In contrast, Industry 5.0 will emphasize the importance of a human-centric industry and its service to humanity. This will involve a renewed focus on social aspects, enabling companies to be more ethical and socially responsible in their practices [16,28,29].

Industry 5.0 complements and extends the Industry 4.0 paradigm. Merging between real and virtual worlds is crucial to gather and generate useful data to create solutions to face the challenges, enhancing the safety, security, and comfort conditions of people [30–32]. Thus, Industry 5.0 is a strategy that has resulted from a forward-looking exercise to help frame how industrial developments and emerging societal trends and needs can co-exist, driving the transition to human-centric, sustainable and resilient systems [16].

The human-centric approach puts people's needs and goals at the forefront, leveraging technology implementation to suit human interests. Consequently, the primary focus is on humans and employees. Additionally, Industry 5.0 is directed towards building sustainable systems, creating circular processes and cutting down energy usage in order to protect the environment. Furthermore, resilience refers to the construction of systems endowed with exceptional robustness, flexible processes and adaptable production capacity to accommodate the changing market requirements [16].

In addition, the concept of Industry 5.0 is related to the one of Society 5.0. Both of them are focused on a shift of society, economy and industry towards a new paradigm aimed at creating a people-centric society [16,33,34]. Society 5.0 concept was presented in 2016 [35] and its aim is to stimulate economic growth while solving societal and environmental problems, enhancing the quality of life and creating a society that attends to the different needs of people, regardless of region, age, sex, language or disabilities [36].

Therefore, the paradigms of Industry 4.0 and 5.0 can create synergies to promote the elimination of wastes (3M) within the workplaces and foster healthy work environments.

2.3. Lean Thinking, Industry 4.0 and Industry 5.0

In the past few years, the relationship between Industry 4.0 technologies and lean practices has been studied, and the potential of combining the two areas and the benefits associated with this union. This integration of the two domains has been initially referred to as Lean Automation [15]. Enhancing Lean Production solutions using new technologies represents a huge potential for the current industrial landscape and brings several opportunities for the smart factories' context [15,37].

The emerging technologies associated with Industry 4.0 can provide numerous benefits when integrated with Lean Thinking principles [38]. However, it is important to evaluate how effective each technology is in a particular context to make the most of this symbiosis. Many mistakes have been made over the years and emerging technologies should be implemented only after a thorough cost-benefit analysis determined by an issue that cannot be resolved in any other way. This is significant because these technologies require a considerable investment and skillset, which may not be accessible for companies [39].

The most frequent advantages that come from the fourth industrial revolution technologies employed in lean are often related to data collection, communication between different productive actors, data analysis capability, and data display. When these technologies are combined with lean principles and concepts, they can effectively reduce non-value-adding activities in businesses, improving employee satisfaction. Moreover, it was concluded that AR technology can effectively promote ongoing improvement and eliminate waste, as well as support problem-solving and decision-making, enhance HF, and facilitate communication and data sharing [38].

In fact, each Industry 4.0 technology has an important role in supporting the implementation of each one of the Lean Thinking principles. By applying the correct Industry 4.0 technologies, organizations will be more aware of the value for the client and will map properly value streams to eliminate wastes and to have flow. At the same time, production will be pulled by the client using Industry 4.0 technologies available and a continuous improvement process will be possible. Implications of these result in a sustainable, human-centric and resilient production system, as required by Industry 5.0 [18].

2.4. Ergonomics and Human Factors

The ability of humans to work is directly related to their well-being and health, being extremely important to provide people with favourable working conditions, maximizing their well-being and promoting their safety. Moreover, the technological developments enabled by Industry 4.0 could play a crucial role in creating waste-free workplaces that address Industry 5.0 pillars. According to Hancock and Diaz [40], technology is the most powerful shaping force on the planet and its individual impact is most evident in human factors. Therefore, ergonomics can mediate these synergies between operators and technology, enhancing the work environment and the design of healthy workplaces.

Unfavourable work environments and conditions, as well as the exposure of workers to risk factors, can lead to the emergence of physical disabilities. Once the disability restricts the worker's physical aptitude to undertake the tasks as usual, preventing them from lifting weights or moving, it is said that the worker is enduring a work-related MSD [41].

Work-related MSDs that are caused by repetitive tasks and high demanding working conditions remain to be one of the most significant problems in industrialized countries and one of the biggest concerns of corporations [42]. It has a massive effect on the labour market and significantly influences the health and well-being of the work force, escalating the number of health-related absences and decreasing productivity in organisations [43].

Logistics activities in warehouses and supermarkets, where the ergonomic conditions are, most of the time, not suitable for workers and the manual tasks, such as loading and unloading, represent a high risk of developing MSD [44,45]. Manual material handling highly increases the rate of MSD in workers, being one of the most difficult and physically demanding tasks due to repetitive movements, awkward postures of limbs or forceful exertion [46].

However, logistics plays a vital role in supply chain management, ensuring the delivery of products at the right time, in a safe and effective way. Despite the emergence of the new and essential concept of Logistic 4.0, which comprises the implementation of Industry 4.0 technologies in logistic activities, the primary discussion is mostly regarding efficiency, enhanced tracking and delivery to the customer [47]. Less importance has been given to HF in logistics and operator overload, overburden, stress and safety in the logistics field and how industry 4.0 technologies, AR in particular, can overcome these issues [48].

2.5. Augmented Reality and Human Augmentation

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 [49]. 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 allows the improvement of work performance and efficiency in a manufacturing environment [6,7]. 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 [50].

Nevertheless, AR applications should take into account all human senses [51] and aspects such as touch and haptic sensations can be employed to enhance the perception of the actual environment [52]. The goal is to enable organizations to join together processes and visualizations [50], which simplifies the user's experience by incorporating virtual details and reinforcing their understanding and involvement with the real world, augmenting the sense of reality in real-time [6].

In the last years, the way of providing information to operators has been changing [49,53–55]. AR technology offers a range of chances for the manufacturing sector [56], since it can give operators access to data that cannot be obtained with their regular senses. What is more, this data is supplied in the pertinent context and when it is necessary [57].

AR has traditionally been primarily visual, enhancing 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. In addition, 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 [58]. In sum, AR can be used to augment human senses, cognitive abilities and physical capabilities.

The hardware used by AR technology can be divided into several categories: Head-Mounted Displays (HMD); Hand-Held Displays (HHD), Wrist-Worn Displays (WWD) and Spatial Augmented Reality (SAR) [59]. Moreover, Augmented Audio Reality (AAR) allows the augmentation of hearing sense, in order to perceive virtual sounds as an extension to the natural ones, creating a hybrid augmented environment [60], while the creation of super-strong humans in an industrial environment can be enabled by the use of wearable, lightweight, flexible and mobile exoskeletons [61]. Figure 1 shows the different types of AR, categorized into six different applications.

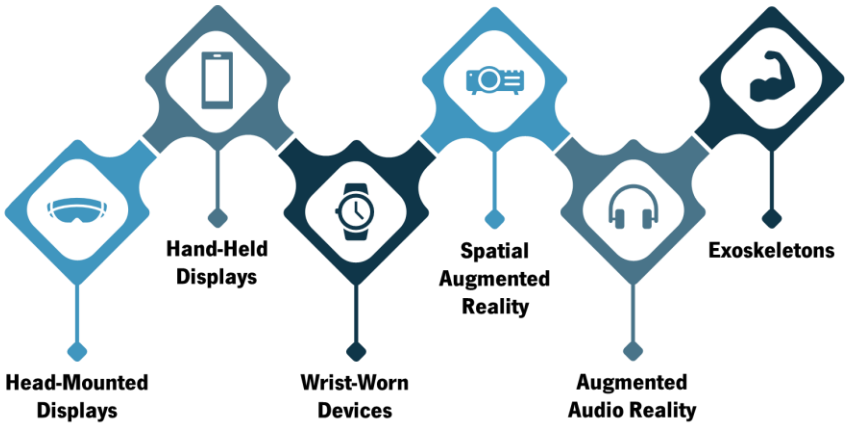

Figure 1. Types of AR [59].

AR technology has the potential to augment all human senses, providing virtual data to workers and extending, for example, their sight or hearing functions. Nevertheless, the prospects with regard to the utilization of this technology in industrial surroundings are not just restricted to sensory improvement, it is also possible to augment human beings in terms of their intellectual or cognitive abilities [62], as well as enhance their physical capabilities using exoskeletons in order to improve ergonomic conditions [63], allowing new forms of human actions [64].

AR application in the industrial environment holds a huge potential to augment human capabilities, specifically within the logistics area, allowing the improved of performance and efficiency, enhancing cognitive capabilities and reducing inequalities within workplaces [59].

Superimposing computer-generated information in the real world, in order to give relevant data that is not accessible within the real world, such as work instructions, directions or safety instructions, is one of the most promising possibilities of AR technology in a human-based environment [62]. This emerging technology has enabled the move from traditional paper-instructions to the utilization of 3D visualization procedures in recent years, which carries a significant potential regarding the elimination of waste caused by delays and human errors [65,66], as well as the reduction in training and operating times and the fostering of working conditions, quality, productivity and efficiency [67,68].

A recent review of the literature on this topic [69] summarizes 36 cases of AR technology applications 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. Furthermore, WWD equipped with barcode and QR code scanning technology are commonly used for order- picking and 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 [70]. Additionally, 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 [71]. WWD and AAR enable a hands-free operation that allows the employee to relieve the physical workload and manipulate the packages with both hands [72].

The implementation of new techniques and the instruction of workers on the necessary skills can be time-consuming and may impede the effectiveness of logistics operations. However, the use of AR technology during the training period can result in employees with the necessary knowledge to complete complex and challenging tasks, and this can boost productivity and shorten their learning curve [73].

Moreover, AR has the potential to enhance workers' cognitive capabilities, provide feedback and data for safety measures, or even alert the operators regarding an immediate hazardous situation or danger in real-time [74].

AR solutions can also improve the quality of life for individuals with disabilities and the elderly, making the workforce more inclusive and sustainable., These solutions help to reduce disparities in the workplace [64], holding a set of benefits to assist workers with disabilities [75] In addition, they enhance physical capabilities, through the usage of exoskeletons to improve working conditions and allow operators to perform their tasks longer and lift heavier weights, while reducing the physical workload, injuries, accidents and risk factors [58].

Human augmentation 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, relevant information is provided to operators, in order to enhance human life and allow new Human-Machine Interface solutions [64]. This approach is centred on the AR users and based on a human-centered real world merged with an information world [62].

Operator 4.0 is a concept that has emerged in Industry 4.0 context and can be understood as an Augmented Operator that performs collaborative work with machines and robots, being enabled by CPS and advanced technologies [76]. AR is a critical enabling technology for improving information transfer between the digital world and smart operators in the physical world [77]. The term Operator 4.0 refers to smart and skilled operators, assisted and augmented by systems that enable a reduced physical and cognitive workload during task performance, allowing them to be more creative and innovative, fostering continuous improvement without compromising productivity [76]. Therefore, the Augmented Operator paradigm is enabling the engagement and empowerment of workers [78], giving people more time to learn, think and innovate.

To take advantage of what Industry 4.0 has to offer and successfully utilize emerging technologies such as AR, businesses must develop human-centred production systems that put the needs of workers first. This technology will have a direct impact on operators and their work areas, creating a new interaction between humans and machines. This connection between the real and digital worlds will merge digital and physical worlds, resulting in a socio-technical transformation in smart factories and a novel Human-Machine Interface approach, resulting in the elimination of wastes in the workplace, non-value-added activities and hazards. Additionally, it will reduce the amount of effort required of workers during task performance, promoting good health within the organizations and providing equality for all, no matter their capabilities or disabilities, and creating a safe and secure working environment.

2.6. Critical Analysis

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

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

AR application in an industrial context allows the enhancement of HF, reducing operation times and human efforts and improving ergonomic conditions, as well as, mitigating the risks and eliminating human errors in workplaces. Furthermore, in achieving this, wastes are reduced which 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 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 the project reported in this paper, as shown in Figure 2.

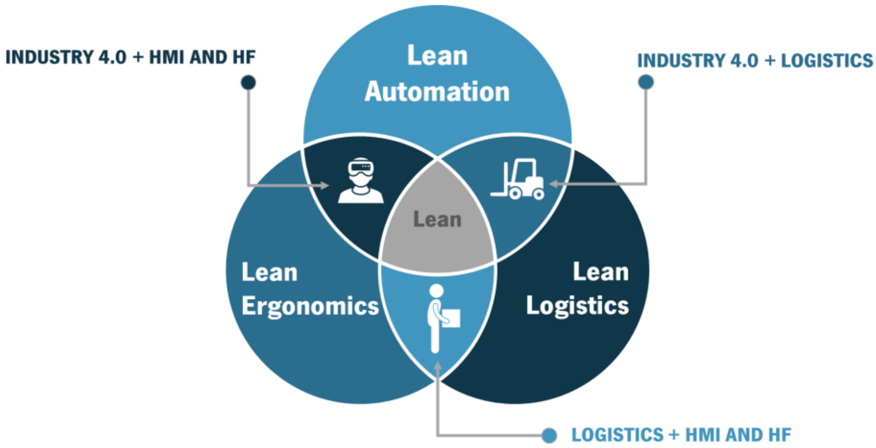

Figure 2. Integration of three lean domains [59].

This project intended to address the identified literature gaps and foster the creation of human-centric systems, proposing a methodology 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

3.1. Research Questions and Research Methodology Framework

In order to understand the relationship between AR technology, Lean, and HF, the main research question of the project presented in this paper (RQ1) has been raised and addressed. This general question forms the basis of the project and was further divided into two sub-questions (RQ 1.1 and RQ 1.2), which were the main focus of this research. These questions, depicted in Table 1, seek to understand the ways in which this technology can be used to improve processes and create synergies between industry 5.0 and Lean.

Table 1. Research questions.

RQ#	Research Question
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?

Following the definition of capabilities and senses in order to augment, the second research question (RQ 2) seeks to identify the most suitable AR solutions that best suit logistic processes. This question also aims to define the use cases of each technology to augment the capabilities and senses identified in the previous questions.

In order to achieve the above-mentioned research questions, a research methodology framework was designed that consisted of the accomplishment of four main phases, namely:

1. Literature review;
2. Case study analysis;
3. Methodology definition;
4. Analysis and discussion.

3.2. Research Design and Strategy

The research questions raised in the previous section have determined the most suitable research design and strategy, the most suitable collection techniques and analysis procedures, as well as the time horizon over which the project is undertaken.

Therefore, this research reflects the philosophy of positivism, since the data collection process is strongly based on observable reality and the analysis and conclusions will result in law-like generalisations [79], while an inductive approach has been used during data collection and analysis, since this research has started without a predetermined theory or conceptual framework [80,81].

The most appropriate research strategy to answer the research questions and address the objectives of this project was the case study, since it consisted of an in-depth analysis of an observable phenomenon within its real-life context. A single case study was considered, since it was deployed within a single organisation, with an embedded case that allows the analysis of multiple relevant units within that organisation [81].

Regarding research choices, there are several data collection techniques that can be used in case studies [82]. Mixed methods, both qualitative and quantitative have been applied during the deployment of this case study, including several research methods which have been used, such as meetings, unstructured interviews, company visits and observation, *gemba* walks, and video recording and analysis. Furthermore, a cross-sectional study has been developed on 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 [81].

Consequently, in order to answer the research questions, the focus was on the deployment of the case study which consisted of the development of a methodology to assess risks within logistic workplaces. Then, it was proposed mitigation measures based on AR, followed by the analysis of theories and results and, lastly, conclusions drawn.

4. Case Study Presentation

This study focuses on a tier-one supplier in the automotive industry, located in Portugal. Founded in 1990, this company is specialized in the manufacturing and development of multimedia systems, electronic equipment, primarily navigation systems and automotive instrumentation. With around 4000 staff members, the company based its management model on the TPS and Lean principles in order to increase competitiveness and eliminate waste from existing processes.

The logistics department was the focus of this work and 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 3):

1. Incoming;
2. Internal logistics for final assembly;
3. Internal logistics for Surface-Mount Device (SMD) assembly;
4. Shipping.

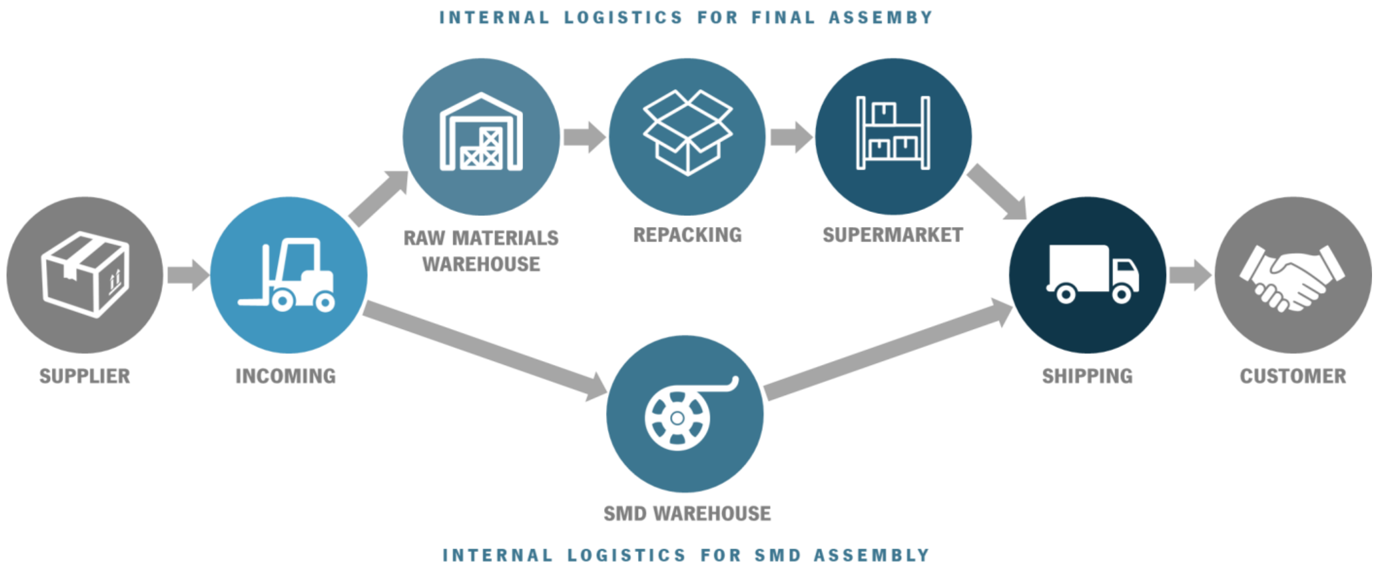

Figure 3. Areas of Material Flow and Physical Logistics section [59].

The logistic processes within this section were analysed from an ergonomic and safety point of view, with a special focus on activities that represent greater human effort or where more work-related accidents or incidents occur.

A rigorous analysis and process mapping were carried out within these areas, with a special focus on the following tasks:

1. Incoming tasks;
2. Warehousing tasks;
3. Repacking tasks;
4. Final and SMD assembly supermarkets tasks;
5. Lines supply tasks;
6. Shipping and dispatch tasks.

The flow of information is ensured in real time, through the use of internal software tools that are integrated with the company's Enterprise Resource planning system.

The conclusions drawn and the opportunities for improving working conditions were used for the developed methodology.

It is important to emphasize that the company has several employees who work to improve ergonomic and safety conditions. The factory has an Ergonomist, responsible for evaluating the working conditions within the workplace and implementing solutions to enhance ergonomic conditions and reduce the risk of MSD. Furthermore, there is a Safety Specialist in the logistics department that is responsible for analysing the occurrences in this department. At the same time, this specialist promotes the best practices and implements correction and mitigation actions in order to eliminate risks. In the safety area, the company also has a Technician for Health and Safety at Work that is responsible for the risk evaluation in every area within the plant, identifying the risks, prioritizing and scoring them based on their frequency and severity.

Therefore, these three professionals can join forces to ensure workers' well-being in the workplace, reducing the risk of accidents, incidents, and MSD, while establishing safer work environments with improved ergonomic conditions. However, in the past, collaboration between them was not always the case, and their efforts were not always integrated with all stakeholders. Each professional used their own methods, and the results of their work were not shared among each other in a standardized way.

The goal of this project was the combination of ergonomic, health, and safety functions into one unified methodology. This involves creating a risk assessment methodology for the logistics area that promotes standard work and helps evaluate risks faced by logistics operators. The methodology involves proposing mitigation measures based on Augmented Reality technology to reduce the risks. The development of this methodology is outlined in the following chapter.

5. Methodology for Risk Assessment for Ergonomics and Safety in Logistics

The Risk Assessment for Ergonomics and Safety in Logistics (RAES-Log) methodology developed in this intends to identify the critical logistic areas and processes in order to assess and evaluate the risks regarding safety and ergonomics during task execution in order to propose mitigation measures based on AR.

In order to improve working conditions and mitigate risks to address Lean and Industry 5.0 principles, it is necessary to identify and evaluate safety and ergonomic risks within workplaces, as well as determine which human senses and capabilities should be augmented. This will lead to the definition of the requirements for the successful implementation of AR.

Although this project focuses on the use of AR, the methodology presented can be used to analyse the requirements of any disruptive technology that has the potential to offer solutions to ergonomic risks and safety issues in workplaces. This can improve working conditions, promote workers' well-being, and reduce the chances of developing MSD.

This methodology 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, as depicted in Figure 4. The main phases of RAES-Log are:

1. Occurrence analysis;
2. OSH risk evaluation and mitigation measures;
3. Ergonomic assessment and mitigation measures.

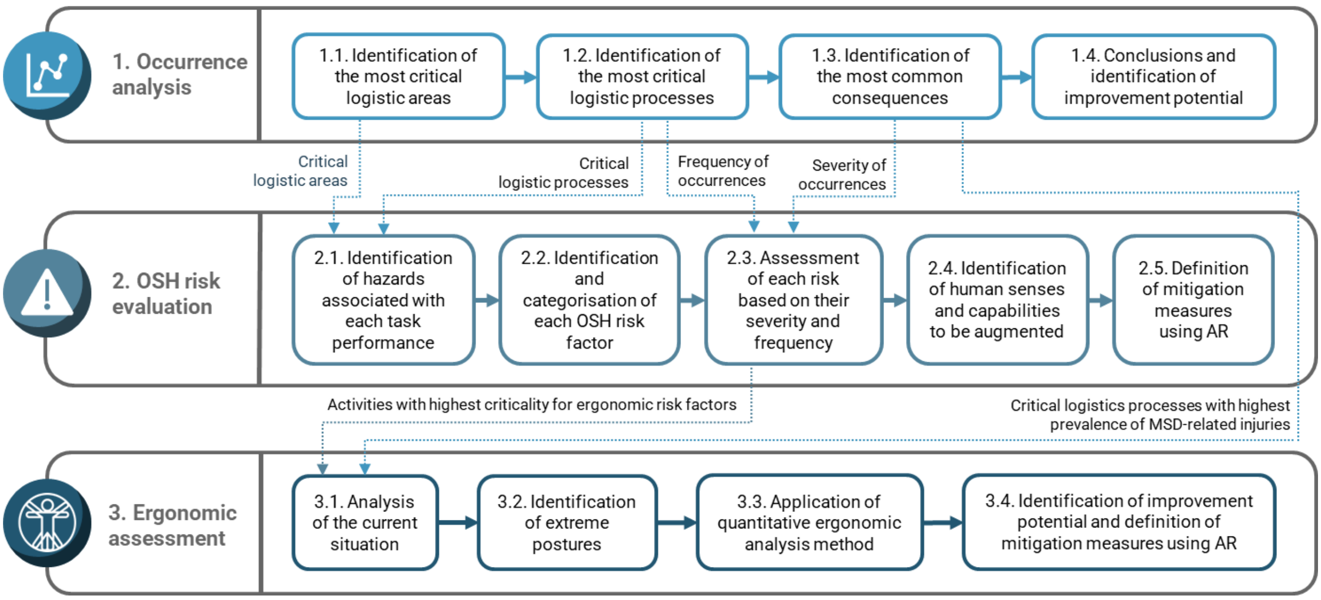

Figure 4. Overview of RAES-Log and detailed phases and steps [59].

5.1. Occurrence Analysis (Phase 1)

The first phase of this methodology is the occurrence analysis, based on the number of work-related accidents and incidents within logistic workplaces over the last years. This phase consists of the identification of the most critical logistic areas and processes, based on the frequency of occurrences.

Afterward, the most common consequences of occurrences are identified, through the analysis of the most injured parts of the body and the types of injury. This analysis will allow drawing some conclusions regarding the occurrences' incidence, frequency, and severity, as well as the improvement potential identification, which is the last step of the first phase.

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 will be further analysed during the OSH risk assessment (phase 2). Furthermore, the frequency (or probability) of the occurrence of a certain risk and its severity (estimated based on the most common consequences and type of injuries) will be necessary during the risk assessment.

Finally, the identification of the processes with the highest prevalence of MSD-related injuries will be useful to select the processes that will be analysed during the third and last phase of this methodology, which consists of the ergonomic risk assessment of the most critical logistic processes regarding ergonomic issues.

Table 2 provides an overview of the first phase regarding the required information to perform each step or input, the methods applied during each process and the expected outputs or results. In the next sections, more details about each step that comprises the occurrence analysis phase will be given.

Table 2. Overview of inputs, methods and outputs of each step of occurrence analysis [59].

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

5.2. OSH Risk Evaluation and Mitigation Measures (Phase 2)

During the second phase of RAES-Log methodology—OSH risk evaluation and mitigation measures—the previously identified most critical logistic areas are analysed in order to identify the main hazards associated to each task performance, followed by the identification and categorisation of each OSH risk factor.

Subsequently, each risk is assessed and scored based on its frequency or probability of occurrence (determined during the occurrence analysis) and its severity (related to the consequences of occurrences), which allows the identification of the activities with the highest criticality for ergonomic risk factors.

After this assessment, the human senses and capabilities that should be augmented in order to mitigate OSH risks are identified and, lastly, mitigation measures using AR solutions are proposed.

Table 3 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.

Table 3. Overview of inputs, methods and outputs of each step of OSH risk evaluation and mitigation measures [59].

Steps of Phase 1	Inputs	Methods	Outputs
2.1. Identification of hazards associated with each task performance	• Critical logistic areas (step 1.1) • Critical logistic processes (step 1.2)	• Qualitative analysis	• Hazards associated with each task performance
2.2. Identification and categorisation of each OSH risk factor	• Hazards associated with each task performance (step 2.1)	• Qualitative analysis	• OSH risk factors
2.3. Assessment of each risk based on their severity and frequency	• Ergonomic risk factors (step 2.2) • Physical safety risk factors (step 2.2) • Frequency of occurrences (step 1.2) • Severity of occurrences (step 1.3)	• Quantitative analysis • Qualitative analysis	• Activities with highest criticality for physical safety and ergonomic risk factors
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 • Literature review	• Human senses and capabilities to be augmented
2.5. Definition of mitigation measures using AR	• Human senses and capabilities to be augmented to mitigate physical safety risk factors (step 2.4) • Available AR solutions	• Qualitative analysis • Literature review	• Mitigation measures using AR for physical safety risk factors

5.3. Ergonomic Assessment and Mitigation Measures (Phase 3)

Finally, the third phase of this methodology consists of the ergonomic assessment and mitigation measures. The first step consists of the analysis of the current situation for the processes with the highest prevalence of MSD-related injuries (identified during phase 1) and the activities with the highest scores regarding ergonomic risks (determined during phase 2), 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 during the next step. Afterwards, the most suitable quantitative ergonomic analysis method is applied, based on the nature of performed tasks, in order to assess the ergonomic risks associated with task 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 worker's physical capabilities.

Table 4 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 4. Overview of inputs, methods and outputs of each step of ergonomic risk assessment and mitigation measures [59].

Steps of Phase 1	Inputs	Methods	Outputs
3.1. Analysis of the current situation	• Critical logistic process with highest prevalence of MSD-related injuries (step 1.3) • Activities with highest criticality for ergonomic risk factors (step 2.3)	• Qualitative analysis	• Duration of exposure • Frequency and repetition of movements • Force demands
3.2. Identification of extreme postures	• Dimensions of levels to be reached during tasks performance	• Quantitative analysis • Qualitative analysis	• Adopted working postures
3.3. Application of quantitative ergonomic analysis method	• Nature and characteristics of tasks • Duration of exposure • Frequency and repetition of movements • Force demands	• Quantitative analysis	• Level of risk to which workers are exposed regarding ergonomic conditions (score)
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) • Available AR solutions	• Qualitative analysis • Literature review	• Mitigation measures using AR for ergonomic risk factors

5.4. Methodology Overview

An overview of the proposed methodology for RAES-Log, as well as, the main phases, each step and the main outputs and results are presented in Table 5.

Table 5. Overview of methodology phases, steps and main outputs [59].

Phase	Step	Output
Phase 1. Occurrence analysis	1.1. Identification of the most critical logistic areas	• Internal logistics (72% of occurrences; incidence rate: 30% for accidents and 75% for incidents) • Incoming and raw materials warehouse (22% of occurrences; incidence rate of 23 for accidents and 105 for incidents)
	1.2. Identification of the most critical processes	• Materials handling (48% of accidents and 46% of incidents) • Transportation (23% of accidents and 27% of incidents) • Picking (20% of accidents and 20% of incidents)
	1.3. Identification of the most common consequences	• Part of body injured: • Upper extremities • Lower extremities • Back, including spine and vertebra in the back • Type of injury: • Wounds and superficial injuries • Dislocations, sprains and strains
	1.4. Conclusions and identification of improvement potential	• Critical logistic areas: used during phase 2 • Critical processes with highest prevalence of MSD-related injuries: used during phase 3

Table 5. *Cont.*

Phase	Step	Output
Phase 2. OSH risk evaluation and mitigation measures	2.1. Identification of hazards associated with each task performance	• Hazards associated with each task performance within the two most critical logistic areas: • Internal Logistics • Incoming
	2.2. Identification and categorisation of each OSH risk factor	• Categories of OSH risk factors: • Physical safety risk factors • Ergonomic risk factors
	2.3. Assessment of each risk based on their severity and frequency	• Parameterisation of risk evaluation criteria (frequency and severity) • Categorisation of risks criticality based on obtained scores • Definition of acceptability criteria
	2.4. Identification of human senses and capabilities to be augmented	• Human senses: sight and hearing • Capabilities: cognitive and physical
	2.5. Definition of mitigation measures using AR	• Augmentation of sight sense: HMD, HHD and SAR • Augmentation of hearing sense: AAR • Augmentation of cognitive capabilities: HMD, HHD, SAR and AAR • Augmentation of physical capabilities: WWD and exoskeletons
Phase 3. Ergonomic risk assessment and mitigation measures	3.1. Analysis of the current situation	• Activities with highest criticality for ergonomic risk factors (identified during step 2.3): • Final and SMD assembly supermarkets tasks • Incoming tasks • Critical processes with highest prevalence of MSD-related injuries (identified during steps 1.2 and 1.4): • Picking operations within SMD warehouse area • Lifting and lowering loads operations within incoming area
	3.2. Identification of extreme postures	• Unfavourable postures to reach materials: • Above head level • Above shoulder height • Bellow knee height
	3.3. Application of quantitative ergonomic analysis method	• Quantification of ergonomic risk factors and risk of MSD: • EAWS: ergonomic analyses of repetitive loads and cycling tasks • NIOSH: tasks that require asymmetrical lifting and lowering tasks with both hands
	3.4. Identification of improvement potential and definition of mitigation measures using AR	• Use of WWD equipped with barcode scanning functionality • 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 for this specific case study and analysed processes, as well as the proposed AR solutions to mitigate risks within logistic workplaces.

It is important to consider that these outputs concern the application of this methodology to a specific case study. For different case studies, different outputs will be expected. However, the phases and steps of the methodology must be followed in the same way.

Moreover, as previously mentioned, the RAES-Log methodology can be used to evaluate the application of other technologies within workplaces, as long as they have the potential to improve working conditions and reduce ergonomic risks in order to improve workers' safety.

Moreover, in order to analyse the improvement potential associated with the implementation of these methodologies and study the worker's opinions and acceptance, an analysis involving logistic workers in case study has been carried out and presented in the next chapter. Furthermore, this analysis intended to validate the conclusions made during the three phases of the RAES-Log methodology.

6. Analysis and Discussion

6.1. Identified Improvements Potential

It is fundamental to assess the current risks in workspaces and the possible effects of AR technology implementation and acceptance. To do this, a questionnaire was designed and administered to collect worker's opinions on the implementation of these solutions in their workspaces. This questionnaire aims to analyse and evaluate the potential for improvement that comes with the implementation of the AR solutions presented in the previous section, in order to reduce risks and improve ergonomic conditions at workplaces.

The designed questionnaire was based on the Nordic Musculoskeletal Questionnaire (NMQ) [83], which consists in a standardized methodology that allows the comparison between complaints regarding different parts of the body [84]. 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:

1. Incoming and raw materials warehouse;
2. Internal logistics.

Furthermore, within the abovementioned critical areas, special attention has been given to the tasks with the highest criticality regarding the HSE risk assessment carried out during step 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 of the developed methodology. These critical tasks are presented in Table 6.

Table 6. Logistic tasks with highest criticality levels regarding HSE risk factors [59].

Logistic Area	Tasks
Incoming and raw materials warehouse	Incoming Warehousing
Internal logistics	Repacking Final and SMD assembly supermarkets Lines supply

Moreover, during phase 3 of the RAES-Log methodology, lifting and lowering loads operations within the incoming area and picking operations within supermarkets have been analysed in order to assess the risk factors regarding ergonomic conditions. Special attention was given to the workers performing these two operations, and they were invited to take part in the study to evaluate the AR solutions proposed in step 3.4 of the methodology.

From a population of 188 workers within the two most critical logistic areas, a sample of 50 workers has been defined to make inferences on the population. This calculation considers 10% of the margin of error, 90% of the confidence level and 50% of the response distribution. Therefore, 50 workers, who participated voluntarily, were interviewed during the course of their workday while doing their tasks. The questions were posed in the form of an interview and noted down, with explanations given as needed.

The questionnaire summary, structure and used instruments are presented in Table 7.

Table 7. Summary of questionnaire structure, parameters assessed and used instruments [59].

Category	Parameters Assessed	Used Instruments
A. Workers' characterization	• Age • Work experience • Tasks performed	–
B. Musculoskeletal symptomatology	• Diagnosed MSD • Work-related occurrences • Classification of pain	Numerical pain scale [85]
C. Perception of exertion	• Assessment of physical exertion perceived by the workers; • Identification of the most demanding tasks.	Category Ratio-10 [86]
D. Workers' opinion and acceptance	• Assessment of worker's opinions about the possible AR solutions to implement in workstations	Five-point Likert scale [87]

Therefore, this study pursued 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;
4. Assess proposed AR solutions acceptance indicators based on the workers' opinion.

For this purpose, the results of each category are detailed in the next section. The full questionnaire is presented in Appendix A—Questionnaire.

6.2. Results

This research found that the prevalence of MSD among logistic workers in this case study is high, with 56% of participants reporting at least, one issue. The most commonly reported regions were shoulders (66%), lumbar region (66%) and neck (46%), according to the NMQ.

When asked about physical effort, 78% mentioned handling heavy loads as the leading complaint. Additionally, processes such as the picking cycle in supermarkets (36%), tasks that require the worker to reach lower levels (20%) and repalletization in the incoming area (14%) presented a high physical demand for the workers.

The highest levels of perceived strain were reported for activities involving heavy lifting, repeated movements, uncomfortable body positions, and material stored in hard-to-reach places. Furthermore, the cognitive effort was also a problem, due to workers having to find products and materials in a timely manner while being aware of any risks in their environment.

When it came to the AR solutions proposed to lessen the risks identified in the RAES-Log methodology, the majority of workers had a favourable opinion and felt confident that they would be able to improve their working conditions and mitigate existing risks. In particular, they had trust in technologies such as exoskeleton technology (90%) and WWD (82%), which are likely to reduce physical strain and decrease the risk of work-related MSD.

Regarding solutions for reducing cognitive workload, such as AAR and HMD, workers also felt that AR solutions could aid by reducing their mental strain throughout the working day. However, these technologies were seen as less important than those designed to decrease physical exertion, with acceptance ratings of 80% and 68%, respectively. Therefore, workers are generally optimistic that AAR and HMD can help to reduce their cognitive effort and contribute to better working conditions.

The global worker's opinion regarding the proposed AR solution is expressed in Figure 5, where is possible to understand that, for all the solutions, the majority of workers showed a positive judgment about these technologies to mitigate risks within their workplaces.

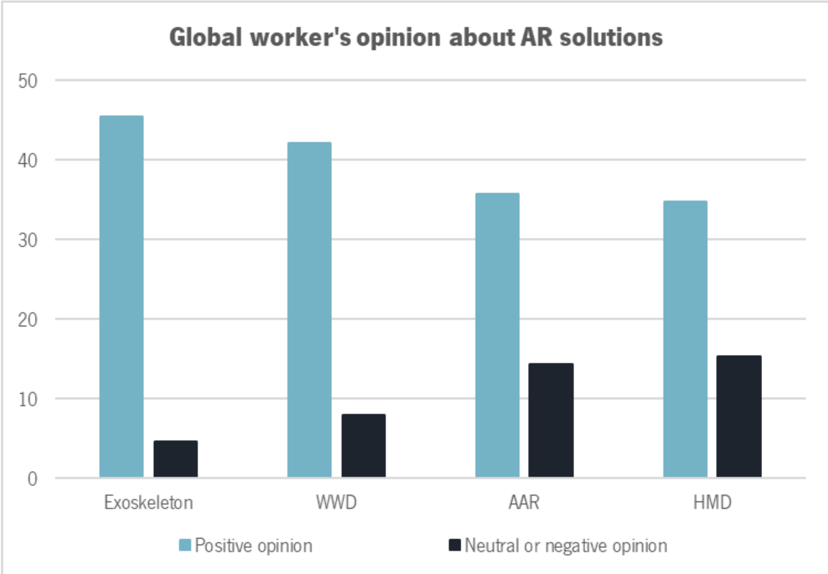

Figure 5. Global worker's opinion about the impact of proposed AR solutions [59].

Workers have the highest confidence in exoskeleton technology, which they feel can reduce the physical strain associated with handling heavy materials, a common complaint in the logistics industry. They also have a high level of trust in WWD, particularly in SMD supermarkets where workers carry heavy devices to scan the barcodes throughout the day. AR solutions such as AAR and HMD were seen as less important, but still provide an essential role in reducing cognitive workload and improving working conditions.

Overall, workers were positive about the AR solutions put forth, showing enthusiasm and optimism about their potential to improve safety in their workplaces. It is important to recognize that the input of workers was key in this process, as they actively participated in the study, providing their opinions about the changes and solutions being proposed. Anonymity enabled them to be honest about their concerns and complaints as well as what is working well on their workstations. With the right implementation of these technologies, their working conditions can be improved, with a decreased risk of MSD and both physical and cognitive workload.

7. Conclusions

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 of the potential 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 of every production system and they were the main motivation of this work. For this reason, this paper presents a methodology named RAES-Log that intended to analyse and define AR implementation requirements within logistic workplaces in order to mitigate the existing risks and study the potential enhancement of working conditions through the implementation of AR technology.

The project presented in this paper was only possible due to the context lived in the company that for a long time been trying to implement Lean Thinking. Aware of the difficulties they have been facing in implementing this organizational philosophy, company ergonomic specialists recognized the importance of this methodology to improve work conditions in the logistics area. The lean mindset was fundamental to develop in this company the feeling of everything could be improved and Industry 4.0 technologies bring advantages that were inexistent before. By doing this, the company is on a good track to accomplish the Industry 5.0 pillars.

7.1. Research Limitations

The work reported in this paper has been developed having one of 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 amount of confidential business information. Therefore, the collection of the required data can be seen as the major limitation of this project, since essential 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 to 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.

Furthermore, the project was a single case study analysis, liable to be subjective when applied to other companies. However, these issues were 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.

7.2. Future Work

Despite the good achieve results, there is still a 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, which require 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.

Therefore, the main opportunity for future research directions regards 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 critical 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 imperative 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 for 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.

Author Contributions: Conceptualization, A.C.P.; methodology, A.C.P., A.C.A. and P A.; validation, A.C.A. and P.A.; formal analysis, A.C.P.; investigation A.C.P.; data curation, A.C.P.; writing—original draft preparation, A.C.P.; writing—review and editing, A.C.A. and P.A.; visualization, A.C.P. and A.C.A.; supervision, A.C.A. and P.A.; project administration, A.C.P., A.C.A. and P.A.; funding acquisition, A.C.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by FCT, the Portuguese national funding agency for science, research and technology, Doctoral scholarship SFRH/BD/139533/2018. This work was also supported by FCT within the R&D Units Project Scope: UIDB/00319/2020.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are openly available in *RepositoriUM* from University of Minho [59].

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A Questionnaire

Category 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: ________________

Category 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 A1:

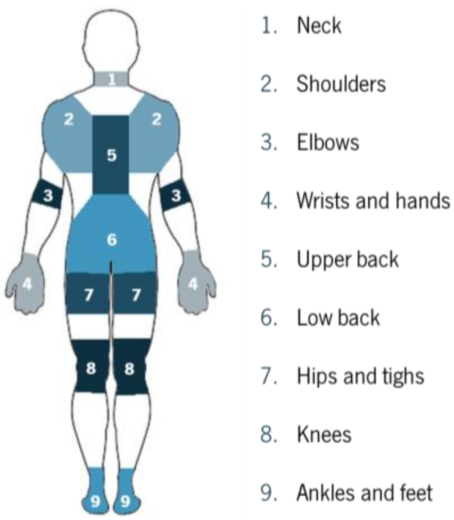

Figure A1. Body map.

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: ____

Category 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: ____________________	○	○	○	○	○	○	○	○	○	○	○	○

Category 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 A2). 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 A2. Example of an exoskeleton [88].

	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 A3). They weigh about 40 g and would replace the PDA, which weighs 400 g.

Figure A3. Example of WWD [89,90].

	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 A4). It weighs about 180 g 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 A4. Example of AAR [91].

	0	1	2	3	4	5
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 A5). It weighs around 560 g 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 A5. Example of HMD [92].

	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: ____________________

References

1. Kagermann, H.; Wahlster, W.; Helbig, J. *Securing the Future of German Manufacturing Industry: Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0*; Acatech— National Academy of Science and Engineering: München, Germany, 2013.
2. Schmidt, R.; Möhring, M.; Härting, R.-C.; Reichstein, C.; Neumaier, P. Industry 4.0—Potentials for Creating Smart Products: Empirical Research Results. In Proceedings of the International Conference on Business Information Systems, Poznań, Poland, 24–26 June 2015; Springer: Berlin/Heidelberg, Germany, 2015; pp. 16–27.
3. Weyer, S.; Schmitt, M.; Ohmer, M.; Gorecky, D. Towards Industry 4.0—Standardization as the Crucial Challenge for Highly Modular, Multi-vendor Production Systems. *IFAC-PapersOnLine* **2015**, *48*, 579–584. [CrossRef]
4. Kagermann, H.; Wahlster, W. Ten years of Industrie 4.0. *Sci* **2022**, *4*, 26. [CrossRef]
5. Pereira, A.C.; Romero, F. A review of the meanings and the implications of the Industry 4.0 concept. *Procedia Manuf.* **2017**, *13*, 1206–1214. [CrossRef]
6. Furht, B. *Handbook of Augmented Reality*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2011.
7. Sääski, J.; Salonen, T.; Liinasuo, M.; Pakkanen, J.; Vanhatalo, M.; Riitahuhta, A. Augmented Reality Efficiency in Manufacturing Industry: A Case Study. In Proceedings of the NordDesign 2008 Conference, Tallinn, Estonia, 21–23 August 2008; pp. 99–109.
8. Ho, P.T.; Albajez, J.A.; Santolaria, J.; Yagüe-Fabra, J.A. Study of augmented reality based manufacturing for further integration of quality control 4.0, A systematic literature review. *Appl. Sci.* **2022**, *12*, 1961. [CrossRef]
9. Rupa, C.; Srivastava, G.; Ganji, B.; Tatiparthi, S.P.; Maddala, K.; Koppu, S.; Lin, J.C.-W. Medicine drug name detection based object recognition using augmented reality. *Front. Public Health* **2022**, *10*, 881701. [CrossRef]
10. Bharath, G.; Ch, R.; Karthik, M.; Chowdary, M. Revelation of geospatial information using augmented reality. In Proceedings of the 2021 Sixth International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET), Chennai, India, 25–27 March 2021; IEEE: New York City, NY, USA, 2021; pp. 303–308.
11. Gorecky, D.; Schmitt, M.; Loskyll, M.; Zühlke, D. Human-machine-interaction in the industry 4.0 era. In Proceedings of the 2014 12th IEEE International Conference on Industrial Informatics, INDIN, Porto Alegre, Brazil, 27–30 July 2014; pp. 289–294.
12. Gladysz, B.; Tran, T.A.; Romero, D.; van Erp, T.; Abonyi, J.; Ruppert, T. Current development on the Operator 4.0 and transition towards the Operator 5.0: A systematic literature review in light of Industry 5.0. *J. Manuf. Syst.* **2023**, *70*, 160–185. [CrossRef]
13. Michalos, G.; Karagiannis, P.; Makris, S.; Tokçalar, O.; Chryssolouris, C. Augmented Reality (AR) Applications for Supporting Human-robot Interactive Cooperation. *Procedia CIRP* **2016**, *41*, 370–375. [CrossRef]
14. Ohno, T. *Toyota Production System: Beyond Large-Scale Production*; CRC Press: Boca Raton, FL, USA, 1988.
15. Kolberg, D.; Zühlke, D. Lean Automation Enabled by Industry 4.0 Technologies. *IFAC-PapersOnLine* **2015**, *48*, 1870–1875. [CrossRef]
16. Breque, M.; De Nul, L.; Petridis, A. *Industry 5.0, towards a Sustainable, Human-Centric and Resilient European Industry*; European Commission, Directorate-General for Research and Innovation: Luxembourg, 2021.
17. Huang, S.; Wang, B.; Li, X.; Zheng, P.; Mourtzis, D.; Wang, L. Industry 5.0 and Society 5.0—Comparison, complementation and co-evolution. *J. Manuf. Syst.* **2022**, *64*, 424–428. [CrossRef]
18. Alves, A.C. Lean Thinking: An essential mindset. *IEEE Eng. Manag. Rev.* **2022**, *50*, 127–133. [CrossRef]
19. Womack, J.P.; Jones, D.T.; Roos, D. *The Machine That Changed the World: The Story of Lean Production*; Rawson Associates: New York, NY, USA, 1991.
20. Liker, J.K. *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*; McGraw-Hill Education: New York, NY, USA, 2004.
21. Alves, A.C.; Ferreira, A.C.M.; Maia, L.C.; Leao, C.; Carneiro, P. A symbiotic relationship between Lean Production and Ergonomics: Insights from Industrial Engineering final year projects. *Int. J. Ind. Eng. Manag.* **2019**, *10*, 243–256. [CrossRef]
22. Dul, J.; Neumann, W.P. Ergonomics contributions to company strategies. *Appl. Erg.* **2009**, *40*, 745–752. [CrossRef] [PubMed]
23. Maia, L.C.; Alves, A.C.; Leão, C.P. *Do Lean Methodologies Include Ergonomic Tools?* Portuguese Society of Occupational Safety and Hygiene (SPOSHO): Guimaraes, Portugal, 2012.
24. Brito, M.F.; Ramos, A.L.F.A.; Carneiro, P.; Gonçalves, M.A.; de Vasconcelos Ferreira, J.A.; Frade, A.B.T. Improving the production performance and ergonomic aspects using lean and agile concepts. *Open Cybern. Syst. J.* **2018**, *12*, 122–135. [CrossRef]
25. Nunes, I.L. Integration of ergonomics and lean six sigma. *A model proposal. Procedia Manuf.* **2015**, *3*, 890–897.
26. Arezes, P.M.; Dinis-Carvalho, J.; Alves, A.C. Workplace ergonomics in lean production environments: A literature review. *Work* **2015**, *52*, 57–70. [CrossRef] [PubMed]
27. Zhou, K.; Liu, T.; Zhou, L. Industry 4.0, Towards Future Industrial Opportunities and Challenges. In Proceedings of the International Conference on Fuzzy Systems and Knowledge Discovery, Changsha, China, 13–15 August 2016; pp. 2147–2152.
28. Ivanov, D. The Industry 5.0 framework: Viability-based integration of the resilience, sustainability, and human-centricity perspectives. *Int. J. Prod. Res.* **2023**, *61*, 1683–1695. [CrossRef]
29. Leng, J.; Sha, W.; Wang, B.; Zheng, P.; Zhuang, C.; Liu, Q.; Wuest, T.; Mourtzis, D.; Wang, L. Industry 5.0, Prospect and retrospect. *J. Manuf. Syst.* **2022**, *65*, 279–295. [CrossRef]
30. Shiroishi, Y.; Uchiyama, K.; Suzuki, N. Society 5.0, For human security and well-being. *Computer* **2018**, *51*, 91–95. [CrossRef]
31. Lu, Y.; Zheng, H.; Chand, S.; Xia, W.; Liu, Z.; Xu, X.; Wang, L.; Qin, Z.; Bao, J. Outlook on human-centric manufacturing towards Industry 5.0. *J. Manuf. Syst.* **2022**, *62*, 612–627. [CrossRef]

32. Mourtzis, D.; Angelopoulos, J.; Panopoulos, N. Operator 5.0, A survey on enabling technologies and a framework for digital manufacturing based on extended reality. *J. Mach. Eng.* **2022**, *22*, 43–69. [CrossRef]
33. Deguchi, A.; Hirai, C.; Matsuoka, H.; Nakano, T.; Oshima, K.; Tai, M. What is society 5.0. In *Society 5.0.*; Springer: Singapore, 2020; pp. 1–23.
34. Mourtzis, D.; Angelopoulos, J.; Panopoulos, N. A Literature Review of the Challenges and Opportunities of the Transition from Industry 4.0 to Society 5.0. *Energies* **2022**, *15*, 6276. [CrossRef]
35. Keidanren, J.B.F. *Toward Realization of the New Economy and Society—Reform of the Economy and Society by the Deepening of "Society 5.0.*; Keidanren: Tokyo, Japan, 2016.
36. Fukuyama, M. Society 5.0, Aiming for a new human-centered society. *Jpn. Spotlight* **2018**, *1*, 47–50.
37. Rahardjo, B.; Wang, F.-K.; Yeh, R.-H.; Chen, Y.-P. Lean Manufacturing in Industry 4.0, A Smart and Sustainable Manufacturing System. *Machines* **2023**, *11*, 72. [CrossRef]
38. Pereira, A.C.; Dinis-Carvalho, J.; Alves, A.C.; Arezes, P. How Industry 4.0 can enhance Lean practices. *FME Trans.* **2019**, *47*, 810–822. [CrossRef]
39. Bittencourt, V.L.; Alves, A.C.; Leão, C.P. Industry 4.0 triggered by Lean Thinking: Insights from a systematic literature review. *Int. J. Prod. Res.* **2021**, *59*, 1496–1510. [CrossRef]
40. Hancock, P.A.; Diaz, D.D. Ergonomics as a foundation for a science of purpose. *Theor. Issues Ergon. Sci.* **2002**, *3*, 115–123. [CrossRef]
41. Berlin, C.; Adams, C. *Production Ergonomics: Designing Work Systems to Support Optimal Human Performance*; Ubiquity Press: London, UK, 2017.
42. Nunes, I.L.; Bush, P.M. Work-related musculoskeletal disorders assessment and prevention. In *Ergonomics—A Systems Approach*; IntechOpen: London, UK, 2012; pp. 1–30.
43. Nunes, I.L. Ergonomic risk assessment methodologies for work-related musculoskeletal disorders: A patent overview. *Recent Pat. Biomed. Eng. (Discontin.)* **2009**, *2*, 121–132. [CrossRef]
44. Sun, L.; Zhang, Y.; Shang, K.; Wu, A. Investigation on musculoskeletal disorders of the workers in automobile production logistics. In Proceedings of the 24th International Conference on Industrial Engineering and Engineering Management 2018; Springer: Berlin/Heidelberg, Germany, 2019; pp. 491–498.
45. Afonso, T.; Alves, A.C.; Carneiro, P. Lean Thinking, Logistic and Ergonomics: Synergetic Triad to Prepare Shop Floor Work Systems to Face Pandemic Situations. *Int. J. Glob. Bus. Compet.* **2021**, *16*, 62–76.
46. Rajesh, R.; Babu, R.V.; Ramachandran, S. Ergonomics Redesign of Material Handling Work System in Manufacturing Plant. *Int. J. Innov. Res. Sci. Eng. Technol.* **2013**, *2*. Available online: https://www.semanticscholar.org/paper/ERGONOMIC-REDESIGN-OF-A-MATERIAL-HANDLING-IN-A-Rajesh-Babu/ebe7e21c1a72f854d41de1498c0fb7502280636d (accessed on 21 December 2021).
47. Bigliardi, B.; Casella, G.; Bottani, E. Industry 4.0 in the logistics field: A bibliometric analysis. *IET Collab. Intell. Manuf.* **2021**, *3*, 4–12. [CrossRef]
48. Cimini, C.; Lagorio, A.; Pirola, F.; Pinto, R. Exploring human factors in Logistics 4.0, Empirical evidence from a case study. *IFAC-PapersOnLine* **2019**, *52*, 2183–2188. [CrossRef]
49. Nee, A.Y.C.; Ong, S.K. *Springer Handbook of Augmented Reality*; Springer Nature: Berlin/Heidelberg, Germany, 2023.
50. Falcioni, J.G. Rewritting the Rules of Product Development. *Mech. Eng.* **2016**, *138*, 6.
51. Azuma, R.; Baillot, Y.; Behringer, R.; Feiner, S.; Julier, S.; Maclntyre, B. Recent advances in augmented reality. *IEEE Comput. Graph. Appl.* **2001**, *21*, 34–47. [CrossRef]
52. Kipper, G.; Rampolla, J. *Augmented Reality: An Emerging Technologies Guide to AR*; Elsevier: Amsterdam, The Netherlands, 2012.
53. Pereira, A.; Abreu, M.F.; Silva, D.; Alves, A.C.; Oliverira, J.A.; Lopes, I.; Figueiredo, M.C. Reconfigurable Standardized Work in a Lean Company—A Case Study. *Procedia CIRP* **2016**, *52*, 239–244. [CrossRef]
54. Mourtzis, D.; Angelopoulos, J.; Panopoulos, N. Manufacturing personnel task allocation taking into consideration skills and remote guidance based on augmented reality and intelligent decision making. *Int. J. Comput. Integr. Manuf.* **2023**, *36*, 70–85. [CrossRef]
55. Nee, A.Y.C.; Ong, S.K.; Chryssolouris, G.; Mourtzis, D. Augmented reality applications in design and manufacturing. *CIRP Annals* **2012**, *61*, 657–679. [CrossRef]
56. Ho, P.T.; Albajez, J.A.; Yagüe, J.A.; Santolaria, J. Preliminary study of Augmented Reality based manufacturing for further integration of Quality Control 4.0 supported by metrology. In *IOP Conference Series: Materials Science and Engineering, Volume 1193, Proceedings of the 9th Manufacturing Engineering Society International Conference (MESIC 2021), Gijón, Spain, 23–25 June 2021*; IOP Publishing: Bristol, UK, 2021; p. 012105.
57. Syberfeldt, A.; Danielsson, O.; Holm, M.; Wang, L. Dynamic operator instructions based on augmented reality and rule-based expert systems. *Procedia CIRP* **2016**, *41*, 346–351. [CrossRef]
58. Romero, D.; Stahre, J.; Wuest, T.; Noran, O.; Bernus, P.; Fast Berglund, Å.; Gorecky, D. Towards an operator 4.0 typology: A human-centric perspective on the fourth industrial revolution technologies. In Proceedings of the CIE 2016, 46th International Conferences on Computers and Industrial Engineering, Tianjin, China, 29–31 October 2016.
59. Pereira, A.C.R. The Use of Augmented Reality in the Lean Workplaces at Smart Factories. Ph.D. Thesis, University of Minho, Braga, Portugal, 2022.

60. Härmä, A.; Jakka, J.; Tikander, M.; Karjalainen, M.; Lokki, T.; Hiipakka, J.; Lorho, G. Augmented reality audio for mobile and wearable appliances. *AES J. Audio Eng. Soc.* **2004**, *52*, 618–639.
61. Sylla, N.; Bonnet, V.; Colledani, F.; Fraisse, P. Ergonomic contribution of ABLE exoskeleton in automotive industry. *Int. J. Ind. Ergon.* **2014**, *44*, 475–481. [CrossRef]
62. Tachi, S. From 3D to VR and further to telexistence. In Proceedings of the 23rd International Conference on Artificial Reality and Telexistence, ICAT 2013, Tokyo, Japan, 11–13 December 2013; pp. 1–10.
63. Pereira, A.C.; Arezes, P.; Alves, A.C.; Duarte, F.J. An enhanced human-machine interface enabled by augmented reality—A new approach for human augmentation. In Proceedings of the XIX International Conference on Occupational Risk Prevention, Madrid, Spain, 5–7 June 2019; pp. 178–187.
64. Kymäläinen, T.; Koskinen, H.; Aromaa, S. Design and research for advanced human augmentation in the industrial work context. In Proceedings of the 12th International Conference on Intelligent Environments, London, UK, 14–16 September 2016; IOS Press: Amsterdam, The Netherlands, 2016; pp. 608–614.
65. Weber, A. Visual Work Instructions and the Paperless Factory. *Assem. Mag.* **2014**, *57*. Available online: https://www.assemblymag.com/articles/91946-visual-work-instructions-and-the-paperless-factory (accessed on 3 January 2022).
66. Khoshnevis, M.; Lindberg, E. *Development of a Demonstrator in the Aerospace Industry for Visualization of 3D Work Instructions*; Linköpings Universitet: Linköping, Sweden, 2015.
67. Wang, X.; Ong, S.K.; Nee, A.Y.C. A comprehensive survey of augmented reality assembly research. *Adv. Manuf.* **2016**, *4*, 1–22. [CrossRef]
68. Ropp, T.D.; Thomas, E.; Lee, S.; Broyles, A.; Lewin, P.; Andreychek, C.; Nicol, J. *Creating Hybrid Air Vehicle Technical Work Instructions Using Augmented Reality and 2D Barcode Visualization Technologies*; White Paper; Hangar of the Future Research Laboratory, Purdue University: West Lafayette, IN, USA, 2013.
69. Wang, W.; Wang, F.; Song, W.; Su, S. Application of augmented reality (AR) technologies in inhouse logistics. *E3S Web Conf.* **2020**, *145*, 02018. [CrossRef]
70. Baumann, H. Order Picking Supported by Mobile Computing. Ph.D. Thesis, Universität Bremen, Bremen, Germany, 2012.
71. Stein, R.; Ferrero, S.; Hetfield, M.; Quinn, A.; Krichever, M. Development of a commercially successful wearable data collection system. In Proceedings of the Digest of Papers. Second International Symposium on Wearable Computers (Cat. No. 98EX215), Pittsburgh, PA, USA, 19–20 October 1998; IEEE: New York City, NY, USA, 1998; pp. 18–24.
72. Starner, T.E. Wearable computers: No longer science fiction. *IEEE Pervasive Comput.* **2002**, *1*, 86–88. [CrossRef]
73. Reif, R.; Günthner, W.A. Pick-by-vision: Augmented reality supported order picking. *Vis. Comput.* **2009**, *25*, 461–467. [CrossRef]
74. Stoltz, M.-H.; Giannikas, V.; McFarlane, D.; Strachan, J.; Um, J.; Srinivasan, R. Augmented Reality in Warehouse Operations: Opportunities and Barriers. *IFAC-PapersOnLine* **2017**, *50*, 12979–12984. [CrossRef]
75. vom Stein, A.M.; Günthner, W.A. Using Smart Glasses for the Inclusion of Hearing-Impaired Warehouse Workers into Their Working Environment. In Proceedings of the International Conference on HCI in Business, Government, and Organizations, Toronto, ON, Canada, 17–22 July 2016; Springer: Berlin/Heidelberg, Germany, 2016; pp. 358–368.
76. Romero, D.; Bernus, P.; Noran, O.; Stahre, J.; Fast-Berglund, Å. The operator 4.0, Human cyber-physical systems & adaptive automation towards human-automation symbiosis work systems. In Proceedings of the IFIP Advances in Information and Communication Technology, Iguassu Falls, Brazil, 3–7 September 2016; pp. 677–686.
77. Ruppert, T.; Jaskó, S.; Holczinger, T.; Abonyi, J. Enabling Technologies for Operator 4.0, A Survey. *Appl. Sci.* **2018**, *8*, 1650. [CrossRef]
78. Kaasinen, E.; Schmalfuß, F.; Özturk, C.; Aromaa, S.; Boubekeur, M.; Heilala, J.; Heikkilä, P.; Kuula, T.; Liinasuo, M.; Mach, S.; et al. Empowering and engaging industrial workers with Operator 4.0 solutions. *Comput. Ind. Eng.* **2020**, *139*, 105678. [CrossRef]
79. Remenyi, D.; Williams, B.; Money, A.; Swartz, E. *Doing Research in Business and Management: An Introduction to Process and Method*; Sage Publications Ltd.: Newbury Park, CA, USA, 1998.
80. Yin, R.K. *Case Study Research: Design and Methods*; SAGE Publications: Thousand Oaks, CA, USA, 2009.
81. Saunders, M.; Lewis, P.; Thornhill, A. *Research Methods for Business Students*, 5th ed.; Financial Times Prentice Hall: Edinburgh, Scotland, 2009.
82. Eisenhardt, K.M. Building theories from case study research. *Acad. Manag. Rev.* **1989**, *14*, 532–550. [CrossRef]
83. Kuorinka, I.; Jonsson, B.; Kilbom, A.; Vinterberg, H.; Biering-Sørensen, F.; Andersson, G.; Jørgensen, K. Standardised Nordic questionnaires for the analysis of musculoskeletal symptoms. *Appl. Erg.* **1987**, *18*, 233–237. [CrossRef]
84. Crawford, J.O. The Nordic musculoskeletal questionnaire. *Occup. Med. (Chic. Ill.)* **2007**, *57*, 300–301. [CrossRef]
85. Jensen, M.P.; Karoly, P. Self-report scales and procedures for assessing pain in adults. In *Handbook of Pain Assessment*; Turk, D.C., Melzack, R., Eds.; The Guilford Press: New York, NY, USA, 2011.
86. Borg, G. Psychophysical scaling with applications in physical work and the perception of exertion. *Scand. J. Work. Environ. Health* **1990**, *16*, 55–58. [CrossRef] [PubMed]
87. Likert, R. A technique for the measurement of attitudes. *Arch. Psychol.* **1932**, *140*, 5–55.
88. New Atlas. MATE Is Made to Look Out for Your Shoulders. 2018. Available online: https://newatlas.com/comau-mate-exoskeleton/56625/ (accessed on 3 January 2022).
89. Etiden. Proglove Mark 2, BT, 2D, Sr., BT (BLE, 5.1). 2020. Available online: https://www.etiden.com/PT/m003-eu-proglove-1.html (accessed on 21 December 2021).

90. Datalogic. HandScanner. 2021. Available online: https://www.datalogic.com/eng/retail-manufacturing-transportation-logistics-healthcare/handheld-scanners/handscanner-pd-886.html# (accessed on 3 January 2022).
91. ILS Ltd. Vocollect A500 Mobile Device. 2017. Available online: http://inter-solutions.co.uk/solutions/honeywell-vocollect-voice-solutions/vocollet-werable-mobile-devices/vocollect-a500-mobile-device.html (accessed on 21 December 2021).
92. Microsoft. Business-Ready Solutions for HoloLens 2. 2020. Available online: https://www.microsoft.com/en-gb/hololens/apps (accessed on 21 December 2021).