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XR technologies in the automotive industry: guidelines for their implementation

TESI DI LAUREA MAGISTRALE IN MANAGEMENT ENGINEERING - INGEGNERIA GESTIONALE

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Abstract

The ongoing electrification, shorter product life cycles and increasing demands for car customization have increased the complexity of manufacturing processes in the automotive industry. Therefore, car manufacturers are looking at the implementation of extended reality (XR) technologies to tackle the many challenges they are facing, as well as to improve the flexibility and adaptability of their operations, and thus also their profitability and efficiency. However, despite the rapid advancement of technological developments, a gap is identified in the number of academics addressing the implementation of XR technologies within manufacturing in the automotive industry.

To address the identified gap, this research proposes a three-step process that relies on three sources of data, both theoretical and empirical: a systematic literature review, a set of interviews with XR experts and three case studies attended within Volvo Cars Corporation (VCC). The first step aims to analyse the state of the art of XR technologies within manufacturing in the automotive industry. The objective is to define the main technologies available (i.e. hardware and software), the fields of application where these technologies can be applied and their level of maturity. The second step analyses the benefits that XR technologies may bring to the different fields of application and the challenges that are preventing the advantages of XR to be fully exploited. Finally, based on the findings of the two previous steps, a set of guidelines for XR implementation is proposed, validating the suggested guidelines within VCC.

The data collected and its analysis contribute to depicting the actual state of the art of XR technologies. In particular, on one hand, five different fields in which augmented reality (AR), mixed reality (MR) and virtual reality (VR) can turn beneficial, according to their different level of maturity, are identified. On the other hand, five clusters of challenges (funding, integration, selection, skills and technology) are recognised as obstacles to the implementation of XR technologies. Based on these findings, the model developed proposes that automotive firms follow step-by-step a set of five guidelines considering three main perspectives: technology management, competencies, and organizational structure.

Therefore, the main theoretical contribution of this research is to clarify the state of the art of XR technologies in the automotive industry. While at the same time, the proposed guidelines are intended to be a valuable starting point to support car manufacturers in implementing XR technologies within manufacturing.

Keywords: XR, augmented reality, mixed reality, virtual reality, industry 4.0, automotive, manufacturing, case study, guidelines.

Abstract in lingua italiana

L'elettrificazione in corso, i cicli di vita dei prodotti sempre più corti e la crescente richiesta di personalizzazione delle auto hanno aumentato la complessità dei processi produttivi nell'industria automobilistica. Pertanto, le case automobilistiche stanno valutando l'implementazione di tecnologie di extended reality (XR) per affrontare le numerose sfide che si trovano ad affrontare, nonché per migliorare la flessibilità e l'adattabilità delle loro operazioni, e quindi anche la loro redditività ed efficienza. Tuttavia, nonostante il rapido sviluppo tecnologico, è stata riscontrata una lacuna nel numero di studi accademici che si occupano dell'implementazione delle tecnologie XR nell'ambito manifatturiero dell'industria automobilistica.

Per colmare questa lacuna, la ricerca propone un processo in tre fasi che si basa su tre fonti differenti di dati, sia teoriche che empiriche: una revisione sistematica della letteratura, una serie di interviste con esperti di XR e tre casi studio svolti all'interno di Volvo Cars Corporation (VCC). La prima fase mira ad analizzare lo stato dell'arte delle tecnologie XR nell'ambito manifatturiero dell'industria automobilistica. L'obiettivo è definire le principali tecnologie disponibili (hardware e software), i campi di applicazione in cui tali tecnologie possono essere applicate e il loro livello di maturità. La seconda fase analizza i vantaggi che le tecnologie XR possono apportare ai diversi campi di applicazione e le sfide che impediscono di sfruttarne appieno i vantaggi. Infine, sulla base dei risultati delle due fasi precedenti, viene proposta una serie di linee guida per l'implementazione delle tecnologie XR, validandole sul caso specifico di VCC.

I dati raccolti e la loro analisi contribuiscono a descrivere l'attuale stato dell'arte delle tecnologie XR. In particolare, da un lato, vengono identificati cinque diversi campi in cui la realtà aumentata (AR), la realtà mista (MR) e la realtà virtuale (VR) possono risultare utili, in base al loro diverso livello di maturità. Dall'altro lato, cinque gruppi di problemi (finanziamenti, integrazione, selezione, competenze e tecnologia) sono riconosciuti come ostacoli all'implementazione delle tecnologie XR. Sulla base di questi risultati, il modello sviluppato propone che le aziende automobilistiche seguano passo dopo passo una serie di cinque linee guida considerando tre aspetti principali: gestione della tecnologia, competenze e struttura organizzativa.

Pertanto, il principale contributo teorico di questa ricerca è quello di chiarire lo stato dell'arte delle tecnologie XR nell'industria automobilistica. Allo stesso tempo, le linee guida proposte vogliono essere un valido punto di partenza per supportare le case automobilistiche nell'implementazione delle tecnologie XR all'interno della produzione.

Parole chiave: XR, realtà aumentata, realtà mista, realtà virtuale, industria 4.0, industria automobilistica, manifatturiero, caso studio, linee guida.

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EXECUTIVE SUMMARY OF THE THESIS

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I. Introduction and theoretical background

Extended reality (XR) is an umbrella term used to encompass all the forms of computer-generated environments such as AR, MR and VR. Consumer demand for these technologies is highest in the creative economy, such as gaming. On the other hand, XR is also capturing the interest of businesses of all sizes. There are several explanations for this. Better XR platforms have been developed, and there has been an overall increase in knowledge and experience, as well as increased competence in solving technological problems and understanding business cases. In addition to this, XR has been promoted as most businesses have been compelled to operate remotely in response to the Covid-19 pandemic. This boosted public trust in technical advancement and hastened the spread of AR, MR and VR technologies. [1]

The benefits these technologies may bring are related to the possibility of merging real and virtual worlds. In particular, engineers can visually prototype new ideas, making it easier to see problems and visualize adjustments. Factory workers can learn new procedures using immersive technology and customers may see, customize, and virtually kick the tires of various models. [2]

Therefore, the unlimited potential offered by the possibility of overlaying a digital model on reality is gaining considerable interest in the manufacturing industry. In particular, in the automotive one. As of 2022, this industry faces three main challenges: the ongoing electrification, the shorter car life cycles and the increasing demand for car customisation. These three challenges together are adding to the complexity of manufacturing operations. Therefore, car manufacturers are looking at the implementation of XR technologies to tackle these challenges and improve the flexibility of their operations, and thus also their adaptability and efficiency.

However, due to the rapid technological development, there is a lack of clarity concerning the actual state of the art of these technologies. Namely, which of them are already developed enough to be applied on a full scale in the production line and where these technologies may be applied. In addition, the benefits XR technologies may bring, as well as the challenges that may arise in their implementation, are also far from being clear. This has the main impact on how car manufacturers are approaching the process of XR implementation, which in most cases happens without a clear vision or roadmap.

Therefore, this research aims at providing car manufacturers with support for XR implementation and analysing and also presenting the actual state of the art of these technologies, together with their main benefits and challenges.

II. Research methodology

To accomplish the presented aim, a solid methodology is required. Therefore, the Design Research Methodology (DRM) provided by [3] is adopted and slightly adapted to this specific scenario.

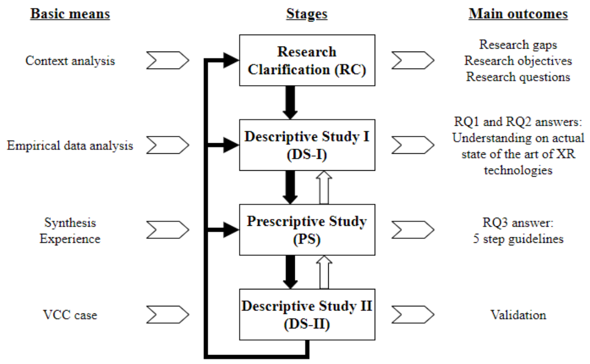
The DRM follows four stages, as shown in Figure I:

1. Research Clarification (RC). Based on context analysis, the research aim, and thus the research gaps (RG), objective (RO) and questions (RGs), are identified.
2. Descriptive Study I (DS-I). Given the clear goal and focus of the research, three different sources of empirical data are considered to describe the initial situation:
    a. A systematic literature review. With Scopus as the chosen database for the research, several alternative research strings and keywords were chosen according to the various XR technologies and perspectives to be examined. To make the study more transparent, they were divided into six distinct clusters, each with its own collection of keywords.
    b. A set of interviews with XR experts coming from VCC, Audi, Volkswagen and CEVT. The approach followed was that of a semi-structured interview. As a result, a pool of questions has been prepared. However, depending on how the interview was performed, the format has been adapted to ensure that greater knowledge was extracted from the respondents.
    c. Three case studies attended within VCC, to evaluate first-hand the actual usage of XR technologies within an automotive company.

    The aim is to give a clear understanding of the actual state of the art of XR technologies in the automotive industry, thus answering the first two RQs.
3. Prescriptive Study (PS). The increased understanding of the existing situation, together with the theoretical and practical experience matured on the topic, can be exploited to develop a valuable method for XR implementation, providing guidelines to support car manufacturers in this process. Therefore, the aim is to address the third RQ.
4. Descriptive Study II (DS-II). Finally, the proposed method is validated by applying it to the VCC case. The aim is to investigate, first of all, its applicability in a real-world case. Then, its ability in providing the firm with valuable support in the XR implementation process.

Nevertheless, the DRM has not been applied following a set of rigorously and sequentially executed steps and supporting methods. Iterations take place between stages. In particular, an additional DS-I is necessary at the PS stage to obtain more information on the three primary perspectives considered in the model: technology management, competencies, and the firm's organisational structure. Furthermore, the results of the DS-II stage will need a review of the preceding stages in future research in order to address the identified limitations of the existing model.

Figure I. DRM Methodology, inspired by [3].



III. Results

The research had the aim to provide car manufacturers with valuable support for XR implementation. To accomplish this task, a deep analysis of the actual state of the art was required to fully understand, first of all, where these technologies may be applied and then which are the related benefits and challenges.

As of 2022, five main fields where XR technologies are already applied or under investigation within manufacturing areas have been identified:

- Assembly. AR and MR are applied to support operators while performing assembly tasks by superimposing on their sight all the specific set of tasks and instructions to be performed. This can turn beneficial for car manufacturers since it leads to a significant reduction of the operators' cognitive load, as they do not have to remember all the sequences of tasks. Moreover, this can in turn results in a minimization of human-related errors, and thus an increase in the quality rate. However, both these technologies are not mature enough to be applied on a full scale yet.
- Ergonomics. AR and VR are well developed and adopted to support ergonomics assessments, namely, to detect and solve any ergonomics issues. The implementation of AR and VR in this field proved to shorten the production development process, allowing for time and cost savings thanks to the problem's early detection and no need for detailed mock-ups.
- Layout. AR and VR are well developed and adopted to support the layout design process, giving the possibility to look at how the future production layout could look like. And make any improvements if needed. The creation of an interactive and immersive environment for layout discussion and brainstorming certifies the benefits of using AR and VR to increase layout design and analysis process efficiency. In particular, as seen for ergonomics, XR technologies allows also in this case for time and cost savings thanks to the problem's early detection and no need for detailed mock-ups.
- Maintenance. AR and MR are being studied to provide maintenance operators with real-time data regarding the machines' status, the failures cause and the instructions for repairing, which could increase the companies' ability to predict failures. Moreover, both AR and MR are being studied to allow remote assistance to the maintenance operators, with the aim of increasing the overall maintenance process quality.
- Training. VR is well developed and adopted to let the operators train in a fully virtual environment. This has the main benefit of reducing the educational costs since car manufacturers do not need to stop the production line or do not have to waste material for training. Moreover, XR technologies are proven they can lead to a higher trainees' engagement and involvement, resulting in a higher knowledge retention rate compared to the traditional training programs. While MR is being studied in the same field with the same purpose, it is still in an exploratory phase.

However, the implementation and usage of XR technologies in the presented fields are not without their difficulties. In particular, several challenges have been identified. All the different types of challenges have been grouped into five different clusters, which are:

- Funding. Lack of funds and their misallocation has been highlighted, mainly due to a general lack of vision and roadmap for XR implementation.
- Integration. The high presence of silos is preventing car manufacturers from achieving a high level of internal integration and collaboration.
- Selection. Car manufacturers are struggling to understand which, among AR, MR and VR is the most suitable technology according to their needs.

- Skills. Being XR are quite new technology, firms are missing the right competencies and capabilities to handle these technologies.
  - Technology. XR hardware and software are experiencing a high number of technical limitations such as AR glasses' limited field of view.

IV. How to implement XR technologies

Based on the results provided, there are many reasons behind the need for a comprehensive set of guidelines for supporting XR implementation:

- The lack of a roadmap and a vision witnessed during the interviews performed.
- Lack of academic contribution to XR implementation.
- The high number of challenges gathered. In particular, 28 challenges were discussed.

As a result of the above considerations, it is worth noting that companies are constantly attempting to prepare themselves for industry 4.0 adoption. However, there are still numerous gaps in the implementation of specific technologies. Therefore, because there is no defined or standardized methodology, opting to embrace and implement XR technologies might be problematic [4]. Given all of these considerations, as well as the fact that designing an effective strategy for leveraging Industry 4.0 technology is one of the most important components of correctly exploiting the technologies [5], it was decided to present a thorough set of guidelines.

The set of guidelines advises on how to select, approach and exploit XR technologies in the short term and then continuously manage these technologies to achieve long-term value. More in detail, the guidelines are divided according to five main steps, which focus their attention on before and after the XR implementation.

As of before their implementation, the steps are the following:

1. Vision alignment. The first stage is to identify the strategy to be pursued and to determine whether XR technologies constitute a business opportunity or not. The choice to invest in XR technology is decided at this stage.
2. XR selection. the second step concerns the decision of which XR technology to implement. When the decision to adopt XR technologies has been made, it is essential to understand which of them to use. It is a fundamental step to select the correct technology to avoid making mistakes that can both affect the result and waste money and skills.
3. Implementation factors. The third step involves developing a strategy for adopting the previously designated XR technology. This is the phase of business transformation where organisations often focus on developing a disciplined implementation approach. [6]

While for what concerns after the XR implementation, the steps are the following:

4. Monitoring. The fourth step is to monitor the technology once it has been installed. The idea is to guarantee that what has been done corresponds to the expectations that existed before implementation. As a result, it is critical to ensure that they are on pace to fulfil their long-term objectives, which necessitates ongoing monitoring.
5. Reinforcement. The final step is to decide how to enhance the monitored performance. This can be accomplished by upgrading the present XR technology or by replacing it with market-developed technology. As a result, businesses may leverage their assets and capitalise on current business strategies. Firms, on the other hand, may capitalise on innovation possibilities, allowing them to be more inventive and proactive.

Finally, it is important to mention that an effective XR adoption and implementation plan must consider (1) technology management-, (2) skills - and (3) company structure-related aspects. Therefore, these three perspectives have been considered while providing practical guidelines for XR adoption and implementation in each step. In particular, these three identified views allowed for a cross-sectional analysis of the different steps and thus allowed for a clear idea of the considerations that need to be made in each of the steps.

V. The VCC case

The proposed set of guidelines has then been tested and validated in the case of Department A within VCC. The aim was to verify the feasibility of the proposed model and its ability to provide valuable support for car manufacturers.

Following the five different guidelines, it can be stated that XR technologies are the means by which VCC can achieve the desired objectives of improving production efficiency and creating the best condition for the operators. In particular, based on the different activities to be performed, VR is highly recommended for layout analysis and testing, while AR to perform ergonomics assessment. Furthermore, a set of KPIs and skill matrices has been developed to support the monitoring of XR performances.

However, the main contribution coming from the proposed set of guidelines regards Department A's organisational structure. In particular, a flatter organisation is suggested, with the creation of a common XR team for the whole department, divided into two small teams dedicated to the exploitation and exploration of XR technologies.

VI. Discussion

This research work positioned itself in the exploration of the industrial use of XR and analyses it through the lens of the automotive industry, particularly in manufacturing areas.

The results obtained came from the combination of the three different sources of data. The merge of academic findings with both interviews and case studies from the industry can be considered of great importance as it helped to combine the different perspectives. This then led to a more comprehensive analysis of the actual state of the art, a more detailed and up-to-date list of benefits and challenges and a comprehensive set of guidelines encompassing three different perspectives.

Moreover, the opportunity to apply the proposed set of guidelines to the case of VCC's Department A gave the possibility to highlight both expected and hidden benefits and limitations this approach may bring. In particular, the main advantage of applying these guidelines is that, by following them, it is possible to ensure that technologies are selected, implemented and monitored in the best possible way.

VII. Conclusions

The aim of the research is to provide a valuable support to car manufacturers for XR implementation, based on a deep and up-to-date knowledge of their current state of the art.

The theoretical contribution that this research has been able to provide concerns with all three research questions. In particular, each one contains new findings that can close the identified gaps. First of all, the research has provided a clear description of the actual state of the art of XR technologies, highlighting five fields where they can be applied, as well as the related benefits and challenges. Secondly, the proposed guidelines represent a big step for theory as they guide car manufacturers. This is a great achievement as it allows researchers to get an overview and understand the general process of applying XR technologies.

In addition to providing value to the theoretical context, this research has also brought value to the industrial world as well. In particular, the thesis offers many practical insights that can be applied in the corporate world. Firstly, the first two RQs can turn useful when car manufacturers are approaching the world of XR technologies and are looking for a comprehensive analysis of the actual state of the art. Moreover, the second valuable contribution concerns the innovative aspects that each phase of the guidelines proposes. The guidelines embrace the entire XR technology journey according to the challenges companies face. The overview includes the adoption decision, choice of technology, factors to consider during implementation, monitoring and possible improvements. Each point in the guidelines provides added value to the company and guidance toward the implementation of XR technologies.

However, the study is also characterised by two main limitations, which nevertheless leave the way open for many opportunities for future research. The first limitation concerns the lack of consideration of the financial and economic aspects of the three research questions. A suggestion for future researchers could be to conduct a deep analysis of the devices and software costs, as well as to include the financial perspective when proposing the set of guidelines for XR implementation. The second limitation is strictly connected with the application and validation of the proposed set of guidelines only in the case of VCC. Therefore, future researchers could apply the guidelines developed in the case of other car manufacturers and contexts, such as different industries, to verify their goodness once more and allow making changes with the aim of improving the proposed model.

Contents

1 Introduction

Extended reality (XR) is an umbrella term for all types of integrated real-and-virtual environments, including augmented reality (AR), virtual reality (VR), and mixed reality (MR). As a result, XR may refer to any technology ranging from a basic digital overlay to a completely digital and immersive experience [1]. Furthermore, AR, MR, and VR have progressed from a niche technology to a rising trend in a variety of businesses in recent years. The reasons are many, including improved XR platforms, have been developed, increased general knowledge and experience, better competence in technological problem-solving and a better understanding of business cases. In addition to this, XR has been promoted as most businesses have been compelled to operate remotely in response to the Covid-19 pandemic. This strengthened public trust in technical advancement and accelerated the proliferation of XR technology [2]. As a result, the global market for AR, VR, and MR reached $30.7 billion in 2021 and is expected to reach $300 billion by 2024 [3].

As of today, industries in the creative economy (i.e. gaming, live events, video entertainment and retail) have the most demand for XR technologies. Nonetheless, XR is capturing the interest of businesses of all sizes. Indeed, the limitless possibilities given by the ability to superimpose a digital model on reality pique the interest in manufacturing areas, notably that of the automotive industry [3].

However, the long-term potential of these technologies is still unknown, and their future applications remain unclear. Specifically in the automobile industry, the hardware and software employed in the specific field where XR may be used and the benefits they can provide in the manufacturing areas still need to be thoroughly examined and clarified [4]. Furthermore, the development and distribution of new technologies in the market pose a large number of unanswered issues to organisations which are fighting to remain competitive and establish a coherent strategy for their implementation and usage. As a result, the following research gaps (RG) have been identified:

RG1: Lack of clarity concerning the actual state of the art of XR technologies in the automotive industry within manufacturing.

RG2: Lack of clarity concerning the benefits XR technologies may bring and the challenges automotive companies are facing.

RG3: Lack of academic contributions regarding the implementation of XR technologies in the automotive industry within manufacturing.

Therefore, the research intends to address these gaps by first analysing the current state of the art of XR technologies in the automobile industry within manufacturing domains. The focus is on the primary technologies that are being researched or have already been implemented, emphasising their main fields of application and maturity level. To gain a better understanding of the current state of the art, the benefits they may provide as well as the challenges that companies face when dealing with these technologies are examined. The final goal of the research is, then, to provide car manufacturers with guidance for XR implementation. In particular, a set of guidelines are developed considering three main perspectives: technology management, competencies and organisational structure. With the aim of providing a more qualitative rather than quantitative research, other aspects, such as the financial perspective, are not considered at this stage. Finally, the suggested approach is verified by applying it to the VCC case. The research objective (RO) can then be summarized as follows:

> *RO: Define the state of the art of XR technologies, together with their benefits and challenges, and provide guidelines for their implementation in the automotive industry within manufacturing.*

Based on the identified RGs and proposed RO, the following three research questions (RQs) have been identified:

> *RQ1: What is the state of the art of XR technologies in the automotive industry within manufacturing?*
>
> *RQ2: What benefits and challenges may arise in applying XR technologies within the organization?*
>
> *RQ3: How to implement XR technologies within manufacturing in the automotive industry?*

A robust methodology is required to answer the three RQs, and thus the formulation and validation of a valuable set of guidelines, based on a deep understanding of the actual situation. Among all available approaches, the Design Research Methodology (DRM) provided by [5] is utilized and adapted to fit this specific scenario. The approach is divided into four stages (i.e., Research Clarification, Descriptive Study I, Prescriptive Study I, and Descriptive Study II) and is based on three theoretical and empirical data sources (i.e., a systematic literature review, a set of interviews with XR experts and three case studies attended within VCC).

To provide the reader with a broader understanding of the research, the following statements can help to identify the delimitations of the project:

- The research is designed to have a qualitative approach, as it intends to provide a clear picture of the state of the art of XR technologies.
- The research is focused on the study of XR technologies applied to the fields of manufacturing. Therefore, their usage in other areas, such as final product or product development is out of research's scope.
- The time frame of this thesis work is delimited to 19 weeks.

- Financial factors and variables related to the implementation and selection of XR technologies are not considered. This decision is due to reduced time and data availability. Also, XR technologies are developing rapidly, making the financial aspect highly variable over short periods of time. This decision prevents rapid obsolesce of the research results.
- The method includes insights from companies which will be anonymized due to confidentiality reasons.

For the sake of this report, the structure is summarised in the following Table 1.1.

Table 1.1. Report structure

Chapter	Content
1. Introduction	Provides the background of the research, together with the identified gaps, the aim, the three research questions and the delimitations.
2. Theoretical background	Provides an introduction to the concepts required to position the research.
3. Research methodology	Provides a description of the methodology followed and of the sources of data used.
4. Results	Synthesises the results of the first descriptive study and thus provides answers to the first two research questions.
5. How to implement XR technologies	Exhibits the proposed set of guidelines.
6. The VCC case	Exhibits the practical application of the proposed set of guidelines on the case of VCC.
7. Discussion	Discusses the results obtained.
8. Conclusions	Concludes the report by summarising the main findings of the research. Moreover, the theoretical and industrial contributions are presented, followed by the possibilities for future research.

2 Theoretical background

This section aims to define and clarify the idea of Industry 4.0 and XR technologies. The main trends and technologies are explained to make the document more understandable to the reader. This is crucial since both the context and the main technological trends are important as all activities in the industry are strongly influenced by consumer needs and technological changes.

2.1. About Industry 4.0

Consumer adoption of new technology is growing rapidly [6], resulting in fundamental market shifts and a new wave of digital-driven disruption. Value is shifting away from legacy products, which are becoming increasingly commoditized, and toward the data that those products generate and the insights that data generates. At the same time, industrial manufacturing productivity has come to a stalemate. In fact, after lean adoption and outsourcing/offshoring trends during the 1970s through the early 2000s, leaders must look for innovative ways to use technology to efficiently improve manufacturing [7].

In this context, Industry 4.0 envisions a new industrial revolution in which advanced manufacturing processes and the Internet of Things are coupled to build networked production systems that can communicate, analyse, and use data to drive more intelligent activities and decisions in the physical world. Companies must incorporate new technologies and digital capabilities into their assets to profit from the transformation to Industry 4.0. This is what is called digital industrial transformation [7].

Specifically, the digitalization of the manufacturing sector has been enabled by several disruptive technologies that have been collected into four clusters [8]:

- Data, computational power, and connectivity.
- Analytics and intelligence.
- Human-machine interaction.
- Digital-to-physical conversion.

The technologies from these clusters enable the translation of the physical into the virtual world and the connection back from the virtual to the real world [8].

Focusing on human-machine interaction (HMI) as the research topic, this category mainly refers to the communication and interaction between a human and a machine via a user interface, where the human and machine agents should no longer be thought of as separate entities, but rather as part of a dynamic unit or team working toward a common goal, which may include dynamic job allocation among participants [9]. In this context, many different technologies have been recently brought to the market and the resulting benefits are enormous in many areas. Training, industrial companies, the shopping & retail sector and entertainment are mainly enjoying these technologies [2]. The specific human-machine interaction technologies are analysed in the next paragraphs.

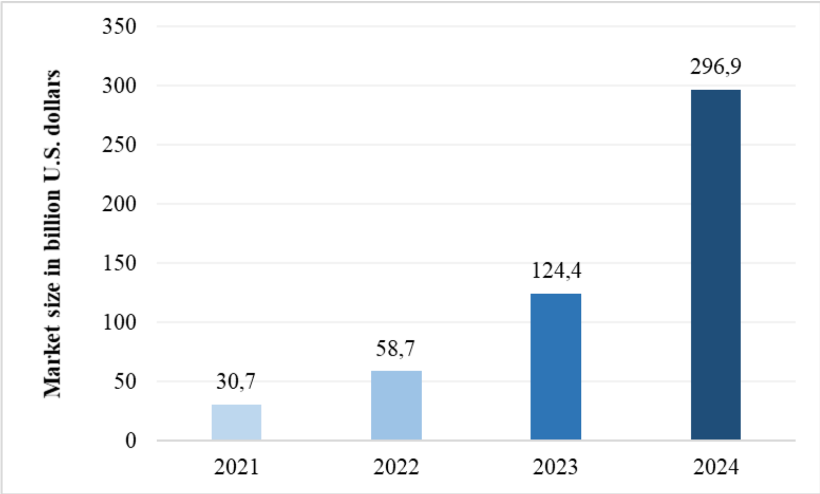
In addition, Industry 4.0 has proven to be a technological and cultural structural improvement that can enhance sustainability and develop the triple bottom line concept. Its goal is to fulfil the resource demands of current and future generations while minimizing environmental impact [10]. According to [11], Industry 4.0 can create long-term industrial value creation across the three economic, ecological, and societal triple bottom line dimensions by enhancing resource efficiency. The digital revolution enables organisations to become more efficient by adopting the latest technologies in the production system. Thus, Industry 4.0 provides an advantage by producing quality products at a lower cost and ensures efficient use of non-renewable resources [12]. In this context, XR technologies share with all the other Industry 4.0 technologies the goal of improving efficiency within companies and creating a more sustainable future.

2.2. About XR Technologies

Extended reality (XR) is an emerging umbrella term used to encompass all the forms of computer-generated environments such as augmented reality (AR), virtual reality (VR) and mixed reality (MR). Therefore, with XR it is possible to refer to all the technologies which range from a simple and digital overlay to a fully, digital and immersive experience [1]. The X in the acronym of extended reality not only stands for extended but can be interpreted as a variable to represent all those future technologies that will be incorporated under this umbrella term [13].

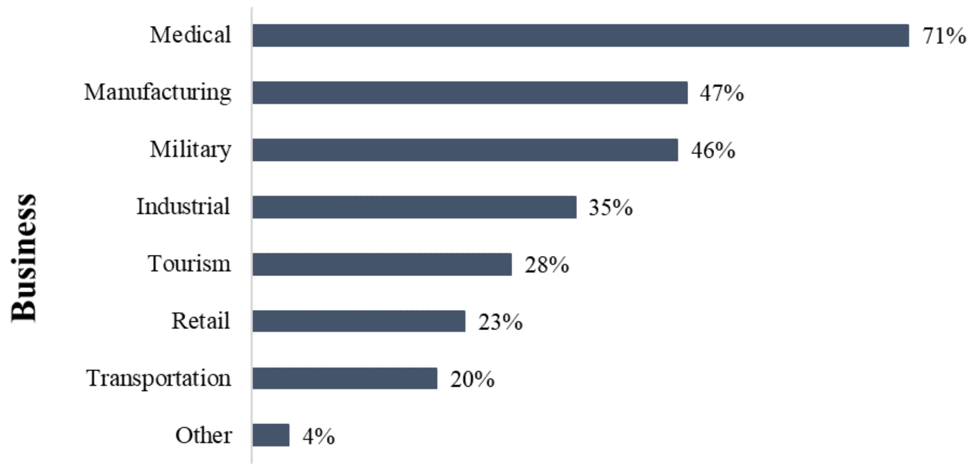
In recent years, from a niche technology to a burgeoning trend in numerous industries, AR, MR and VR have come a long way. The reasons for this are many. Better XR platforms have been created, there has been an overall growth in knowledge and experience, and greater expertise in both overcoming technical challenges and understanding business cases. In addition to all of these, XR has also been pushed as most companies have been forced to work remotely in response to the Covid-19 outbreak. This increased people's confidence in technological progress and accelerated the spread of virtual and augmented reality technology [2]. Consequently, the global market for AR, VR and MR has reached $30.7 billion in 2021, expecting to grow to about $300 billion by 2024, as shown in Figure 2.1 [3].

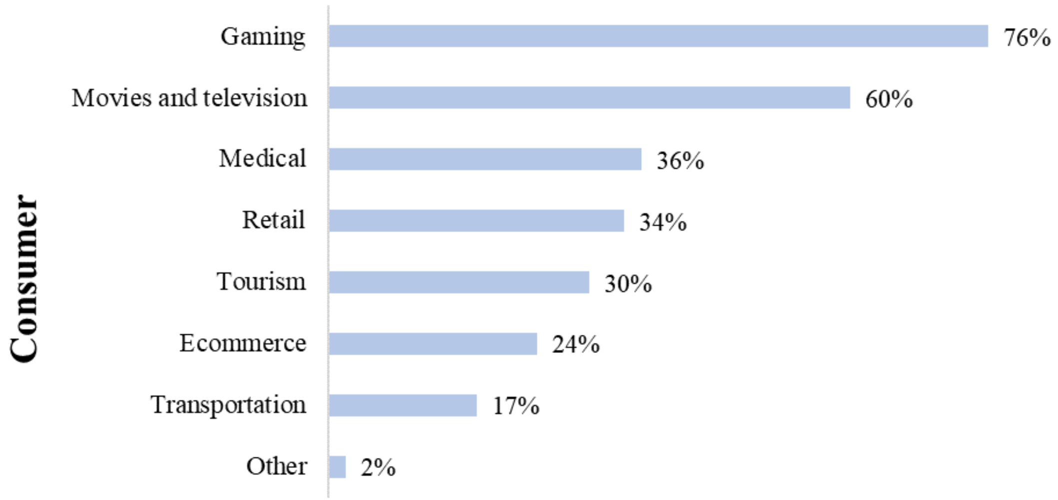
Figure 2.1. XR market size [3].



As of sectors, extended reality has more impact on, both consumers and businesses are considered. Figure 2.2 gives a broad view of the sectors. The highest consumer demand comes from industries in the creative economy such as gaming. Nevertheless, XR is attracting the attention of businesses of all types. Indeed, the unlimited potential offered by the possibility of overlaying a digital model on reality is gaining considerable interest in the manufacturing industry. In particular, automobile manufacturers benefit from a variety of AR and VR applications. Engineers can now visually prototype new ideas, making it easier to see problems and visualize adjustments. Factory workers can learn new procedures using immersive technology. Customers may see, customize, and virtually kick the tires of various models [3].

Figure 2.2. Business and Consumer sectors implementing XR, [3].

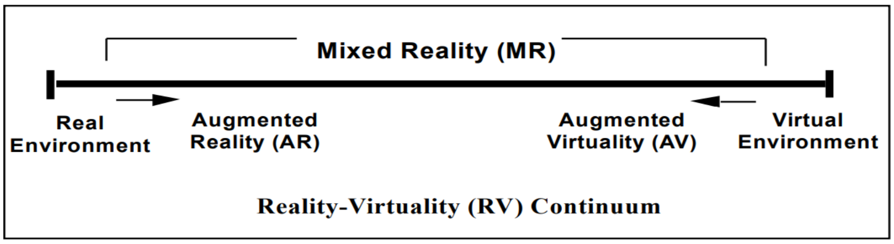




2.2.1. XR and the reality-virtuality continuum

It is necessary to distinguish different XR technologies and identify how they relate to the transformation from a real to a virtual environment. An appropriate approach is provided by Milgram's reality-virtuality continuum [14] in Figure 2.3.

Figure 2.3. Milgram's reality-virtuality continuum.



According to this representation, the real environment is an environment made up entirely of real items and includes everything that can be seen whether viewing a real-world scene in person, via a window, or a (video) display. This is in contrast to a virtual environment or virtual reality that consists exclusively of virtual objects, such as traditional computer visual simulations, either monitor-based or immersive. Therefore, the level of virtuality increases from left to right, with AR, augmented virtuality (AV) and then VR.

2.2.2. Augmented Reality (AR)

AR merges the virtual and real worlds with a virtual overlay that can add pictures, textual information, films, or other virtual components to the user's real-time viewing of the physical environment [15]. Therefore, AR allows the user to perceive the real environment while having virtual things superimposed or composed with it. For this reason, rather than replacing reality entirely, AR enhances it. Indeed, the real-world environment is augmented by computer-generated perceptual information, ideally across multiple sensory modalities, including visual, auditory, haptic, etc. [16].

This technology commonly uses a digital camera in a webcam or mobile phone to capture real-world data. Then, through either wearable, both head-worn and spatial, (e.g., smart glasses) or handled (e.g., tablet or smartphone) devices, AR enhances the real environment experience with virtual overlays.

To sum up, then, AR systems must have the following three characteristics identified by [17] and still relevant today:

- Combines real and virtual.
- Static virtual overlay on the real world.

2.2.3. Mixed Reality (MR)

MR is a hybrid kind of XR that combines augmented reality and virtuality. As a result of the merging of the physical and digital worlds, it utilizes an overlay of virtual material that can interact with the real environment, facilitating interaction across realms [13]. Therefore, virtual objects not only overlap with the actual environment with MR systems, but users may also interact with them as if they were real objects, taking them one step farther than AR. In this situation, the user stays in the real-world environment while digital material is added to it, and the user can interact with virtual objects.

A headset with an integrated computer, transparent glass, and sensors is required for an MR experience. Embedded sensors commonly map the real-world environment in real time so that virtual objects may interact with it and be changed by users. MR is, in some ways, a more immersive and interactive version of AR.

2.2.4. Augmented Virtuality (AV)

The distinction between MR and AV may be minor and hazy, but it is nevertheless significant. AV refers to computer-generated possible world situations enhanced with actual, virtual constructs (i.e., objects, people) [18]. With AV is, therefore, possible to create a fictional universe and populate it with real people and items.

2.2.5. Virtual Reality (VR)

VR is a computer-generated virtual world that allows users to interact with, move around, and be entirely immersed in it [13]. As a result, VR allows the user to enter a three-dimensional (3D) environment through a computer screen, where he or she may interact with these worlds as if they were real [19].

Immersion and interactivity are fundamental concepts. Immersion is blocking out all distractions and concentrating just on the content that the participant wishes to work with. The capacity for people to engage with events in the virtual world is referred to as interactivity [20].

There are three typical setups for VR systems [21]:

- The first setup belongs to the so-called *desktop virtual reality* since it uses conventional, computer input and output devices such as keyboard, mouse and monitor [20]. It is usually made up of a standalone headgear that gives a virtual reality experience using a smartphone and either cardboard or an integrated solution.
- The Cave Automatic Virtual Environment (CAVE) is the second setup, which involves multiple large projection screens to serve as the room's walls and floor, with viewers fully immersed.
- The third option is to use a standalone computer with a Head-Mounted Display (HMD). HMDs are virtual reality headsets that consist of two LCD panels placed in a glasses-like device and fixed relative to the wearer's eye location. They display the virtual environment by using a tracking system to retrieve the user's head orientation (and position in certain circumstances) [22]. The user is entirely immersed in a virtual environment with which he or she may engage in this manner. This configuration has risen to prominence in recent years since it has gotten more inexpensive and provides an excellent VR experience [21].

It is possible thus to identify four key elements of virtual reality [23]:

- Virtual world.
- Immersion.
- Sensory feedback.
- Interactivity.

2.2.6. XR hardware and software description

To get a better picture of the XR technologies described above, this section aims to give an overview of the most commonly used hardware and software. It is important to mention that the list of hardware and software is constantly changing. This is because XR is still an extremely young technology and therefore new, updated versions of the hardware and software come onto the market every few months.

2.2.6.1. Hardware

Several XR devices have been created over the years. These are growing increasingly powerful while also becoming smaller and easier to operate. The most widely used devices can be grouped according to the type of XR to which they belong concerning the reality-virtuality continuum [21].

The XR devices differ not just in look but also in terms of the technological features they offer. The key factors are:

- Weight: it is the major factor affecting the device's ergonomics. The battery's size, and thus their weight, and where they are placed are the crucial characteristic that influences the device's weight.
- Operating mode: it determines whether the device is a stand-alone system or requires external computer connectivity. The kind of connection to a computer is determined by whether it is wired or wireless. The applicability of an XR device for a specific manufacturing situation is determined by the possible combinations of these criteria.
- Field of vision (FOV): it defines the size of the viewable area. It has a direct impact on the quantity of virtual data that can be displayed. The binocular FOV of human eyes is approximately 114 degrees horizontally [24]. In an ideal world, all displays used in XR systems will have the same FOV, allowing users to enjoy a seamless experience with all necessary information presented correctly.
- Frames per second (FPS): it refers to the frequency at which consecutive frames of a moving image appear on a screen. A higher FPS means smoother motion for the content. On the contrary, lower FPS may produce motion jitter, resulting in motion sickness. It is important to note, however, that FPS is governed not just by the hardware but also by the software. As a result, it is critical to fine-tune virtual sceneries throughout development to reach the appropriate FPS.

These variables interact and have an impact on the entire user experience.

2.2.6.2. Software

In the manufacturing industry, XR systems may be built with a range of software options. The open development platform and the expansion of existing commercial software are the two key groupings. The distinction between the two is that the first provides full development control and hence a more personalized experience, whilst existing commercial software provides limited freedom because its features are dependent on software provider upgrades [21].

The most important open development platforms are:

- Unity3D.
- Unreal Engine.
- Steam.

The importance of open platforms has rapidly increased during the years since the big and active communities on these platforms have produced constantly expanding features that the industrial industry may easily include in its own unique XR development. In the development of XR, open platforms are becoming increasingly vital [21].

On the other side, the most important established commercial software are:

- Plant simulation (Siemens).
- VRED (Autodesk).
- Robot Studio (ABB).
- Vuforia Studio.

The benefits of using this software are many. It saves cost and development time and facilitates the integration of XR within the manufacturing industry. Moreover, using this software requires fewer capabilities and therefore a faster implementation is expected. Oppositely, the major drawback is the lack of freedom due to limitations caused by the developers [25].

3 Research methodology

This chapter presents the research objective and the followed methodology is presented.

3.1. Research objective

The growing demand for XR technologies is fuelled by the eagerness of companies to take advantage of the opportunities they offer. Until recently, AR, MR and VR were terms related only to the world of video games, cinema and entertainment in general. However, the possibility of merging the real and virtual worlds started also attracting the interest of the world of manufacturing.

Considering a particular focus on the automotive industry, the ongoing electrification, shortened car life cycles and increasing demands for car customization are adding to the complexity of manufacturing processes in this industry. Therefore, car manufacturers are looking to the development of extended reality (XR) technology to address the issues they are facing. Nevertheless, the hardware and software used, the exact field where they can be implemented and the benefits they can bring in the manufacturing areas are still far to be analysed and clearly stated [4]. Moreover, the development and release of new technologies in the field are posing several still unclear challenges to organisations, which are struggling to keep up and build a solid vision for their implementation and use. In particular, analysing the literature on these topics following a systematic literature review (SLR) approach as presented in the following Chapter 2.2.1., the research gaps (RGs) summarized in Table 3.1 below are identified.

Table 3.1. Research gaps.

RG Nr.	Research Gap
RG1	Lack of clarity concerning the actual state of the art of XR technologies in the automotive industry within manufacturing. Particularly, lack of clarity concerning: • The difference between the different XR technologies and their hardware and software. • The field where XR technologies can be applied in the automotive industry within manufacturing. • The maturity level of the different XR technologies within the identified fields of application.
RG2	Lack of clarity concerning the benefits XR technologies may bring and the challenges automotive companies are facing.

RG3	Lack of academic contributions regarding the implementation of XR technologies in the automotive industry within manufacturing.

Therefore, the research aims at addressing these gaps, first of all, by analysing the actual state of the art of XR technologies in the automotive industry within the manufacturing areas. The attention is focused on the main technologies that are under investigation or have already been applied, highlighting their main domains of application and their maturity level. To have a clearer image of the actual state of the art, also the benefits they may bring and the challenges that organizations are facing when dealing with these technologies are analysed. Based on these findings, the ultimate objective is to provide valuable guidelines for XR implementation, validating the proposed method by applying it to the VCC case. The research objective (RO) can then be defined as follows:

RO: Define the actual state of the art of XR technologies, together with their benefits and challenges, and provide guidelines for their implementation in the automotive industry within manufacturing.

3.1.1. Research questions

Based on the identified RGs and proposed RO, three research questions (RQs) have been identified.

The first one aims at addressing RG1. The attention is focused on which XR have been adopted or is being researched thus far, considering the technological aspects (i.e., hardware and software used), their field of application, the drivers that are leading to their introduction and whether these technologies are mature or not.

RQ1: What is the state of the art of XR technologies in the automotive industry within manufacturing?

To have a better understanding of the current state of the art of XR technologies, the second RQ aims at addressing RG2. The purpose is to clearly define the benefits XR may bring, and thus why these technologies should be considered within manufacturing in the automotive industry, are also of interest. Nevertheless, the introduction of new technology is not without its challenges and difficulties, especially in a complex industry such as the automotive one. Therefore, identifying the challenges of implementing XR technologies within the organisation is crucial to have a clearer picture of why these technologies are not being implemented and which are the factors that are preventing their full exploitation. Therefore, the second research question focuses on analysing the benefits and challenges that may arise in implementing these technologies within manufacturing.

RQ2: What benefits and challenges may arise in applying XR technologies within the organization?

Based on the previous answers, it is possible to evaluate the benefits and challenges a car manufacturer should consider while introducing a particular XR technology in one or more of the identified fields of application. Nevertheless, as of 2022, a model for XR implementation has not been defined yet. Therefore, it is of interest for the research team to address the RG3, developing a model to implement XR technologies. The model to be defined aims to act as a set of guidelines to support car manufacturers in implementing XR technologies within manufacturing areas, maximising their value and avoiding the challenges previously highlighted.

RQ3: How to implement XR technologies within manufacturing in the automotive industry?

3.2. Research design

Based on the presented aim, the research requires a robust methodology to allow the research team to answer the three RQs, and thus the formulation and validation of a valuable model, based on a deep understanding of the actual situation. Among all the possible methodologies available, the Design Research Methodology (DRM) proposed by [5] is followed and slightly adapted to this particular case.

The DRM follows four stages, as shown in Figure 3.1:

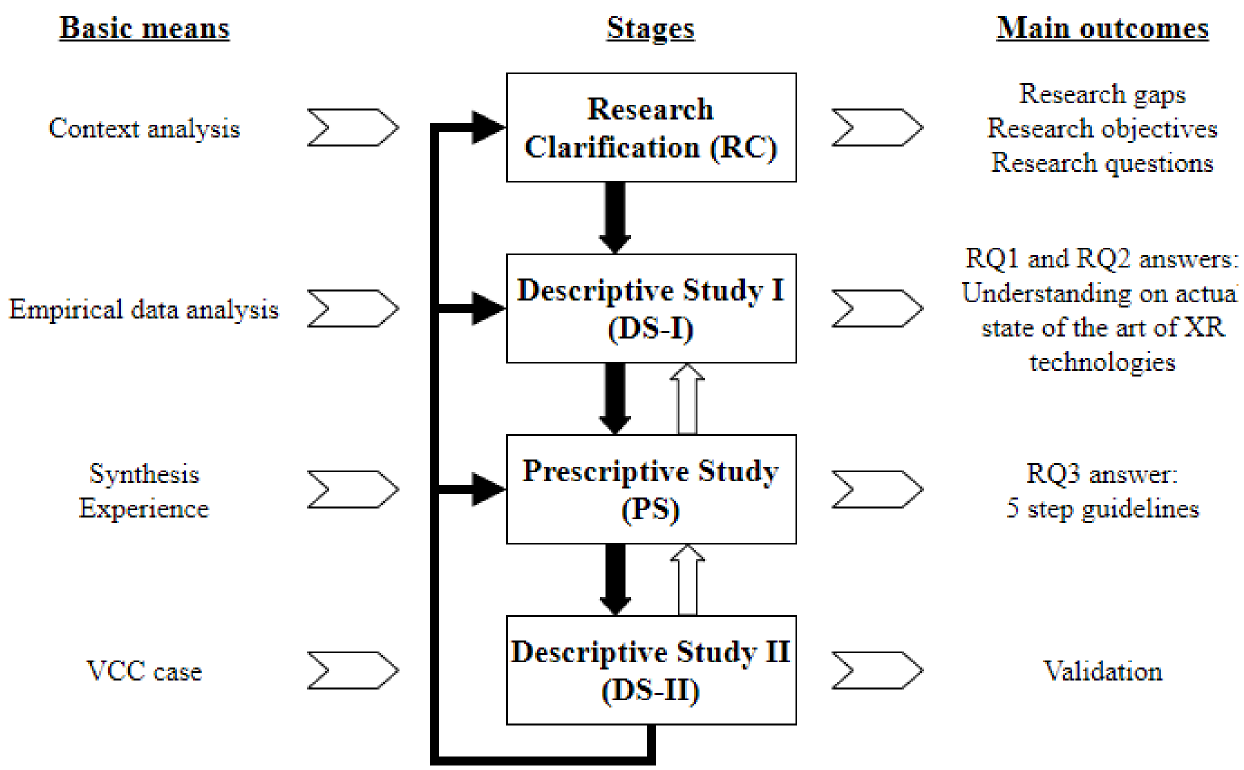
1. Research Clarification (RC). Based on context analysis, the research aim, and thus the research gaps, objectives and questions, are identified and addressed in Chapters 1 and 2.1.
2. Descriptive Study I (DS-I). Given the clear goal and focus of the research, three different sources of empirical data (i.e., a systematic literature review, a set of interviews with XR experts and three case studies attended within VCC) are considered to describe the initial situation. The aim is to give a clear understanding of the actual state of the art of XR technologies in the automotive industry, thus answering the first two RQs. The results are presented in Chapter 3.
3. Prescriptive Study (PS). The increased understanding of the existing situation, together with the theoretical and practical experience matured on the topic, can be exploited to develop a valuable method for XR implementation, providing guidelines to support car manufacturers in this process. Therefore, the aim is to address the third RQ, whose answer is provided in Chapter 4.
4. Descriptive Study II (DS-II). Finally, the proposed method is validated in Chapter 5, by applying it to the VCC case. The aim is to investigate, first of all, its applicability in a real-world case. Then, its ability in providing the firm with valuable support in the XR implementation process.

Nevertheless, the DRM should not be considered as a set of rigorously and sequentially executed steps and supporting methods. Iterations occur between phases. In particular, while building the set of guidelines, hence the PS stage, an extra DS-I is required to acquire further information on the three different perspectives included in the model: technology management, competencies, and the firm’s organisational structure.

Furthermore, the outcomes of the DS-II stage will necessitate in further studies a review of the previous stages in order to overcome the pointed out limits of the current model.

The linkages between these stages, the basic means utilised in each step, and the main outcomes are depicted in Figure 3.1 below. The bold arrows between the steps represent the core process flow, while the light arrows represent the various iterations.

Figure 3.1. DRM Methodology, inspired by [5].



To accomplish the identified DRM, as already mentioned three sources of empirical data are considered:

- Literature review.
- Interviews with XR experts.
- VCC case studies.

The literature represents a solid base to build an academic knowledge on the actual state of the art of XR technologies, thus on their fields of application, and the main benefits and challenges related to their implementation. Nevertheless, the goal is to reach a more comprehensive understanding of the actual situation, by enriching the academic findings with empirical evidence. Therefore, several interviews collecting insights about VCC, CEVT, Audi and Volkswagen are performed, together with case studies within VCC. According to the guidelines provided by [26], an exploratory descriptive interview through a questionnaire has been designed. The purpose is to answer the research questions focusing on a sample of XR technologies-related experts (i.e., Senior IT strategy manager and XR users and developers). In addition, three exploratory real-world case studies of XR implementation in the automotive industry have also been conducted.

In the following sections, each of the above-mentioned sources of empirical data is presented in detail.

3.2.1. Literature review

The literature review's goal is to examine, critique, and synthesize the literature on the research topic as a starting point. Among the different review methodologies available (i.e. systematic, semi-systematic or narrative, and integrative), a systematic literature review (SLR) approach is the one chosen for the study. [27]

The purpose of using this approach is "to provide a historical perspective of the respective research area" [28]. It summarizes the previous studies on a certain topic, identifies research lines and trends, and investigates associated conceptual ideas. Therefore, this kind of analysis is useful for detecting themes, theoretical perspectives, or common issues within the specified research discipline [29]. Although conducting a literature study is beneficial in any research study [30], it is extremely crucial in the case of XR technologies because it is a cutting-edge subject. Furthermore, as described by [31], the choice of the SLR approach avoids any bias that might affect the validity or relevance of the articles under consideration and ensures repeatability. Because of its framework, all of the reviewers' actions and decisions are meticulously described and published, allowing anybody who follows them to collect the same research and outcomes. As a result, the SLR technique provides constant robustness and reliability.

In this research case, the literature starts with the setting of the objectives and the focus of the review. The aim is to explain why the review is needed, stating its purposes. Then, the methodology followed is exhibited. This means providing the framework for how the iterative searching was done. This implies presenting details on all the sources accessed: the name of the database used for the research, the dates covered, and the keywords used. To assure the robustness of the methodology, the criteria used to include in or exclude from the review of the papers must be exhibited. Once the methodology is shared, the review's results can be presented. In this step, the details and characteristics of the documents are presented. Finally, the review's findings are summarized and exhibited, considering the initial research questions.

3.2.1.1. Review process

Following the formulation of the research questions that will be answered, it is essential to identify the papers that will be used to answer them. The following review methodology aims to guide a robust literature review, which can be replicated without the risk of incurring a research bias or a lack of accuracy. Therefore, the source of the research papers is stated, as well as the keywords used in the research and the criteria considered to select and evaluate them.

The main database is Scopus. The choice was dictated by the fact that Scopus is the world's biggest archive of peer-reviewed publications used in literature reviews [32].

Several search strings with particular keywords and search criteria have been developed and utilized in the search engine to focus the research on the issues of the study: the XR technologies adoption, their applications, the benefits brought and the challenges faced in the implementation process in the automotive industry. Furthermore, examples of successful implementation plans are also considered, embracing the different perspective the research team consider crucial (i.e., technology management, competencies and the company's organisational structure). Due to the different XR technologies and perspectives to be analysed, several different strings and keywords were selected. To make the analysis clearer, they were grouped into six different clusters, each one with a specific set of keywords. In this way, the research followed a logical structure that can be summarized with the following group of strings and the related keywords used to filter the research:

- Group 1 focuses on AR technology.

  Research string: TITLE-ABS-KEY ("augmented reality" AND ("automotive industry" OR "manufacturing")) AND (LIMIT-TO (EXACTKEYWORD , "Automotive Industry")) AND (LIMIT-TO (EXACTKEYWORD , "Augmented Reality")).

- Group 2 focuses on MR technology.

  Research string: TITLE-ABS-KEY ("mixed reality" AND ("automotive industry" OR "manufacturing")) AND (LIMIT-TO (EXACTKEYWORD , "Mixed Reality")) AND (LIMIT-TO (EXACTKEYWORD , "Automotive")).

- Group 3 focuses on VR technology.

  Research string: TITLE-ABS-KEY ("virtual reality" AND ("automotive industry" OR "manufacturing")) AND (LIMIT-TO (EXACTKEYWORD , "Automotive Industry")) AND (LIMIT-TO (EXACTKEYWORD , "Virtual Reality")).

- Group 4 on the challenges faced in the implementation of the above-mentioned technology in the automotive industry within the manufacturing area.

  Research string: TITLE-ABS-KEY ("augmented reality" OR "mixed reality" OR "virtual reality" AND ("automotive industry" OR "manufacturing") AND "challenges") AND (LIMIT-TO (EXACTKEYWORD , "Virtual Reality") OR LIMIT-TO (EXACTKEYWORD , "Augmented Reality") OR LIMIT-TO (EXACTKEYWORD , "Mixed Reality")) AND (LIMIT-TO (EXACTKEYWORD , "Automotive Industry") OR LIMIT-TO (EXACTKEYWORD , "Manufacturing")).

- Group 5 focuses on the technology management aspect, with a particular interest in examples related to XR technologies cases.

Research string: TITLE-ABS-KEY (technology AND (transformation OR transition OR management) AND manufacturing AND ("augmented reality" OR "mixed reality" OR "virtual reality")).

- Group 6 focuses on the competencies management aspect and the suggested organisational structures to deal with XR technologies.

  Research string: TITLE-ABS-KEY ((manufacturing OR automotive) AND ("augmented reality" OR "mixed reality" OR "virtual reality" OR "industry 4.0")) AND ((competenc* OR capabilit* OR skill*) AND (build* OR develop*)) AND ((organization* OR compan*) W/2 structur*)).

The different research string groups are built in such a way the resulting articles can answer the three different RQs. In particular, Groups 1-4 are assessing RQ1 and RQ2, while Groups 5-6 RQ3.

Browsing the database without a limited timeframe lead to a final number of 695 papers. Therefore, a robust methodology for the evaluation and selection of only valuable papers is necessary. The approach followed is documented in the form of a PRISMA flow diagram [33] as shown in Figure 3.2. It depicts the flow of information through the different phases of a systematic review. The researchers evaluate this approach, adapted to the case of a systematic review, as the most suitable to assure the transparency of the research.

According to the sequential flow, the previously mentioned identification phase is followed by a screening phase. This phase is crucial to extract only those papers that can provide valuable contributions to this research work. To assure the transparency of the process and the appropriateness of the selected papers Table 3.2 exhibits the set of criteria identified.

Table 3.2. Inclusion and exclusion criteria.

Nr.	Inclusion Criteria	Exclusion Criteria
1	Author's name is available.	Author's name is not available.
2	Published in English and available online.	Published in other languages or not available online.
3	Published in a scientific journal or conference paper.	Published in other document types.
4	Published in a scientific journal from 2015.	Published in a scientific journal before 2015 or dealing with obsolete technologies.
5	Published in a conference paper from 2017.	Published in a conference paper before 2017 or dealing with obsolete technologies.

6	XR technologies in the automotive industry and/or manufacturing.	XR technologies in other sectors (e.g., medicine and education).

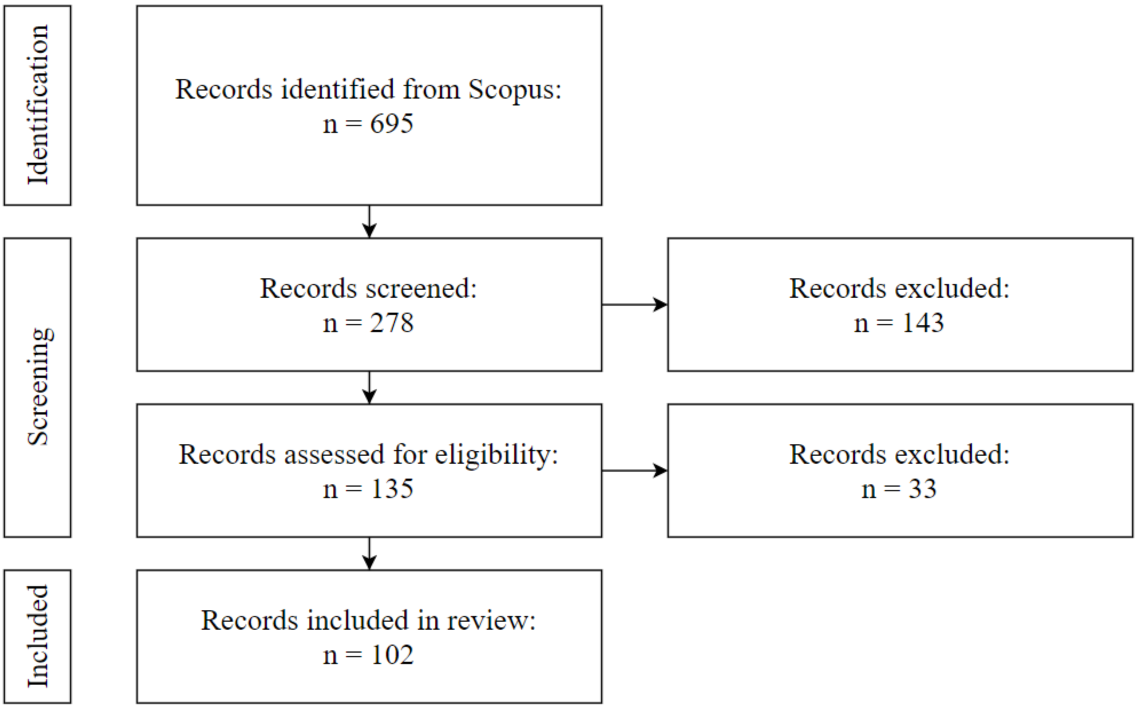
First, the author's name must be clearly stated to assure the first degree of reliability of the topic addressed. Secondly, the papers must be written in English and available online to make them accessible to a broader set of further readers. Then, they have to be published in a scientific journal or conference paper. The first document type is crucial since scientific journals have more rigorous reviewers [32]. The latter has been examined because they most likely include developing trends and issues. The screening phase aims at selecting only the papers that can contribute to the research. Therefore, considering the increased development and implementation pace of the XR technologies only in the latest years, the papers published in a scientific journal from 2015 were considered. Regarding the conference proceedings, the publications from 2017 were only deemed. This decision is based on the attitude of the conference papers to present the most actualized results. Limiting the time span of the research from 2015 onwards is something that has been done also by other researchers in the field of XR technologies, such as [21]. Furthermore, the first XR device, namely the AR headset HoloLens 1, was released by Microsoft only in 2016 [34].

At the end of this selection, 278 papers are screened. Then, the sixth criterion has been applied. The abstract of each paper has been carefully read to distinguish between relevant and irrelevant papers accordingly. In this phase, the snowballing approach proposed by [35] was also used to extend the research from the produced publications by analysing papers either cited in or that cited the screened ones. The aim is to identify additional relevant articles through the reference lists of the articles found using the search strings, also considering those out of the settled timeframe. In the end, this results in papers being eligible for review.

The relevant ones were then read entirely by the two researchers autonomously. Finally, as a consequence of the complete procedure, a database of 102 publications was included in the research as the baseline of the critical analysis, ensuring the high quality and thoroughness of the study.

Figure 3.2 exhibits the methodology followed and documented in the form of the PRISMA flow diagram.

Figure 3.2. PRISMA flow diagram.



3.2.1.2. Review analysis and statistics

To provide a comprehensive literature review analysis, the selection of publications was entered into a Microsoft Excel spreadsheet in order to do a thorough literature analysis. Papers have been classified and chronologically organised to demonstrate the advancements made by XR technologies-related topics throughout time. As a result, the contributions have been categorised according to the two criteria listed below:

a) Publication's main characteristics. The article's author(s), the first author(s)'s country affiliation, the article's title, its year of release and its source type and title are exhibited.
b) Research string group. The article is categorized according to the research string group it comes from, and thus the research question addressed.

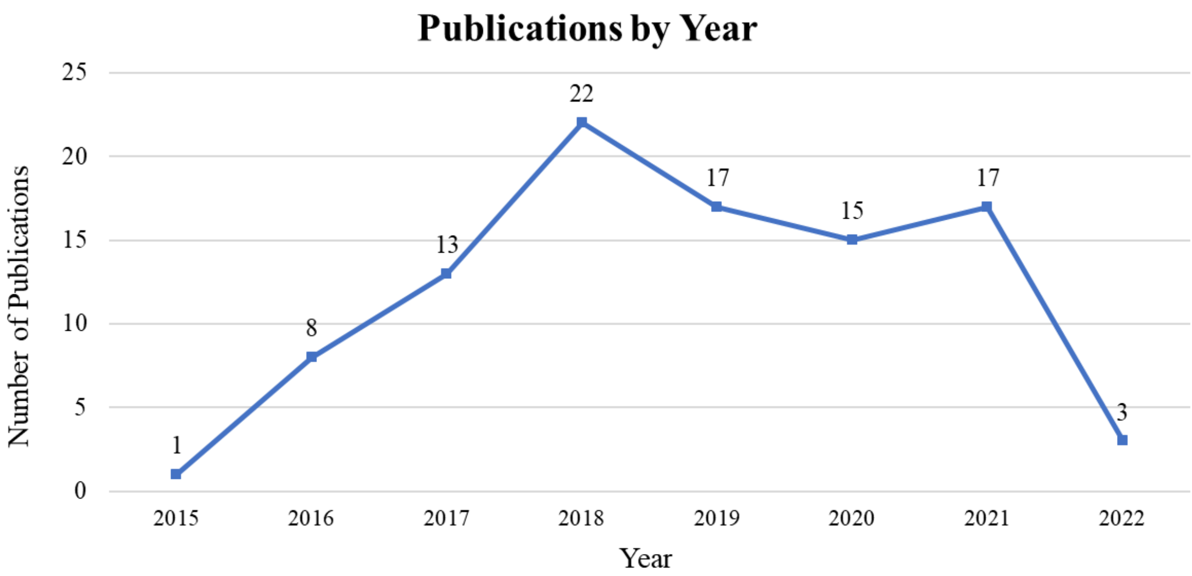
3.2.1.2.1. Publications by Year

Figure 3.3 below exhibits the publication trend of studies on XR technologies within manufacturing. The first publication of interest dates back to 2015. Onwards, the number of publications each year has progressively increased, hitting a peak in 2018 with 22 papers published and a 69% growth over the previous year. This demonstrates the quick academic's rising interest in XR technology applied to manufacturing.

Since 2017, the number of articles has stayed fairly steady, with a slight decline in 2020. Furthermore, although the first paper list was collected in February 2022, the number of papers published in the first month of the year is about half of those released in 2016. This, along with the fact that 72% of the shortlist is based on contributions published after

2018, leads the research team to believe that academic interest in XR technologies within manufacturing is a long way from being depleted. Moreover, this also states the robustness of relying only on the most recent publications, limiting the time span from 2015 onwards.

Figure 3.3. Publications by year.



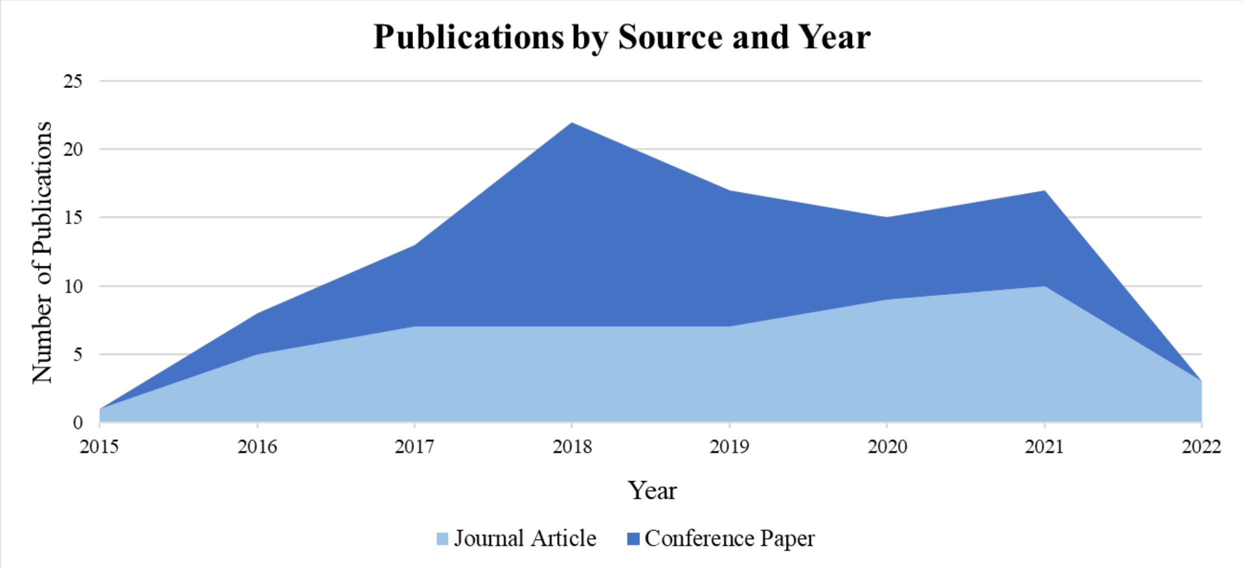
3.2.1.2.2. Publications by Source

The partition between journal articles and conference papers is almost balanced. 54% of the included papers were published in scientific journals, while the remaining 46% were in international conference proceedings. The three main subject areas are engineering (28%), computer science (25%) and business, management and accounting (13%).

The journals in which more than one article has been published are *Journal of Manufacturing Technology Management* (5), *Applied Sciences* (4) and *Virtual Reality*, *Robotics and Computer-Integrated Manufacturing*, *CIRP Annals* and *Technological Forecasting and Social Change* (2). Meanwhile, the most present conferences are *Procedia CIRP* (13), *Procedia Manufacturing* (4) and *Procedia Computer Science* (3).

It is worth noting that according to Figure 3.4 conference proceeding is the main contributor to the publications' peak shown in 2018, with double the proceedings of 2017. This confirms the attitude of the conference papers to focus on the most actualized topics.

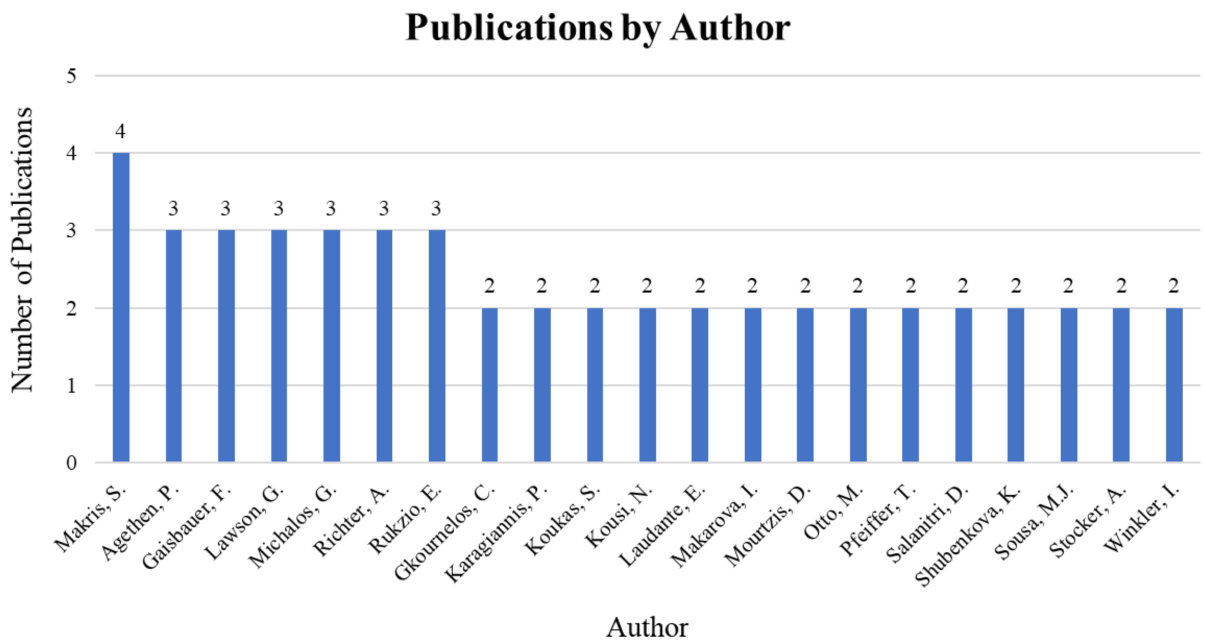
Figure 3.4. Publications by source and year.



3.2.1.2.3. Publications by Author and Country

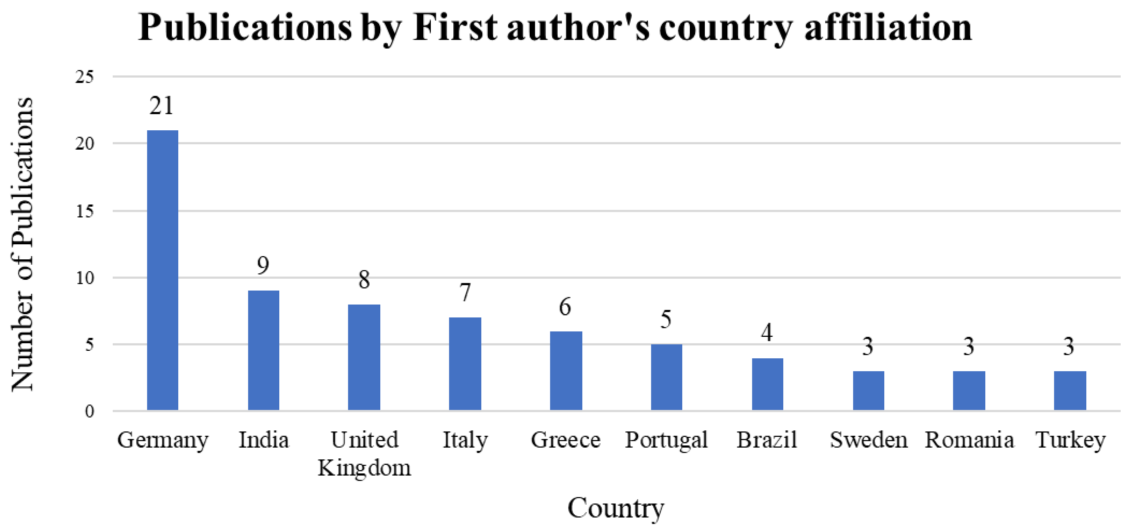
Figure 3.5 exhibits the authors with more than one publication. The 21 authors listed below contributed to 48% of the papers included in the research.

Figure 3.5. Publications by author and country.



Analysing more in detail the first author's country affiliation, Figure 3.6 shows that the highest contribution comes from Germany, with 20% of the whole publications. Furthermore, considering a macro-region perspective, it is worth noting that 73 contributions were published by European researchers, followed by Asian (19), North American (4), South American (4) and African (2). The conclusion can therefore be drawn that the topic of XR technologies within manufacturing is of more interest in Europe and Asia.

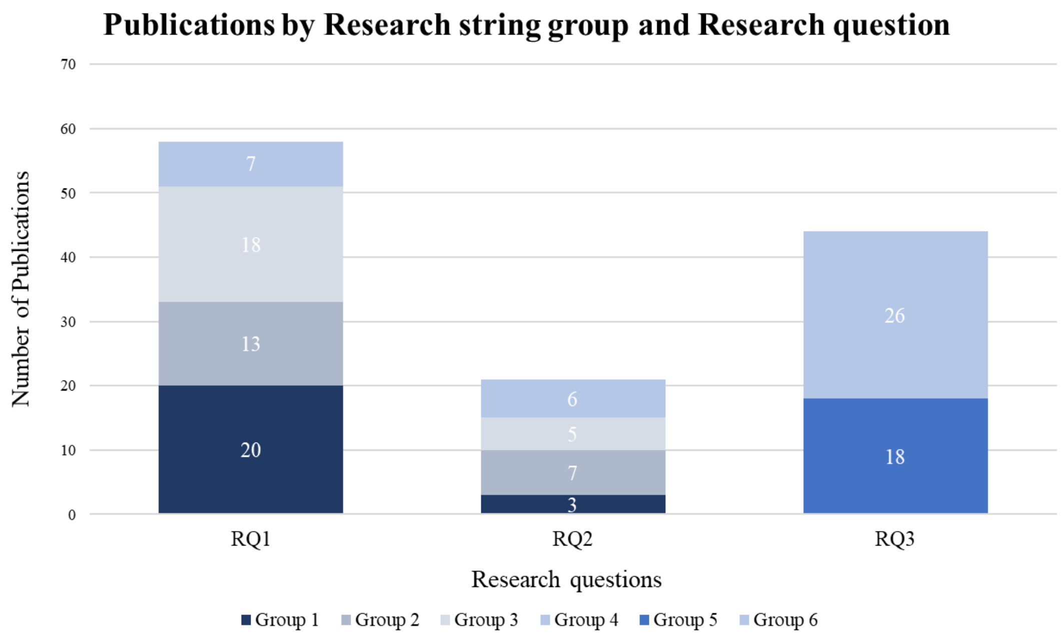
Figure 3.6. Publications by first author's country.



3.2.1.2.4. Publications by Research questions

Figure 3.7 shows how the documents were used to answer the three RQs, according to the group of research strings from which they were obtained. The total number of papers is greater than the number of papers included in the research since one article or conference proceeding can address one or more research questions at the same. As a result, RQ1 is the most addressed with 58 papers, followed by RQ3 (44) and RQ2 (21).

Figure 3.7. Publications by research string and question.



3.2.2. Interviews

The exploratory descriptive interview has been conducted to address three main targets:

- Collect data to answer RQ1. Specifically, portray the actual use of XR technologies in the automotive industry, highlighting application areas and the hardware and software used.
- Collect data to answer RQ2. The goal is to deeply understand the major XR-related benefits and the challenges organizations are facing with the implementation and use of these technologies.
- Collect data to answer RQ3. In this case, according to the interviewees, the analysis focuses on getting first insights into how the actual problems could be solved and what is missing to enable smooth XR execution.

The framework followed is that of a semi-structured interview. Therefore, a pool of questions is prepared. Nevertheless, according to how the interview is conducted, the structure can be adjusted to assure of extracting broader knowledge from the interviewees. In both cases, the questions will avoid any kind of inference, allowing the interviewees to answer frankly and without bias.

3.2.2.1. Interviewees

To avoid bias or lack of accuracy, the candidate pool is designed to gather XR experts with diverse backgrounds, and expertise, and from different organizations. The prerequisite for selecting interviewees is their knowledge of the subject of the research study.

One disadvantage of this methodology is that only workers who are current or future users of XR technologies are solicited to participate. Indeed, other engineers or disciplines may benefit from XR but are unaware of its possibilities. Nevertheless, the major goal of the interviews is to collect direct impressions from those who are using these technologies every day. Moreover, collecting a representative from each possible engineering field would be outside the scope of the research.

Therefore, the selected number of interviewees is five. Since the research is conducted within VCC, four candidates belong to the Swedish automotive organization. The remaining belongs to the Chinese automotive supplier CEVT. Nevertheless, to collect insights coming from more than the only Swedish car manufacturer, one interviewee with previous experience in Audi and Volkswagens has been interviewed.

The following Table 3.3 summarizes the selected group of respondents.

Table 3.3. Interviews list.

Interviewee Nr.	Company	Department	Role	Date	Duration
1	VCC	E	Metaverse and XR developer	22/02/2022	56 m
2	VCC	A	Method Developer OLP/Simulation	24/02/2022	42 m
3	VCC	C	Virtual Manufacturing Engineer	25/02/2022	1 h 06 m
4	VCC, previously Audi and VW	E	Senior XR Developer	25/02/2022	46 m
5	CEVT	Manufacturing Feasibility	Manufacturing Engineer	07/03/2022	50 m

3.2.2.2. Interview structure

The questions are structured according to different question levels [26]:

- Questions level 1 identify the specific [36] inquiries that are asked to the interviewees on the field. The questions are divided into two subcategories: standard questions and target questions. While standard ones are asked of all respondents, target ones may vary depending on the respondent's role and expertise in the different technology or its field of application.
- Questions level 2 identify the inquiry questions and are the research questions. Level 1 questions have been used to get information to answer level 2 questions.

The interviews are structured in the following three parts.

3.2.2.2.1. Part 1

The objective of this section is to set the interview in the best possible way. As a preliminary phase, the interview will start:

- Introducing daily work to create a pleasant atmosphere.
- Mentioning why the interview is important for the research.

- Requiring permission to record the interview.

3.2.2.2.2. Part 2

The goal of this section is to gather introductory information regarding the actual use of XR technologies. More in detail, the focus is on what XR technologies are being used and their scope. Particular attention is given to why these technologies are being implemented and how they can assist the processes of the organization. The second object is to uncover possible misalignment between the XR expectations and their actual results and highlight the main challenges that the organization is facing.

According to what was said above, the second part is structured following the first two research questions:

1. *RQ1: What is the state of the art of XR technologies in the automotive industry within manufacturing?*

   This section investigates the XR technologies used in different organizations and departments, focusing on the hardware and software used, the drivers that lead to their implementation, their selection process, and their maturity. Therefore, the specific questions are:

   a) Please describe the XR technologies you are using within your department or organization (e.g., which technologies, the hardware and software are used).

   b) Please define the introduction process of these technologies (e.g., the reasoning behind and the purpose of their introduction, the criteria chosen to select the technology and its hardware and software).

   c) Please describe the field of application of the XR technologies used (e.g., what they are used for and how).

2. *RQ2: What benefits and challenges may arise in applying XR technologies within the organization?*

   This section focuses on the benefits related to the introduction of XR technologies in the organizations' daily activities and the challenges the XR experts are facing while dealing daily with the selected XR technologies. The aim is to collect insights regarding the actual level of competencies and capabilities and any limitations of the XR. Therefore, the questions are:

   a) Please describe how XR technologies can support you in your daily activities.

   b) Please define how your department or organization is equipped to deal with XR technologies in terms of competencies and capabilities. Also, identify the capability that you and your department or organization would like to develop further and how you are supposed to build them.

c) Please describe the limitations of the XR technologies you are using and practical cases in which they cannot be applied or fail in delivering the expected outcome.

3.2.2.2.3. Part 3

This section has the purpose of gathering impressions and suggestions on how the issue pointed out in the previous section could be solved. The underneath objective is to state possible guidelines that should be followed to allow a smooth implementation of the XR technologies and uncover their potential.

3. *RQ3: How to implement XR technologies within manufacturing in the automotive industry?*

This last section includes more open questions and does not follow a specific and fixed structure, allowing the interviewees to answer spontaneously with possible suggestions to improve the usage of the technologies. Nevertheless, to foster the discussion the following questions can be asked:

a) According to the challenges you pointed out, please explain from your perspective how they could be solved.

b) Please provide an example of an ideal scenario in the implementation and usage of XR technologies within your department or organization.

3.2.3. Case Studies

The exploratory case study analysis is characterised by several distinctive features that make it suitable for this context [26], [37]:

- The phenomenon is investigated in its real surrounding.
- Multiple sources of data are used to acquire information related to the phenomenon of interest.
- The analysis relies almost exclusively on qualitative data.
- The objective of the research is to provide a detailed picture of the phenomenon, comprising its features, variants, how it operates, and the factors that shape the pattern observed.

Therefore, the case study analysis has been selected to evaluate first-hand the actual usage of XR technologies within an automotive company. Since the research is carried on within VCC, the three case studies analysed belong all to the Swedish car manufacturer. Table 3.4 summarizes the cases attended.

Table 3.4. Case studies list.

Case Nr.	Objective	XR Technology	Date	Duration
1	Ergonomics scenario analysis on a four-screws tightening operation.	AR & VR	01/03/2022	1 h 30 m
2	Solutions brainstorming and visualization for ergonomics issues related to under shield assembling operations.	AR	08/03/2022	30 m
3	Evaluation of a new painting line layout.	AR	10/03/2022	45 m

The aim is c. Moreover, particular attention is paid to evaluating the main challenges the organization is facing in terms of competencies and technologies.

To assure the robustness and transparency of the analysis, each case is evaluated in three sequential phases: preparation, running and analysis.

3.2.3.1. Preparation

In the beginning, the aim is to collect the main information needed to understand and fulfil the case study. Therefore, the topic of the case is analysed and the expected outcome is stated. The decision among which XR technology to be used is also explained.

3.2.3.2. Running

In this phase, the VCC case is performed. The XR team and the client department collaborate to visualize the topic under investigation and use the previously selected XR technology to discuss possible solutions. In this phase, two main variables are considered: time spent on the case and the model reliability, and thus its quality.

3.2.3.3. Analysis

Finally, the outcome is analysed. The aim is to understand how the XR technology has been used to provide the selected solution. Then, the outcome is evaluated based on its alignment with the expectation of the client department and its implementation feasibility.

4 Results

In this chapter, the main findings coming from the three sources of empirical data are presented separately. Then, the results are compared and summarised to answer the first two research questions and provide valuable insights that will lay the basis for the last one.

4.1. Literature review

The analysis of the selected scientific publications enabled the identification of key trends in the application of XR technologies in the automotive industry, particularly in the manufacturing area. In the following paragraphs, the technologies used will be described according to their field of application and together with the main benefits they may bring and the challenges that are preventing their full exploitation.

4.1.1. XR technologies and their state of the art

The literature results provided the research team with the academic background regarding the state of the art of XR technologies implementation in the automotive industry. According to the results, the technologies identified are AR, MR and VR. The following results summarise the major findings in terms of the technologies under investigation or already adopted, together with the hardware and software used, their fields of application and the drivers that are leading to their implementation. Finally, it is possible to assess whether or not these technologies are mature to be applied in the identified domains.

4.1.1.1. Hardware and software

According to the papers analysed, the hardware used in the automotive industry may differ depending mainly on the XR technology adopted. Starting from AR, Microsoft HoloLens 1 is the device used in all the exploratory studies or practical usage of this technology, and in particular in those of [38], [39]. When it comes to MR, HoloLens 1 is still one the most common devices, together with Google's Oculus Rift and the most recent HoloLens 2 [40]–[42]. Furthermore, HTC is the main provider of VR headsets, with its HTC Vive and Vive Pro mentioned by [43], [44] in their publications. Finally, regarding the software, all the above-cited papers refer to the usage of 3D Unity.

4.1.1.2. Field of application

Five main application fields in which XR technologies are now being studied or already applied have been identified: assembly, ergonomics, layout, maintenance, and training. For each of these fields, the main drivers that are leading to the implementation of these technologies are analysed, together with the ongoing studies or practical applications of XR technologies in the identified domains.

Assembly

Manual assembly lines, where workers conduct operations with the assistance of tools and equipment along with a series of workstations, are among the most common production processes in the automotive industry [36]. This sector is now dealing with an increase in the variety of its products. Furthermore, the upcoming electrification and the mixed model production on a single line added to the complexity of manual assembly tasks [39]. Moreover, the possibility of offering more variants per model and introducing new models more quickly is limited by present mass production technology and equipment, which are incapable of enabling product variety [45].

Production and research engineers have resorted to the notion of Human-Robot Collaboration (HRC) to meet the need for more personalised goods and smaller lot sizes [46]. The advantages of deploying such production cells are found in the creation of flexible and highly reconfigurable production systems that can readily adjust their operation to suit diverse product families, much like a human operator would. By allocating tasks based on their skills, it is feasible to combine the benefits of high payload industrial robots with human capabilities in a fenceless environment [47]. Therefore, these hybrid production systems enable HRC to seek to fully use the strengths of human operators, such as intellect and cognitive competencies, while using robot repeatability, dexterity, and strength [45]. To enable the HRC to be exploited to its full potential in terms of operational efficiency, and to ensure operator safety, it is of paramount importance to find new ways to convey information to the engaged staff while ensuring that each member receives the necessary information in a timely and understandable manner [48].

AR is beneficial for these purposes since it can deliver real-time interactive instructions superimposed on the workers' sight while immersed in the assembling environment, guiding them through the operations [49]. More specifically, AR provides operators with the necessary documentation and information at the right time, reducing the mental effort they must make: 2D or 3D information, animated or not, related to the execution procedure, steps to be taken, the tool used, or the task to be performed can be provided [50]. Furthermore, the operator can use the hands-free interface to submit his inputs, such as photographs or text, to a remote server for archiving [51]. As a result, AR assembly instructions prove to be very useful in assisting production line operators in managing the continually changing configurations of products in a mass-customized environment such as the automotive industry [48]. In addition, by visualizing data from a robot's controller and presenting visual alerts to raise their awareness of a potentially dangerous scenario, the AR technique intends to increase operators' safety feeling and acceptability when working close to huge industrial robots [52], [53]. Indeed, the AR system can include functionality such as robot workspace and trajectory visualization, audio/visual alarms, and production statistics (Makris et al., 2016).

Exploratory studies on the implementation of AR technologies in the assembly tasks to enhance the HRC and support the workers have been conducted by [39], [48].

The first proposed combining HoloLens with Unity 3D to reduce cognitive load during manual assembly activities at Daimler AG. In terms of the various evaluating criteria (i.e. perceived cognitive load, usability, and performance), the results indicate that AR-based instruction methods are more appropriate for the investigated environment (using 3D CAD simulation data as a method for providing instructions and proposing the investigation of the effectiveness of using simulation data for instruction) than baseline textual paper-based instructions [39].

In the second study, AR was employed to present assembly instructions to operators, obtaining them automatically from CAD files and leveraging existing knowledge saved in digital form. The suggested method proposed an algorithm for automated assembly instruction production and storage of the files required for the application that the operator utilizes to produce the AR assembly instructions on demand. As a result, the program is adaptable to production re-scheduling since the operator is provided assembly instructions based on the job currently allocated to the production schedule, with no prior preparation (Mourtzis et al., 2019).

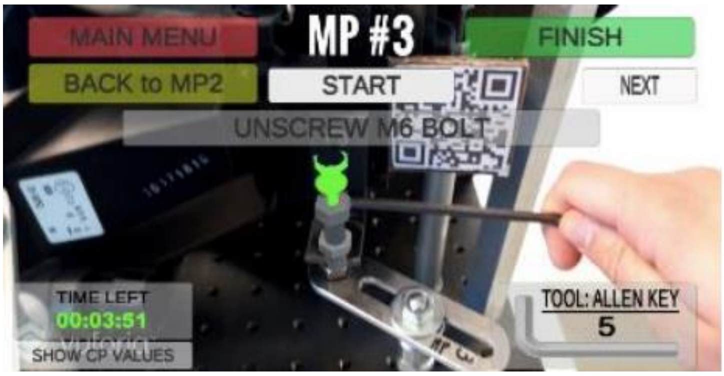
Nevertheless, AR is not the only XR technology under investigation to support manual assembly tasks and enhance the HRC. MR represents the step further allowing a stronger interaction and communication between the real and the virtual world. Besides the creation and visualization of virtual items in the real environment as an AR application, MR also allows for the manipulation of those same objects, allowing for a unique interaction between the user, the virtual, and the real world [36], [41]. Therefore, MR can generate digital paths between the assembly spot and the next component to be assembled or present a 3D representation of the component at the assembly location, in the proper position, providing an animation that depicts the assembly process's direction [54]. Moreover, MR can enhance the HRC by supporting the operator by providing various information about the current robot task and allowing the worker to connect directly with the robot to adjust the intended task throughout the cooperation [40].

Exploratory studies in the field of MR have been conducted by [36], [40], [41].

The first paper investigates the integration of direct human-robot communication in an MR interface that allows the operator to change the collaboration mode online while giving the collaborative task's current state. To do so, the Oculus Rift device together with its tracking sensor for human pose localization is used. The MR interface is intended to inform the human about what the robot is currently doing. The user will be able to communicate directly with the robot by toggling between cooperation modes using the Oculus provided controller. The combination of the Oculus Rift device with the Unity platform lets the operator be aware of the active robot task and gives him/her the possibility to command the robot directly and efficiently. [40]

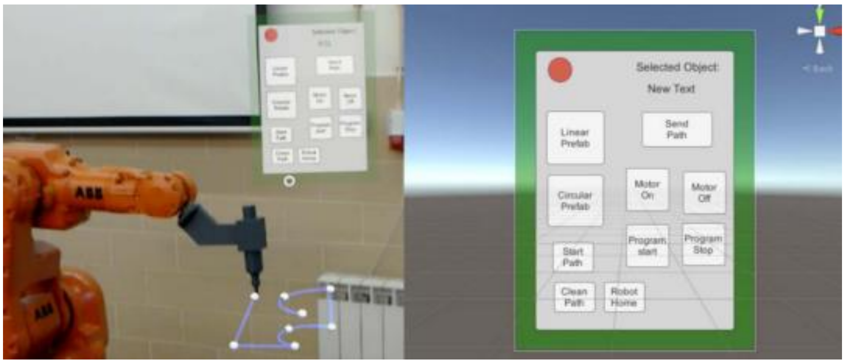
The second study focuses on the creation of a revolutionary assembly workstation with HRC and MR to assist employees during automobile panel fitting procedures. The system is based on the creation of an algorithm capable of converting panel spacing values measured by a laser gauge mounted on the collaborative robot into instructions for the worker to perform the panel fitting operation appropriately as shown in Figure 4.1 below. (Mura & Dini, 2021)

Figure 4.1. MR assembly application.



Finally, the last paper presents a possible implementation of MR on a robotic setup. The aim is to provide information closely connected to the activity being performed, as well as by placing virtual objects in the actual environment and allowing users to interact with them as if they were real objects. Through the use of the Microsoft HoloLens device, the operators can look at the superimposed planned pathways on the real workpiece and manipulate them, correcting or fine-tuning the planned ones or adding new paths on the fly, as exhibited in Figure 4.2. [41]

Figure 4.2. MR assembly robot application.



The suggested approaches increase the flexibility of the production line by connecting the operators to the digital systems and assembly robots in the production, augmenting the visualized content with crucial information about the production status and client order management. Moreover, the system can significantly boost the overall inspection process accuracy and time consumption [51].

Therefore, it can be said the experiments on the usage of AR and MR demonstrated minimizing human mistakes, execution times, and employees' mental stress while increasing their awareness and safety [47]. Indeed, their applications reduce the time required for the operators to acquire the essential information and deliver input to the system from their workstations to milliseconds. Moreover, the AR and MR support in performing the assembling tasks can have a direct impact on the overall quality of the process, minimizing the risk of human-related error [55]–[57]. It also boosts the operator's willingness to operate alongside large industrial robots without safety fences. Furthermore, it reduces stoppages and improves the training process by providing better and more understandable information straight to the production lines without the use of paper signs. Finally, tracking the task messages sent from the system to the operators and the robots improves production supervision [58].

Ergonomics

When it comes to manufacturing, ergonomics is critical since it examines the relationship between humans and workspaces, including human anthropometry, physiology, anatomy, and biomechanics, among other things. This domain includes things like posture analysis, weightlifting, repetitive activities, and work design. As a result, everything in the workplace (tools, gadgets, handling items, etc.) must be built so that a worker can do activities with efficient motions, using little energy, and with a low and minimized risk of damage. As with the other sections described above, the automotive industry has begun to implement cutting-edge technologies such as the XR when it comes to ergonomics [59].

In particular, this area is of critical importance since late detection of ergonomic problems during, for example, assembly operations can result in a lack of productivity, high correction costs, and a major impact on operator well-being. This is because altering traditional manufacturing tools when they are nearly complete is difficult and costly. Everything in the early phases of development, on the other hand, is frequently done in a virtual model. Therefore, it is very valuable to be able to realize problems as early as possible to save time, and money and protect workers from being exposed to undue risk of harm [59]–[61].

In addition, the automotive industry is increasingly following the market that demands more customized products. Therefore, production and research engineers have implemented a new concept of HRC to have a more flexible and reconfigurable production system that can adapt to the continuous change of product versions. New ways of interaction between humans and robots have been investigated through the HRC concept to obtain the most out of this synergy effect. [47]

This can result in a problematic scenario since robots are machines that operate in a rather big workspace, and hazardous situations might emerge depending on their setup and tooling. Even if robotic arms work in a pre-defined manner, human behaviour is unpredictable, which might lead to disastrous interactions. As a result, there is a critical requirement for cooperation systems that coordinate the operations of these two entities. Standards that attempt to control the interaction between people and automation have caught a first step to establishing cooperation schemes that can ensure the safety of human operators. [47]

In the context described above, XR technologies have been implemented. In particular, VR technology, together with Digital Human Modelling is specifically being utilised to analyse ergonomic hazards during the design phase, which enables the early diagnosis of key concerns and the application of corrective actions, which is more effective and less expensive than a later assessment of these risks. VR may also enhance the realism and efficiency of virtual manufacturing. In addition to the design phase, VR is used to assess the ergonomics of the manufacturing process, to support decision-making on workplace architecture, aided assembly devices, tool replacement, customised operator training, and changes to assembly routines and procedures [59].

Therefore, VR technology within ergonomics brings several benefits. It allows for faster, more accurate, and cost-effective product development processes, as well as acts as a helpful tool for evaluating work assignments and design options without the need for physical mock-ups or production trials. It can also improve human-machine interactions, the overall performance and well-being of the user, and mitigate hidden dangers, among many others [59], [62], [63]. This has been proven by Ford which has achieved the performance of minimizing risk situations up to 70%, based on operator VR learning results [43].

In addition to VR, AR is largely utilised in HRC to reduce the ergonomic burden of assembly procedures that are now conducted entirely by operators, both physically and cognitively. For this purpose, wearable gadgets, such as augmented reality glasses and smartwatches, are employed to decrease the communication gap between operators and robots [47]. Furthermore, AR glasses are also used for the car and production line's ergonomic assessments, with the main benefit of reducing the costs of expensive mock-ups [64]

Layout

Production layout planning (PLP) is the process of determining the optimal physical arrangement of all resources that occupy space within a building. Decisions concerning the arrangement of resources in a factory are made not just when a new facility is being planned. They are made whenever there is a change in the arrangement of resources, such as the addition of a new worker, the relocation of a machine, or the implementation of a new process. Moreover, PLP is an initial task that must be performed by every planning team on a building project, and it entails processing and visualizing complicated information held by many team members. An ideal layout provides safe working conditions for workers, makes the most use of available space, minimizes activity disturbance, and reduces on-site transit time [44].

As previously said, the automotive industry is experiencing several issues as a result of the upcoming electrification. The predicted number of electric vehicles in the future varies greatly between studies. As a result, transformable production systems with an emphasis on scalability should be favoured to limit the danger of hyperproduction [65]. Unfortunately, it is not always feasible to anticipate every future need, particularly during expansion stages, which increases the danger of production losses. As a result, planners typically rely on heuristics and intuitions obtained from experience on comparable projects to create the best feasible site layout [44]. Furthermore, an increasing number of simulation tools might be used to define the layout and investigate the process's production flow as they enable the computation of key performance indicators (KPI) as input to the decision-making process. However, despite the estimated indicators, stakeholders have difficulties visualizing themselves in the proposed layout when just 2D or 3D CAD visualization on a screen is available. Furthermore, it is difficult to consider ergonomics and safety issues without allowing stakeholders to experiment at the scale one the planned layout [66].

Therefore, AR and VR turn crucial in assisting planners in facing the issues that car manufacturers have when dealing with the layout of a production system. The usage of these XR technologies in the planning phases is already well established and it leads to several advantages.

Starting with AR, the use of HoloLens with 3D Unity software reduces the cognitive gap between a virtual scene and its mapping to the actual surroundings [38]. Planning virtual production layouts before setting them up, in reality, saves money, and collaborative situations enable factory layouts to be planned with other planners regardless of their real-world location. AR techniques enable the establishment of an immersive layout design and analysis process by combining digital data into the actual environment. Indeed, the approach used by [38] implies that one or more layouts have previously been built in a desktop application and may be transferred to an AR one. Following the creation of the layouts, the users begin the first setup phase, in which they specify the global coordinate system and load a basic layout. As a result, a wide range of information may be provided to the user. This can include machine data that is already accessible, as well as insights and practicability analyses of assembly procedures. Furthermore, the consequences of changing production layouts or processes may be seen in real-time.

Moving to VR, all of the stakeholders polled by [44] agreed that implementing VR solutions, such as HTC Vive Pro, will improve the overall quality of the planning process. Furthermore, assembly planning specialists observe early shielding of workstations and quicker feedback documentation when integrating ergonomics evaluation and walking path analysis in VR. When analysing maintenance options, material supply, accessibility, and journey pathways in VR, maintenance and logistics planning predict early quality assurance. The deployment of VR training for workers is seen as having the most promise by production line operators. These will lead to risk-free training sooner in the planning phase. Finally, the management anticipates increased employee satisfaction when using

VR as a planning tool owing to the gamification of the planning process [44]. These are direct outcomes of the production system's virtualization, which strives to make faster and more robust decisions in the early phases of development [67]. As a result, the key advantage of using VR solutions in the early stages of PLP is the ability to improve layout quality while reducing cost and innovation time owing to shorter development time and effort. Virtual models may be produced and developed before the production system is implemented. As a result, layout decisions based on VR may be made in the early phases of development in terms of geometrical and functional factors [67].

In terms of the possibilities provided by AR and VR, unlike completely automated simulation systems, XR technologies enable the creation of interactive virtual worlds based on user input to evaluate human labour. Humans are involved in the motions and walk pathways, which are not generated synthetically. As a result, because the findings are generated from captured motions, these interactive systems provide the ability to accurately plan, optimize, and analyse assembly operations in virtual settings. This implies that production planners may conduct a virtual examination of the production at scale one, including visualizing also the material flow. Therefore, with more technical information at the beginning of a project, early project planning can better explore cost-cutting alternatives and prevent the higher cost of adjustments made later in the lifecycle of the project [68].

Moreover, both the AR and VR environments assist layout planners in evaluating several alternatives in a short period of time. The XR platforms also boost the effectiveness of inexperienced planners while also making greater use of the expertise and intuition of experienced team members [69]. Therefore, considering also the introduction of commercial motion capture systems (e.g., Microsoft Kinect), head-mounted displays (e.g., HTC Vive), precise tracking devices (e.g., Optitrack or Vive Lighthouse), and falling costs for large-scale visualization devices, interactive virtual systems are increasingly being used in manufacturing [70].

Maintenance

Industry 4.0 is the fourth industrial revolution in manufacturing, focusing on the development of intelligent products and manufacturing processes. Increased efficiency and flexibility are now driving forces at the heart of industry development, indicating the achievement of large-scale changes in current industrial manufacturing. Automation, digitalization, intelligent control techniques, and information and communication technologies (ICT) integration at all levels of prototyping, process control, maintenance, and services are among the developments [71]. Without the introduction of technologies and processes based on smart manufacturing and smart maintenance, these difficulties would remain unsolvable. When it comes to creating and manufacturing a product, maintenance is a strategic consideration because of the financial and operating time losses, breakdowns and unplanned production stoppages. [72]

Preventive maintenance, which includes periodic inspections and spare component exchange, wastes resources, increases operating and service costs, and it is a major hindrance to effective operations for product manufacturers. Smart maintenance entails incorporating new technologies into maintenance procedures, such as mobile solutions, big data applications, and IoT, to improve production efficiency [73]. The use of smart manufacturing and maintenance techniques and systems based on interoperability, virtualization, decentralization, modularity, and real-time data collecting and analysis to enhance performance, intelligence, cyber security, and compatibility has expanded rapidly in recent years. The industry 4.0 concept of smart production and maintenance is defined by and based on the following technologies: autonomous robots, big data, cloud computing, the internet of things, cyber security, AR and VR. [72]

Because of its potential as an interactive and intuitive interface, AR offers exciting new opportunities in almost all aspects of the automobile industry. This human-centred technology has shown to be beneficial for operators and employees in automobile manufacturing, and AR can help operators with various forms of information superimposed in the work environment [50]. Intelligent predictive maintenance may be enhanced by showing multiple sorts of information in various ways and across numerous platforms, such as augmented reality head-mounted displays (HMDs) [72].

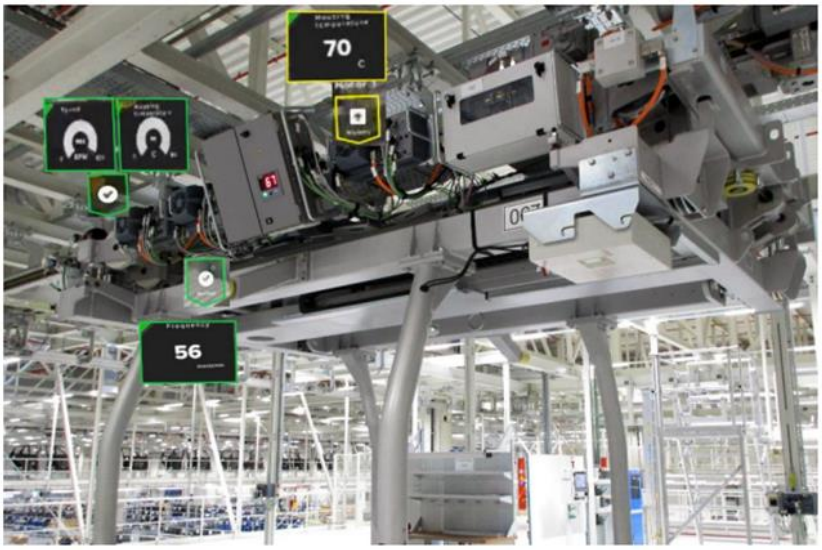
Efficient industrial AR applications must display accurate data in the correct location. The following fundamental components are required in this context [50]:

1. Application that includes application logic and regulates database access.
2. The position and orientation of the user and objects are determined using tracking.
3. Interaction is responsible for registering and processing user input.
4. The presentation builds and displays the AR scene using 3D visualization.
5. Context makes contextual information available to other subsystems.
6. The world model contains data on both actual and virtual things in the user's environment.

In the predictive maintenance context, the AR application implements three main features [72]:

- Support through the visualisation of different types of information, such as assembly sequence, spare parts and data from the condition monitoring system as shown in Figure 4.3. [72].

Figure 4.3. AR maintenance application.



- Maintenance process information provision in real-time through instruction list.
- One point maintenance lessons to support maintenance workers through virtual demonstration.

Based on the experimental findings acquired thus far regarding the preventative maintenance strategy, improvements in the following areas can be expected [72]:

- Increased quality of maintenance processes.
- Increased failure prediction.
- Reduction of unexpected production stops.
- Elimination of human factors.

Besides AR, also MR has been investigated by [42], [73] in the field of remote maintenance. According to the studies, remote help gives an important way for workers to aid workers in their daily work routine when unexpected challenges occur. Currently, the most usual option is to contact a professional technician. Although video calls make the procedure easier, issues occur when an expert has to pinpoint a specific aspect of a machine or equipment part. MR allows for the anchoring of comments and the provision of support assistance on what the technician sees through the HoloLens in the real world, which is presented on the worker's screen in her field of view [42]. This has a direct impact on the time needed for maintenance interventions, drastically reducing the inspection time [73]. Therefore, other than real-time data display, users may interact with and manipulate projected elements and have their surroundings augmented with 3D capabilities provided by MR headsets [74], [75].

Training

Training operators for activities carried out on automobile production lines has traditionally been a lengthy, detailed, and difficult procedure aimed at producing a correct collection of information and actions, as well as sufficient employee training [43]. Customer-oriented manufacturing in the automotive industry has resulted in the development of various distinct models and model variants, as well as a customization process that allows for the inclusion of several optional components. To achieve this product variation, the assembly worker must either identify and remember numerous parts and operations for each product variation (which are frequently changed throughout the day) or spend time consulting instructions or seeking advice from supervisors or managers, regarding the quality of the final product relying on the worker's ability to properly perform the various assembly tasks [76].

Traditional training techniques often include a combination of paper-based and DVD or video-based education, as well as a task demonstration by an experienced worker [76]. However, due to several market trends such as more customer-centric assets, investment in new technologies, the constant pressure to remain competitive in terms of cost reduction, the importance of excelling in quality, and the constant goal of reducing time-to-market, the challenge of providing excellent engineering education has increased [77], [78]. There is a critical need to increase the skills of workers, particularly engineers, in high-tech sectors. As a result, instructional technology development is required, particularly in the fields of virtual and augmented reality. Engineering and technological advancements generate the circumstances for rapid economic growth, but to take advantage of these opportunities, highly skilled professionals are necessary, who must meet higher standards in terms of professional skills and competencies, as well as personal traits [79]. Therefore, technological advancements have prompted several studies exploring the potential of virtual training to improve and speed learning in a realistic and safe environment. In this sense, virtual training refers to training that takes place in a VE, utilizing VR or AR technology [76], [80].

As already mentioned, VR technology is one of how operator training can be executed in such a way that market requirements can be more easily achieved [65]. Virtual training in this context is defined as training that is undertaken within a VE using VR technology which immerses the trainee in a three-dimensional space, simulating a real working environment [79]. It is designed to provide a more intuitive learning environment than traditional classroom-based training, allowing participants to engage with the training system and experience success or failure as a result of their efforts [76].

Several benefits have been proven and identified when performing VR training rather than traditional training:

- Operators' calmness throughout trials has improved. Making a mistake in VR is more than acceptable since the operator can see the dangerous situations it is in. In this scenario, sensory acuity is true interaction, but it is done in a safe environment where the operator may be confident in any situation. [43]

- The trainee can start practising skills in a safe environment from the very beginning of the training. In the VR environment, mistakes have no consequences, so the learner is at ease. The student can repeat tasks as many times as necessary in the virtual reality software to become proficient. [43]
- Decreasing dangerous situations. VR programs educate assembly line employees on how to move ergonomically and safely. As a result, virtual reality training aids in the reduction of workplace injuries. For example, by assessing VR training data and implementing relevant modifications in the assembly process, Ford was able to minimize accidents by 70%. [43]
- Increased flexibility in training and circumstances. When a production line is modified due to the launch of a new product line or the introduction of new machinery, using VR simulations to teach staff is a viable option. Since there is no pilot series to gradually approach the required productivity, workers need to be as productive as possible as soon as the idle time on the production line ends. As a result, VR training proves to be very useful before the production line reopens. [65].
- Better information retention. It has been shown that individuals educated with VR retain more information after two and four weeks than those trained with traditional systems for assembly and disassembly activities. [81]
- Improved performance. Simulated training has been demonstrated to enhance task completion from the 50th percentile to the 66th percentile when compared to real-world training [81]. Moreover, immersive experiences are expected to boost task efficiency and especially the quality of training [77].
- Decreasing education costs. VR tech eliminates the need to purchase expensive experimental training equipment and its damage. Problems such as the consumption of materials, thus effectively saving education costs [82]. Moreover, the VE gives the benefits o training staff who are going to work in designed lines before the end of their building [83].
- Increased involvement. VR training increases the involvement of operators by its similarity with a video game, thus making it more pleasant and conducting to an increased employee loyalty to the company; reducing the migration rate of employees to other companies or turning down their jobs. [43]
- No location constraints. VR training can be adapted to the company´s needs in other departments or locations. [43]

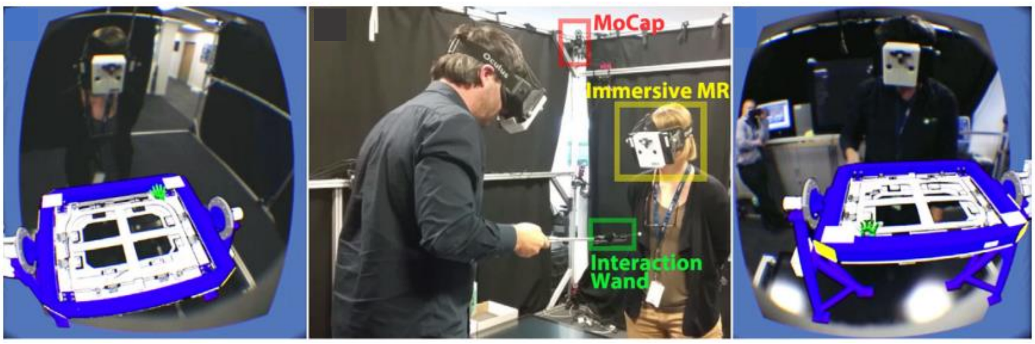
In this context, many different car manufacturer players are integrating VR technology into their training programmes. [43]

Volkswagen trained 10,000 employees in 2018. To this end, the company has developed 30 simulation programs for employees in different fields by building their VR portal, a so-called Digital Reality Hub (virtual meeting rooms, training programs, and knowledge bases) where the employees can interact with the Hub using HTC Vive VR headset and two controllers. Therefore, Volkswagen uses the Digital Reality Hub for interactions among employees located remotely. Digital Reality Hub brings together Volkswagen employees from around the world to work on a shared project without the need to travel. This is extremely useful since Volkswagen headquarters are located in Germany, while the logistics department is in the Czech Republic and its factories are located all over the world. [43]

In addition, also Audi is largely using VR training for its employees as the company believes that the virtual training program's key benefit is that it may be used in any plant, regardless of its location. In particular, Audi does have a complex logistical system that necessitates extreme precision from its staff. As a result, Audi developed virtual reality training to teach logistics workers about ergonomic actions and how to avoid mistakes. [43]

In addition to VR technology, also MR can represent a feasible tool when training operators. Even if much less popular than VR and still in the exploratory stage, MR technology can give workers interactive guides to help them through the procedure. MR-based tools, for example, have been used to instruct inexperienced employees by replicating assembly activities or to provide help during complicated phases of specific assembly scenarios [36]. The use of MR is particularly beneficial when dealing with multi-user collaborative situations in which both the teacher and the learner are present in the same area and are not remotely located. As shown in Figure 4.4, participants may view the teacher leading them through the process using this technology, but without the potential physical danger of the actual operation. Furthermore, a high level of presence and a hands-free experience is ensured [84].

Figure 4.4. MR training application.



Therefore, compared with VR, MR supports better collaboration over a rendered digital representation of the assembly jig and allows for virtual interactions when needed for training [74], [84], [85].

4.1.1.3. Maturity level

The literature provided the research team with a broader understanding of the actual state of the art of XR technologies in the manufacturing field of the automotive industry. According to the papers analysed, it is possible to depict whether or not AR, MR and VR are mature and ready to be applied on a full scale. This can be done, by analysing separately each field of application of each technology.

Based on the results of the literature, AR is under investigation in two main domains: assembly and maintenance. The studies presented by [39], [73] investigate the introduction of AR-based assembly operations. Similarly, [50], [72] evaluated the introduction of AR glasses to support maintenance activities. Nevertheless, these are only introductory and exploratory studies, conducted in an experimental environment far from the real world. This leads to the conclusion that AR is still far from being implemented in the assembly and maintenance domains in the short term. The same conclusion is presented in the studies of [46], [54], [86], which highlighted critical challenges that are preventing their exploitation and that will be further analysed in the following chapter.

On the other hand, the same AR technology has already been applied to daily ergonomics- and layout-related activities. Different practical examples of AR usage or conclusions based on real-world application of this technology in the ergonomics domain have been presented by [47], [58], [64]. The same can be said for layout thanks to [38]. Therefore, this leads the research team to assess a high level of maturity of AR in both ergonomics and layout fields.

Regarding MR, the actual technology and skills limitations are restricting MR from being applied on a large scale. Despite the high number of potentials related to its application, this technology is still not enough mature to be applicable in daily activities. Nevertheless, several exploratory studies are being conducted in the field of assembly [36], [40], [41], maintenance [41], [42], [73] and training [84], [85].

Finally, VR is the XR technology that shows a high level of maturity in the identified fields of ergonomics, layout and training. In all these domains, several of the papers analysed refer to practical real-world applications of VR or exhibit conclusions based on them. In particular, [59], [62], [63] for ergonomics, [67], [70] for layout and [43], [65], [76], [81]

4.1.2. Benefits and challenges

Along with the numerous benefits that XR technology may provide for the automobile sector, it is also important to recognize that XR technology has some limitations that may result in some drawbacks. When it comes to their implementation on a large scale, several criticalities can be pointed out and prevent their usage. [81].

In the following paragraphs, the major benefits and challenges that came out of the literature review are presented.

4.1.2.1. Benefits

Starting from AR, it can be applied to the assembly domain to support the operators in the manual activities by superimposing the instruction on their field of view. This reduces the workers' cognitive load, minimizing also the risk of human-related errors [47], [55]–[57]. Moreover, the provision of the robot trajectory can increase the operators' safety feeling and acceptability when working with robots [52], [53], [58]. The operators' well-being is also considered when using AR for ergonomic assessments. In this case, the AR-based HDM has the main benefit of reducing the costs for expensive mock-ups, replaced by simplified ones enhanced by AR [64]. Moving to the layout domain, AR turns beneficial since it allows the creation of a collaborative environment where layout planners can discuss different solutions and early detect any shielding or safety issues. This has a dramatic impact on the overall efficiency of the layout design process since AR application can reduce the development and innovation time and efforts and the high costs related to a later adjustment of the layout [44], [67], [69], [70]. Finally, the last field in which AR turns beneficial is when dealing with maintenance operations. Indeed, as shown by [72] the superimposed real-time data can increase the overall quality of the process, providing the maintenance operators with the knowledge necessary to act on a targeted component before it breaks down. This increases the failure prediction and the number of possible unexpected production stops.

Despite MR being still not well established in the automotive industry, the studies by [36], [40], [41] point out the main benefit this technology can bring when applied to support operators' manual assembly tasks. MR goes well beyond the superimposed static instruction of AR, enabling a strong relationship between the real and the virtual worlds. This allows the creation of an assembly path or the highlighting of the components to be assembled. As a result, the information to be reminded by the operator is lower, as well as the risk of possible human errors. The second domain in which MR is being studied is within the maintenance processes. In this case, this technology can increase the overall efficiency of the operations by recognising the surrounding real world and highlighting the component to be repaired or replaced. In addition, MR allows better remote assistance, enabling the remote technician to access the data of the component or machine under maintenance [75]. Finally, the last benefits when dealing with MR are related to the training domain. In this case, this technology allows the creation of an immersive and collaborative environment for both participants and teachers [84]. Moreover, the introduction of virtual objects in the real environment makes the need for the real product or production line unnecessary, thus leading to a significant reduction in education costs [84], [85].

To conclude with VR, the studies highlight VR facilitates faster, more accurate, and cost-effective production ergonomics development, as well as serves as a useful tool for reviewing work assignments and design possibilities without the use of physical mock-ups or production trials. The second domain where VR is nowadays being applied is the layout design process. As seen with AR, VR allows for precise planning, optimisation, and analysis of assembly operations in virtual environments [67], [69], allowing for better exploring cost-cutting options and avoiding the higher costs of modifications made later in the project's lifespan. [67], [69], [70]. Nevertheless, differently from AR, VR enables the creation of a more immersive and interactive rather than collaborative environment [67]. Finally, training is the last domain that benefits from the usage of VR technology. In this field, the advantages coming from the VE are several. They range from higher trainees' information retention [81] and involvement [43] to lower education costs due to not necessary purchase of expensive experimental training equipment or consumption of materials [82]. As a result, the application of VR in the training field allows for overall improved performances, allowing the operators to practise skills in an interactive and immersive environment where making mistakes is acceptable and does not lead to any dangerous situations [43]. Furthermore, this training can start far before a new vehicle is released or the production is built [83].

4.1.2.2. Challenges

Through the review, many different challenges were found. As many of them regard the same main topic or area, these were then grouped to facilitate recognition when comparing the three different approaches. The clusters that have been found in the literature review are:

- Funding challenges.
- Selection challenges.
- Skills challenges.
- Technology challenges.

Funding

One of the problems highlighted in the research papers concerns funding issues and more generally the cost of XR devices. According to [43], [87], this is one of the main challenges associated with VR and one of the reasons why companies desist from applying it.

Selection

The second group of challenges that have been identified concerns the selection of the best XR technology for a certain application. As already mentioned, several applications can be done through the use of XR technologies, but it is necessary to choose the right one. This has been noted as a difficult task by [67]. Determining the best technology to deploy is difficult. The criteria to be examined are many and difficult to evaluate (e.g., the cost of technology integration and software licensing, as well as the time required to turn the provided CAD data into an XR simulation).

Skills

Another cluster regards skills issues. Many different papers have mentioned a lack of skills when applying XR technologies. Training and competencies are needed to exploit these technologies effectively and efficiently.

Below there is the list with an explanation regarding each skills challenge:

- Uncertainty related to psychological and physiological reactions to AR glasses: there is ambiguity regarding users' psychological and physiological reactions, such as stress or head and eye pain. As a result, firms are still undertaking proofs of concept (PoCs), particularly for industrial AR applications [77]. In addition, both MR and VR share with AR the same problems related to the psychological and physiological impact of placing training participants outside their comfort zone, which can make them unable to remember or guess what to do next [84], [88].
- Motion sickness symptoms: some people may feel less present in a virtual world or may have motion sickness-like symptoms because of using virtual reality, which can affect job performance. [59], [89]

Technology

Finally, the largest group concerns with technological problems in the application of XR technologies. As XR technologies are relatively young technology, many different technical problems may arise when using XR devices.

A comprehensive list of technological challenges has been collected through the literature review and is divided by XR technology. In particular, AR and MR share similar issues and therefore the two technologies are analysed together. On the contrary, VR technology faces other issues that are therefore analysed separately. Finally, some shared issues between AR, MR and VR are discussed.

As far as AR and MR challenges are concerned, there are:

- Device weight: one issue is the weight of the devices and the user interface's ergonomic implications on the operator, who is required to wear AR or MR glasses for the duration of his/her shift or the training activities [87], [90].
- Alignment of the real environment and virtual objects: one of the most crucial technical challenges encountered in the selected articles is the alignment of the real environment and virtual objects. Since automotive-related environments are dynamic (e.g., the position of objects changes constantly), the usage of fixed markers to facilitate tracking (e.g., RFID sensors) proves useless. This is particularly relevant for MR, as the devices must ensure to display the assembly instruction at the correct position. Thus, the application must consider the product's various assembly states, as well as varied locations for the component, sources, and workspace [54], [86] leading to a difficult integration of XR technologies [46].

- Limited field of view, which required the HoloLens to be fitted properly and fastened on the wearer's head, was one of the key issues experienced by [53], [91]. When conducting manual chores, the HoloLens is very certain to slip, requiring correction and fixing of the field of vision.
- Technology registration: the most common challenge that is preventing the implementation of AR- and MR-based systems for the automotive industry is the registration technology, as there are not yet sufficiently accurate tracking systems to be implemented on a large scale [50].
- Low-quality image: despite the latest improvements in terms of graphic rendering, the quality of AR visualization quality is still posing an issue, together with the possibility of having high-fidelity haptic devices for collision detection [53], [92].
- Hardware and software (MR only): according to [42] the implementation of MR applications in the short term is still further away than AR since current hardware devices are incapable of meeting the criteria for industrial use (etc. dirt, moisture or safety regulations). Furthermore, the devices' battery life and CPU capacity are insufficient to run the program for an extended length of time.

Regarding VR technology, the technology issues are:

- Lack of sensory feedback: the feeling of touch during assembly processes, the expectation of physical resistance while engaging with virtual structures, vibration and haptic feedback is sometimes not well reproduced [74], [81].
- Mismatch real movement and virtual animation: this issue is about the possible mismatch between the real movement of the user and the virtual animation, hand motion tracking for ergonomics research is unreliable [81], [89].
- Depth perception: near distances have been noted as having issues with depth perception. [81].
- Colour quality: this can be an issue as there are concerns that the bright colours of the CAD elements affected perception in VR [81].
- Logistics issues: such as travel time to multiple venues to locate the VR equipment [82].

There is also a challenge that is shared by all three technologies:

- Lack of efficient interfaces: even though the increasing quality and low prices of XR devices make these approaches more relevant than ever before, automotive manufacturers face challenges due to a lack of efficient interfaces between existing production data and XR solutions [65].

4.1.3. Suggestions for the future

In the literature articles, some suggestions have been made to make XR technologies a better tool. However, an exhaustive list has not been compiled.

The first suggestion is regarding the poor alignment between the real and virtual worlds in AR and MR technologies. Possible solutions have been pointed out by [93], using a digital twin of the production system as a platform for continuous improvement of the physical system. By operating it concurrently with real-world production and keeping it up to date, it is possible to deliver detailed and precise information when needed.

The second idea for improving the use of XR technologies concerns how to make VR technology more industry-friendly by improving sensory feedback. Different recommendations can be implemented and further analysed to make VR technology a better tool for the industry. Having better sensory feedback such as introducing 3D sound for manufacturing as well as an olfactory stimulation for the air quality. Furthermore, it should be prioritized the issue regarding depth perception solving by implementing rich settings, textured backdrops, shadows, a multi-sensory experience, and vibrant/high-quality colours [81].

4.1.4. Literature summary

The literature results are summarized in the following Table 4.1. For each XR technology used, the field of application and the main features in terms of hardware and software are highlighted. Then, their maturity level is exhibited. Finally, the benefits and challenges arising are analysed. The latter are also clustered in four main areas: funding-, selection-, skills- and technology-related issues.

Table 4.1. Literature results summary.

XR Technology	Hardware	Software	Field of Application	Maturity	Benefits	Challenges	Example of Challenges	References
AR	HoloLens 1 HoloLens 2	3D Unity	Assembly	No	- Support operator in manual assembly tasks, reducing the cognitive load. - Minimize the risk of human-related errors. - Increase operators' safety feeling and acceptability when working with robots.	Technology	- Ergonomic impact (i.e. weight and sight) of the devices. - Alignment between real and virtual world due to lack of registration technology.	[38], [39], [43], [45]–[47], [47], [49]–[52], [55], [56], [58], [77], [90], [93]–[100]
	n/d	n/d	Ergonomics	Yes	Lower costs for expensive mock-ups, replaced by simplified ones enhanced by AR.	n/d	n/d	[47], [58], [61], [64]
	HoloLens 1	3D Unity	Layout	Yes	- Establishment of collaborative layout design and analysis process. - Early detection of shielding and safety issues. - Reduced development and innovation time, effort and costs.	Technology	- Low-quality representation of superimposed objects. - Lack of efficient interfaces between production and XR solutions.	[38], [44], [66], [67], [69], [70], [87], [92], [101]–[104]
	n/d	n/d	Maintenance	No	- Increased quality of maintenance processes. - Increased failure prediction. - Reduction of unexpected production stops.	n/d	Alignment between real and virtual world due to lack of registration technology.	[50], [71], [72], [86], [105]
MR	HoloLens 2	3D Unity	Assembly	No	- Support operator in manual assembly tasks, reducing the cognitive load. - Minimize the risk of human-related errors.	Technology	Consider the product's various assembly states, locations for the component, sources, and workspace.	[36], [40], [41], [54], [57], [91], [106], [107]

	Oculus Rift	3D Unity	Maintenance	No	- Increased quality of maintenance processes and reduced inspection time. - Remote assistance.	Technology	- Impossibility to meet criteria for industrial cases (e.g., safety regulations). - Lack of computational power and low battery life.	[73]–[75], [84]
	HoloLens 1	n/d	Training	No	- Decreasing education costs. - Immersive and interactive environment.	Skills	Uncomfortable environment for the training participants.	[36], [74], [84], [85]
VR	n/d	n/d	Ergonomics	Yes	- Faster, more accurate, and cost-effective production development processes. - Helpful tool for evaluating work assignments and design options with no need for simplified physical mock-ups.	Skills	Uncomfortable environment for the training participants.	[43], [58]–[60], [62], [63], [74], [81], [89]
						Technology	- High set-up and maintenance costs. - No feeling of touch and physical resistance.	
	n/d	n/d	Layout	Yes	- Establishment of immersive and interactive layout design and analysis process. - Early detection of shielding and safety issues. - Reduced development and innovation time, effort and costs.	Selection	Determining the best technology to deploy is difficult. The criteria to be examined are many and difficult to evaluate.	[38], [61], [65]–[68], [70]
	HTC Vive Pro	n/d	Training	Yes	- Higher information retention. - Decreasing education costs. - Decreasing dangerous situations. - Increased involvement. - Immersive and interactive environment.	Funding	High cost for VR hardware and software adoption.	[43], [65], [76], [79], [79]–[84]

4.2. XR experts interviews

The performed interviews allowed the research team to gather more information regarding the identified research questions. Data gathered from interviews with specialists in the use of XR technologies are crucial to achieving a deeper knowledge of the topic. The interviews are summarized in Table 4.2 below.

Table 4.2. Interviews list.

Interviewee Nr.	Company	Department	Role	Date	Duration
1	VCC	E	Innovation Leader, Metaverse and XR	22/02/2022	56 m
2	VCC	A	Method Developer OLP/Simulation	24/02/2022	42 m
3	VCC	C	Virtual Manufacturing Engineer	25/02/2022	1 h 06 m
4	VCC, previously Audi and VW	E	Senior XR Developer	25/02/2022	46 m
5	CEVT	Manufacturing Feasibility	Manufacturing Engineer	07/03/2022	50 m

The results of the interviews can be divided into three sections, according to the initial three research questions. The first one regards the implementation of XR technologies. In this section, the main hardware and software, together with the field of application and the way they are used in daily activities are exhibited. In the second section, the attention is focused on the challenges related to their application. They can be clustered in integration, funding, technology and skills issues. Finally, the last section gathers the main suggestions provided by the experts to fully exploit the potential of the XR technologies. These will be the starting point to answer the third research question.

The structure of the three sections is slightly different. The first one is more descriptive and analytical, while the other two are far more subjective. Therefore, it has been considered more valuable to directly report the interviewees' quotations to allow the reader to better understand their thoughts and feelings about the challenges and the given suggestions.

4.2.1. XR technologies and their state of the art

The results of the interviews were crucial to reaching a broader perspective on the real-world application of XR technologies by assuming the perspective of XR experts that deal with them daily. Accordingly, the main hardware and software are highlighted, as well as their fields of application. In addition, the maturity level of these technologies is assessed according to the insights collected.

4.2.1.1. Hardware and Software

The hardware and software used in the automotive industry, as well as the technology applied, are different. According to the interviewees, when it comes to AR the main hardware is Microsoft HoloLens 1, supported by the software Volvo Developed (VD) or Unity 3D. Also, HoloLens 2 are being studied in the assembly field of application. Instead, the VR is deployed mainly through HTC Vive Pro, Pro 2 or Varjo VR3 as headset and Steam, Unity 3D or Unreal Engine as software. The Open Innovation team in VCC is also conducting research on the field of MR and haptics for immersion, supported by a strong collaboration with Varjo and their XR3 headsets.

The differences between the hardware and software used to depend on the requirements of each department. Indeed, all the interviewees pointed out how not all the hardware and software are suitable for their purposes. For instance, looking at the Body in White department in VCC the software used is Unreal Engine, despite the lower graphic quality than Unity 3D. The decision is based on the higher compatibility with the CAD and simulation software (i.e., Process Simulate) used. Another example comes from the Final Assembly department, always in VCC. Here the software used is the gaming programme Steam, which resulted to be the most suitable when dealing with the simulation of the mannequin and manual assembling tasks.

What must be highlighted is also the different ways of introducing these technologies into daily activities. In the Open Innovation team in VCC and the Manufacturing Feasibility in CEVT their introduction is structured and follows a precise path. Part of the team is dedicated to the research of new technologies. Then, they are evaluated based on the purposes and requirements of the department, benchmarked and then finally implemented. Moreover, the team create a strong collaboration with the hardware and software providers to exploit the full potential of the technologies. In the other VCC departments, the implementation of new hardware and software is based on a trial approach. Generally, the first introduction is the result of an individual request by a member of the department who has seen the benefits of the technology in some scientific conferences, through third sources (e.g., technology conventions or papers) or by looking at what other departments are doing. Therefore, there is not a shared and agreed direction when looking at the hardware and software available in the market. This represents another reason for the big differences pointed out previously.

4.2.1.2. Field of application

According to the interviewees, ergonomics, layout planning and training are the fields where AR and VR are mostly used in the major automotive manufacturers and suppliers such as VCC, Audi, Volkswagen and CEVT. In addition, exploratory studies are conducted for AR supporting manual assembling tasks in VCC.

Ergonomics

Starting from ergonomics, both AR and VR are used to let the engineer feel how the production activities impact the human body in VCC and CEVT. The purpose, in this case, is not to solve an issue, but to show the process engineers what it feels like. Indeed, according to interviewees 3 and 5, ergonomic studies are not only a matter of numbers, but people have to try first-hand activities. Therefore, the technologies are used to validate the ergonomics of the designed lines, processes and tools before building them. In this way, it is possible to visualize any problem earlier in the development process, saving time and costs in the future. Another aspect pointed out is the possibility of having a first-person view when looking at the processes. It is possible to get an immersive interaction and feeling with the vehicle and the production.

Interviewee 3:
"The purpose is not for us to solve. The purpose for us is to show how it looks, how it feels and how this is. […] *But after that, you can get kind of information about the feeling that you have when you stand there, how it does feel to the back. It's not only numbers."*

Interviewee 5:

"And we usually see it is good to visualize the first-person view to see if during assembly there is a hidden assembly task or not. […] *I think the best benefit is that it gives you a feeling of how the ergonomics is while assembling the parts on the cars, instead of seeing just a part itself. "*

Layout

Regarding layout planning, VR technology is the main technology used. The headset turns useful when it comes to validating at full-scale the production layout whenever a new process or machine is introduced or after any major changes. According to respondent 2, this virtual simulation is replacing in VCC the so-called slow built, namely when the robots in the assembly line run at 5-10% of the nominal speed to check for collision. This is a cost- and time-consuming activity since the line must be stopped. In a VE, the collision check can be done without any impact on the line. More insights are provided also by interviewee 5, according to who the VR results are used to discuss the assembly line layout with the production and product designers. The aim is to make a better decision on the changes needed on the vehicle or the assembly line, according to their stage in the development process and the resulting costs.

Interviewee 2:

"Whenever a simulation engineer has done both his/her simulation program and his/her robot program, he/she usually goes down to the factory. And they do a slow build: they are running robots at a very low speed, like 5% to 10% speed, and they check that the robot is not colliding with anything. […] *This takes time and it costs money: you need to stop the line, and so on. So that's one possible use case that we have seen that you can do virtually."*

Interviewee 5:

"We discuss this with production and product designers. How hard is it to change the vehicle design? Maybe the design is already in the middle of development and there will be some costs if we make some late changes. On the other hand, it could be pretty hard to change the plant since other vehicles are already in full production right now."

Training

VR technology is also well established in the field of training. VCC, together with Audi and Volkswagen are using the VR headset for several applications such as onboarding of new operators, training on new processes and/or components and after-sales service training. In the first two cases, the virtual training allows the organization to be more reactive and increases the capabilities of the operator when dealing with the introduction of new car models. In the last case, instead, giving the possibility to the after-sales service personnel to try first-hand possible solutions to solve any customer issue can have a dramatic impact on the service level.

Interviewee 1:

"Training can be taken in different ways. So, one is the onboarding of people that are using the technology. […] *Another aspect of training is service training. We do have that software for mechanics and service and repair to understand where, you know, to perform the tasks, in which order. In this way, we are also able to train 100,000 people for the aftermarket.* […] *So they can train their people. Especially if it's a new product."*

Interviewee 4:

"In my previous position at Audi Cars […] *The task was to think about how we could use extended reality to slightly switch the qualification of service mechanics from physical "face to face" training toward visual approaches. So, for example, what we did was create repair training in VR. So, in every repair process, the operator could be trained to grab tools, remove balls, plug in cables, plug off cables, remove components, and replace components. All it is done in VR, fully interactive."*

Assembly

Finally, within VCC the AR is being tested to support manual assembly tasks. Rather than using paper-based instructions or physical templates, the tasks to perform can be superimposed on the operator's sight, together with the projection of the component where it must be positioned. This can have a significant impact on the operator's cognitive load, reducing the number and the sequence of the activities to perform to be reminded. In addition, as mentioned by respondent 1, the use of AR allows to save time and thus money on the creation of temporary templates or fixtures to support assembly tasks.

Interviewee 1:

"They manufacture these 3D parts so that they can, you know, drill holes at specific places based on different car models. And then they print these 3D models for a specific car model. So it's not something that can be reused. So that's a lot of cost for just building it for one model. And then they just have to discard it or recycle it. […] *So we came back to the department with one of our colleagues. He looked into it, he used the HoloLens to sort of project the 3D model on top of the actual surface where they wanted to drill these slots. And then you use the HoloLens to do the actual marking instead of, you know, predict depending on another model to keep on top and use it as a temporary base."*

Nevertheless, the project is still in an introductory phase due to the issues regarding the tracking system needed to assure the deployment of the right information in the right position at the right time.

4.2.1.3. Maturity level

The interview results give the possibility to evaluate whether or not the different XR technology mentioned can be applied in the short term to the field of application identified.

According to interviewee 4, AR shows high potential in the assembly domains. Nevertheless, the technological limitations are preventing their exploitation at full scale. The same cannot be said regarding the ergonomics field, where AR is used every day to support the ergonomic assessments and evaluation of interviewee 3.

MR has only been mentioned without any particular explanation of where this technology is being tested.

Finally, VR is the most widely XR technology adopted as it has been mentioned by interviewees 1, 2, 3 and 5. All these XR engineers are currently using VR for supporting their daily activities in the ergonomics, layout and training domains. This allows the research team to assess the high level of maturity of this technology.

4.2.2. Benefits and challenges

Throughout all the interviews conducted, attention was given to identifying the benefits and challenges different XR teams encounter when dealing with XR technologies. Both benefits and challenges were either expressed naturally during the conversation or the interviewees were specifically directed to outline them.

4.2.2.1. Benefits

The results presented above pointed out several benefits related to the implementation of XR technologies in the automotive sector. These benefits can be summarised according to the technology used.

Starting from AR, its usage in the assembly domain is still in an exploratory phase. Nevertheless, the first studies highlighted the possibility of reducing the operators' cognitive load, decreasing the number and the sequence of the activities to perform to be reminded. Moreover, significant time- and cost savings can be achieved by eliminating the need for temporary templates or fixtures to aid the assembling.

Moving to VR, the VE is beneficial in several domains such as ergonomics, layout and training. In the first field, VR allows for the visualization of any problem earlier in the development process, decreasing the risk of later major adjustments and thus reducing time and costs in the future. Moreover, the first-person view when looking at the process enables getting an immersive interaction and feeling with the vehicle and the production line. This leads to making better decisions on the changes needed, considering possible trade-offs according to the car or assembly line stage in their development process. VR turns also useful in the layout design process avoiding cost- and time-consuming activities such as stopping the production line for robots' collision checks. Finally, training is the last domain where VR benefits have been highlighted by interviewees. Practising operators' skills in a VE proves to increase their competencies and capabilities, in particular when dealing with the introduction of a new car model. Moreover, VR is used to train after-sales and service personnel, increasing the quality of the services provided to the final customers.

4.2.2.2. Challenges

Some similarities were identified among all the interviews. Hence, it was possible to portray the main challenges surrounding the use of XR technologies in different teams and companies. Therefore, the findings highlighting the biggest problems are described below.

The different challenges identified have been clustered as follows:

- Funding challenges.
- Integration challenges.
- Skills challenges.
- Technology challenges.

Funding

Concerning the accessibility to funding, many interviewees have pointed out a lack of clearance and slow procurement of hardware and software. In particular, two interesting sentences have been extrapolated:

Interviewee 2:

"We are constantly looking for money. Our position is more difficult than others because we don't have customer relationships. It is important to be a great salesperson to get financing. "

Interviewee 3:

"I could go to a shop and buy a headset for let's say 1500 euros, but it´s not possible. We must pass through the Volvo offices. But then it takes more than six months to get the stuff in my XR room at the same price."

Integration

Regarding integration, many XR experts showed their concern about the lack of collaboration within VCC where we mainly conducted the interviews. Everyone thinks that close collaboration between departments should help. However, this does not happen, and different silos are built. This results in departments not knowing what has been implemented in others, and thus poor efficiency and effectiveness. These are the key sentences that have been pronounced during the interview:

Interviewee 4:

"We have silos. This is because the company is so huge, that you don't know which people are working on similar things. There is no collaboration."

Interviewee 3:

"We don't speak to each other. I don't know how many in this company are using these kinds of technologies today. They are small little groups all over, but we are not organized."

In addition to internal integration, external integration was also targeted. It has been possible to investigate differences between the company in place and the other major car manufacturers in Europe. Luckily, one interviewee has experience working at Volkswagen Group and detailed what follows:

Interviewee 4:

"A big difference is that Audi is part of Volkswagen Group and so has many synergies opportunities. So, there is a huge knowledge sharing between Volkswagen, Audi, Skoda, and Porsche. Right now, here at Volvo Cars, we are alone more or less."

Related to lack of integration and communication there is also the issue of different hardware and software being used within the company. Different departments use different hardware and software. According to some experts this is not good and creates misalignment between departments:

Interviewee 4:

"If another department is using Unreal software, we can't communicate and share knowledge because in my department we use the Unity software […] *We can't share the knowledge."*

Skills

Internal capabilities are playing an important role within the company. The first challenge to address in this context is how to break through to people who are now resistant to this change, as is the case with any cutting-edge technology*:*

Interviewee 1:

"It's a big company, and we have that syndrome of never inventing here. So, people have a resistance to new things, new tools, new processes […] *People aren't very keen on change, there is resistance."*

And then experts stress the importance of spreading awareness of XR throughout the company so that employees understand the benefits these technologies can bring to their daily work. In their opinion, not enough is being done:

Interviewee 4:

"I think this is important that we create awareness within the company […] *we need to share the knowledge in a way that we can build up capabilities in the company."*

Interviewee 2:

"Currently, I'm talking to everyone, and I am trying to spread the word about VR. We need people to go into VR […] *we need people showing interest in it."*

In addition, XR training is lacking, and no specific training organization is in place to ensure people know about how to use XR technologies:

Interviewee 4:

"I think after having hired new people; the second step is to train these people. And we don't have a real structured way right now."

Interviewee 5:

"So far, we don't have a dedicated person for training or education, it's more me or my whole working team dealing with virtual realities."

Moreover, the company does not have the people capabilities to solve certain problems. An expert specifically said:

Interviewee 4:

"We don't have the resources in house to find a solution for a complex problem. Because not everything within the field of XR is easy to develop, even though I'm an experienced developer, it doesn't mean that I have a solution […] *It's just that there are very complex problems that we are not able to solve in a short amount of time or in a reasonable amount of time."*

Lastly, some experts were asked how they see the future within XR technologies. Some of them highlighted an issue regarding the expansion of XR technologies and how the company thinks to do so:

Interviewee 4:

"Also, the challenge is not right now, but if we scale up what we are trying now and apply this on a larger scale, a challenge will be how can we scale this solution up? How do we ensure to know the dedicated place where these applications can be developed?"

Technology

Both AR and VR hardware and software have been addressed as one of the major issues concerning XR technologies within the company. Mostly because technologies are nowadays evolving rapidly and there is the need for rapid changes as both hardware and software become outdated in a couple of years:

Interviewee 2:
"I would need sure bigger GPU and CPU and RAM and so on and for sure we need different headsets, but the big issue is the budget as technologies update every year."

Moreover, with current technologies, still many technical problems can occur. Even highly experienced programmers cannot solve everything at the moment:

Interviewee 4:
"One big challenge is usability. How to design an application that it's intuitive and easy to use for the user that has no previous experience, now it´s not easy to understand how to use these […] *Another challenge is regarding device limitations. As of now, these technologies allow for a limited field of view, limited battery life, and there might be problems for people who are visually impaired."*

Interviewee 1:
"Objects in VR can appear differently compared to how they appear in real-life. For example, if I want to project a virtual car in front of me in VR, I can place it a hundred meters in unity, but it might not look like a car in real life would be 100 meters away."

Specifically, some AR issues have been highlighted. Examples are the need for physical parts when assessing early concepts problems and the low quality of the images on AR:

Interviewee 5:
"With AR you must at least have physical parts. Otherwise, you won't be able to judge. And usually at that early in the design phase, there are not so many physical parts you can test. […] *The quality of the pictures that showed up on your glass like HoloLens is not as good as VR. So, the accuracy is much higher in VR headsets compared to HoloLens glass, so you won't be able to take samples measuring, for example, doors heights, or having accurate measuring points."*

The same has been done with VR technology. The biggest challenge identified is the impossibility of simulating the forces applied when lifting or moving things in the VR environment:

Interviewee 5:

"One of the biggest challenges is the forces. Because in VR, you don't feel gravity. For example, when you pick up the screw of the car, compared to picking up an engine, it's a completely different posture. And it also should be almost impossible to pick up an engine by humans, you must have lifting tools. But I mean, just for example, in VR everything is like you can pick up with a finger."

4.2.3. Suggestions for the future

At the end of each interview, several questions were asked regarding suggestions for improving the current or future use of XR technologies. Certainly, the answers given by the interviewees were based on the challenges identified by the interviewees during the discussion.

Here in this paragraph, the suggestions given by the interviewees are identified and short citations are inserted with the scope of creating a fluent, more understandable text and allowing getting the perceptions the interviewees had.

The different suggestions have been clustered as follows to improve the three following aspects:

- Improve synergies inside and outside the company
- Expand XR knowledge within the company

Since the lack of synergies is one of the biggest challenges highlighted during the interviews, some suggestions were made on how to improve this aspect. In particular, centralising costs and knowledge to have stronger and closer relationships between different departments would be very helpful in decreasing costs and time:

Interviewee 1:

"We should try to centralize those costs and licenses overview because as a big company like ours, you can have that problem where people start parallel projects with for example HoloLens. Those are two teams working on the same thing, so that's an added cost and they have the same case and requirements. So then if you don't have a good relationship with the suppliers, they could charge you twice."

The same considerations about synergies were made regarding possible inter-firm collaboration. Possible partnerships between companies would allow sharing of knowledge and investment:

Interviewee 5:

"I think collaborations among companies should be possible since we are different organizations, but we are in the same group. So, it should be a potential chance to take care of cooperation. And we already have some cooperation since we are both staffed and involved in sand research projects. So, we have kind of like cooperation, but maybe it can even take it further step by having direct contact between person to person or department to departments."

Another suggestion from the interview is how to ensure the future success of XR implementation across departments. This is primarily done by having people capable of managing XR technologies where XR use is expected to occur:

Interviewee 4:

"We need to create capabilities in the key areas where we think there's a lot of potential for XR. So that in these areas people can apply these technologies or the solutions by themselves without having us or other people within the Volvo organization who have the knowledge doing it for them."

It was also suggested not to rely on external consultants to improve the company´s knowledge of XR technologies. This is because it has already happened that these projects have been carried out but then have come to nothing once the consultants have left the company. Moreover, it´s much better to build internal durable competencies:

Interviewee 4:

"I am not a supporter of consultants, because then we don't get the knowledge inside the company. I think we should not consider using external expertise, instead of building about ourselves. And if we want to have it from outside, I think we should hire these experts. We had already this problem, I was not here at Volvo yet, but I know this, there was a HoloLens project in the factory, and it was fully like created by some consultants and then it was over, and they left and then nobody knew how it worked how to continue."

4.2.4. Interviews summary

The interview results are summarized in the following Table 4.3. For each interview, the main findings in terms of XR technology, hardware and software used are highlighted. Then, the field of application of each respondent is exhibited, together with the main benefits and challenges pointed out. Finally, for the sake of comprehension, examples of the challenges mentioned are presented.

Table 4.3. Interviews results summary.

Interviewee Nr.	XR Technology	Hardware	Software	Field of Application	Maturity	Benefits	Challenges	Example of Challenges
1	AR	HoloLens 2	Unity 3D	Assembly	No	n/d	n/d	n/d
	MR	Varjo XR3	Unity 3D	n/d	No	n/d	n/d	n/d
	VR	Varjo VR3	Unity 3D	Training	Yes	- Allow the organization to be more reactive. - Increase the capabilities of the operator when dealing with the introduction of new car models. - Increase the quality of after-sales/service level.	Technology	*"Objects in VR can appear differently compared to how they appear in real-life."*
							Skills	*"People aren't very keen on change, there is resistance."*
2	VR	HTC Vive Pro	Unreal Engine	Layout	Yes	Avoid costs- and time-consuming activities, such as stopping the production line for robot collision check.	Funding	*"We are constantly looking for money."*
							Technology	*"I would need for sure bigger GPU and CPU and RAM and so on and for sure We need different headsets."*
							Skills	*"We need people to go into VR […] We need people showing interest in it."*
3	AR	HoloLens 1	VD	Ergonomics	Yes	Visualize any problem earlier in the development process, saving time and costs in the future.	Integration	*"We don't speak to each other."*
	VR	HTC Vive Pro 2	Steam				Funding	*"We must pass through the Volvo offices. But then it takes more than six months to get the stuff in my XR room at the same price."*
4	AR	HoloLens 1	Unity 3D	Assembly	No	- Reduce the cognitive load, decreasing the number and the sequence of the activities to perform to be reminded. - Time- and cost-savings	Integration	*"We have silos. This is because the company is so huge, that you dally know which people are working on similar things. There is no collaboration."*

						avoiding the creation of temporary templates or fixtures to support assembly tasks.	Technology	*"As of now, these technologies allow for a limited field of view, limited battery life, there might be problems for people who are visually impaired."*
							Skills	*"We need to share the knowledge in a way that we can build up capabilities in the company."*
5	VR	HTC Vive Pro 2	n/d	Ergonomics	Yes	- Having the first-person view when looking at the process allows getting an immersive interaction and feeling with the vehicle and the production. - Make a better decision on the changes needed on the vehicle or the assembly line, according to their stage in the development process and thus the resulting costs.	Technology	*"One of the biggest challenges is the forces. Because in VR, you don't feel the gravity."*
							Skills	*"We don't have a dedicated person for training or education, it's more me or my whole working team dealing with virtual realities."*

4.3. VCC Case studies

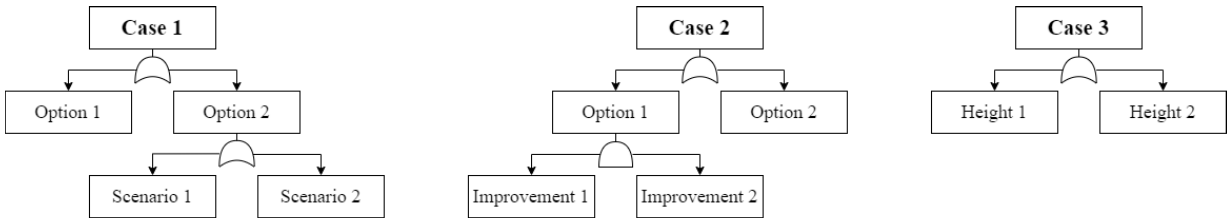
The case studies provided the research team with the opportunity to attend first-hand the application of the XR technologies in a real-world environment such as the Final Assembly department in VCC. The cases attended are summarized in Table 4.4 below.

Table 4.4. Case studies list.

Case Nr.	Objective	XR technology	Date	Duration
1	Ergonomics scenario analysis on a four-screws tightening operation.	AR & VR	01/03/2022	1 h 30 m
2	Solutions brainstorming and visualization for ergonomics issues related to under shield assembling operations.	AR	08/03/2022	30 m
3	Evaluation of a new painting line layout.	AR	10/03/2022	45 m

For the sake of comprehension, Figure 4.5 below shows the structure that will be followed in the various case studies.

Figure 4.5. Case studies structure.



A brief report for each of these cases is exhibited and analysed. Then, the major findings are summarized.

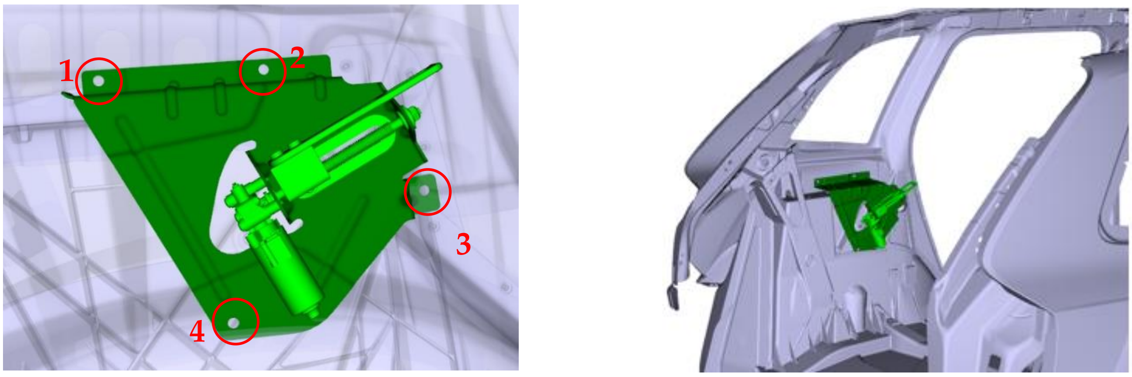
4.3.1. Case 1

4.3.1.1. Preparation

The case analyses the production process of a new electric car whose production is planned to start in a few years in a Swedish plant of VCC, and then it will be expanded to plants in China and the USA. The objective is to solve the ergonomics issues pointed out in the simulation of the production process. The client of the case is an internal department of the company asking for advice and support to solve the issue they are facing.

Initially, the case analysis starts from the desktop-based simulation of the process. The assembly operation consists in tightening four screws on the inside of the lateral part of the car body, specifically at the left rear wheel. Figure 4.6, taken from the desktop-based simulation, shows the position of the part to be assembled and the four screws.

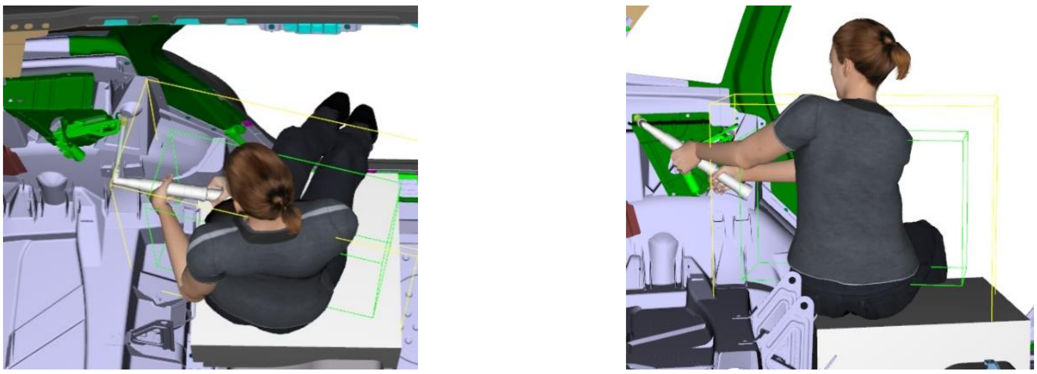
Figure 4.6. Close-up of assembling parts.



As of now, using desktop-based simulation, the operation has been planned to be executed in two possible ways:

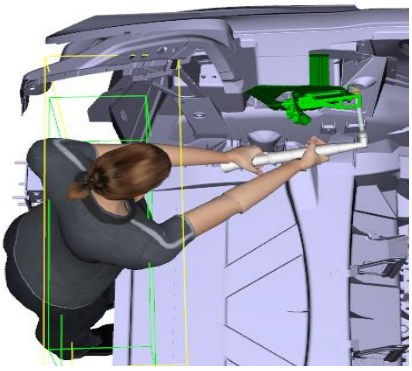
- Option 1 is to perform the task from inside the car body as exhibited in Figure 4.6. The figures show the operation performed with the aid of sitting support, called a pad, which is inserted into the car body to allow the operator to sit inside. According to this simulation, the issues when working in this position are the out of range working position (left) and the consequent trunk posture (right) when tightening the four screws.

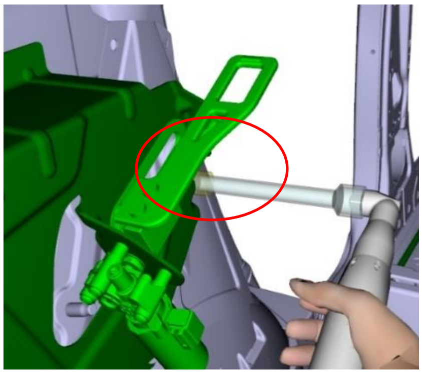
Figure 4.7. Option 1 positions.



- Option 2 refers to performing the task from the rear of the car body as exhibited in Figure 4.8. According to the desktop-based simulation, the only issue would pop up when tightening the 3rd screw (left) since it would be a blinded operation, as circled in red (right). Moreover, only for this screw, the trunk position and then range working position could pose an issue when performing the assembly task.

Figure 4.8. Option 2 positions.



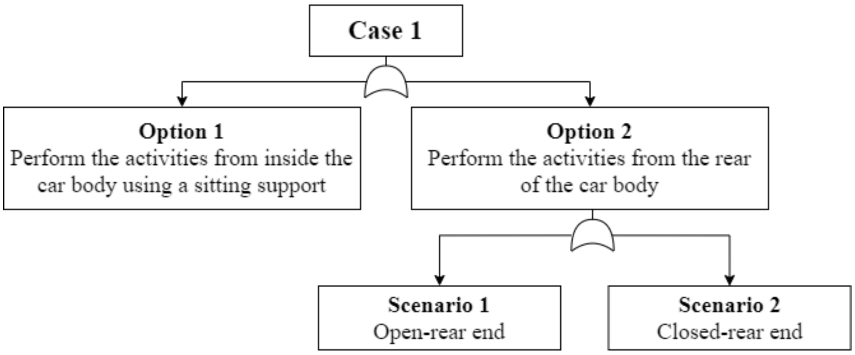


However, this configuration assumes an open-rear end scenario, namely without the rear bumper structure assembled. This is not realistic since the bumper structure is assembled before the four screw-tightening operations. Then, the rear of the car is defined as closed, and it prevents the operator to perform the assigned task as shown in Figures 5-6. Indeed, in a closed-rear end scenario, the task must be performed 400mm behind the simulated open-rear end scenario. Both the client and the XR team cannot decide autonomously to switch from a closed-rear end to the open case scenario on their own. Nevertheless, they could provide to the department in charge of making this decision the suggestions, together with images and video, based on trying first-hand the different scenarios.

Therefore, the goal of the case is to analyse the two options and the two different scenarios of Option 2. Then, evaluate their feasibility in real life thanks to XR technologies. The technologies selected in this case study are both AR, with HoloLens 1 and VD software, and VR, with HTC Vive Pro 2 and Steam software. The main reason why both technologies are used is the lack of objective criteria to understand beforehand which technology would be more advantageous for the client department.

Figure 4.9 below exhibits how the case will be structured.

Figure 4.9. Case 1 structure.



4.3.1.2. Running

The case can be dived into two sections, according to the technology used.

AR technology

The XR team starts analysing Option 1 using AR technology. In the beginning, the team checks that the constraints of the real environment correspond exactly to the AR model. This is crucial to be able to run the simulation and use AR effectively. Once everything is perfectly in place, both options are analysed by the team.

Starting from Option 1, as Figure 4.10 points out, the posture is far from acceptable considering that the operator would have to tighten all the screws in this way. The person who simulated this operation also says that the posture was extremely tiring. Moreover, this person is 190cm tall. If a smaller person is considered, the situation can only get worse. Another reflection regards the importance of AR. In this context, the continuous use of AR is significant because the operation is complex as the operator must be careful not to hit parts of the car, namely those highlighted in light green in Figure 4.6.

Figure 4.10. AR: option 1, open-rear end scenario.

Option 2 is also simulated using AR technology. In particular, both the open- and closed-rear end scenarios are evaluated.

Figure 8 shows the open-rear end case. This situation is assessed as ideal and surely better than the previous one. The main reason is that only the tightening operation of the third screw is posing a possible issue. Indeed, this task requires a slight extension of the arms and the trunk. Nevertheless, no major concerns by the ergonomics specialists are highlighted. Moreover, the fact it is a blind task is also considered not relevant, as it would be possible to put a mark on it to help the operator know exactly where the third screw is.

However, as previously mentioned, this situation is only ideal. In fact, according to some members of the client team, convincing the upper management to change the assembly sequences, and performing the tightening operation before having the rear bumper assembled, is not an easy task. Therefore, the same position considering the closed-rear end case is tested, as shown in Figure 4.11. The presence of the rear bumper affects the distance from which the operator must stand while computing the task. Specifically, the operator position is moved 400mm behind the one test previously in Figure 4.10.

Figure 4.11. AR: option 2, closed-rear end scenario.

After analysing the closed-rear end scenario, the considerations regarding the required posture pointed out several criticalities. In particular, the arms must be extended approximately one metre and the operator's back must bend to reach the furthest screw. In addition, the AR-based simulation considers a 190cm operator while most people are below this height, especially in China where this car should be produced in the following years.

VR technology

The same options are also simulated using VR technology. This requires the team to set up the VR headset and make sure that the virtual environment adheres to reality.

Firstly, Option 1 considering the sitting pad is simulated. In this case, as can be seen in Figure 4.12, the posture of the operator performing the simulation is not at all acceptable. This is the same conclusion that was reached by using AR, and thus the teams rapidly move to simulate Option 2.

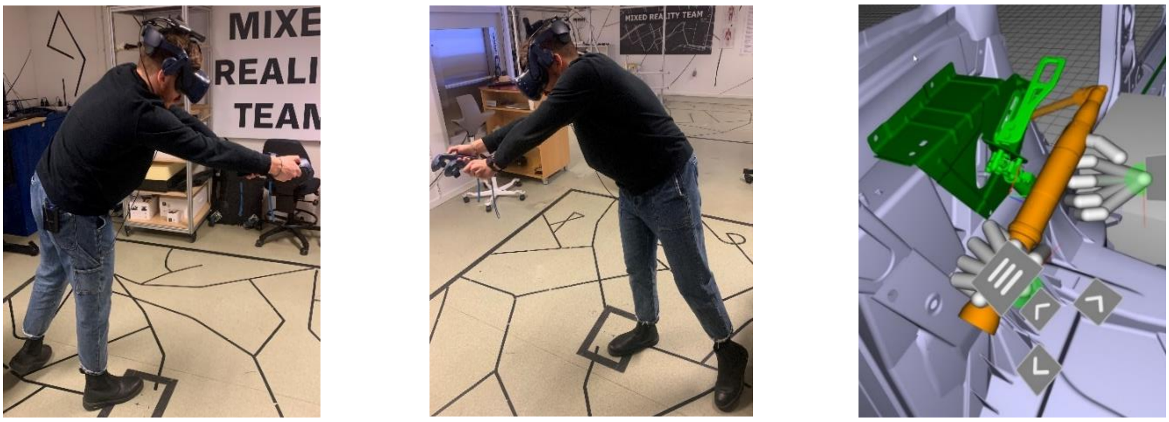
Figure 4.12. VR: option 1.

Secondly, Option 2 and the open-rear end scenario are performed. In Figure 4.13 it can be noticed the position of the operator when tightening the 3rd screw is optimal. Considering that among all the screws, the third is the one that could pose the biggest ergonomics issue, the others do not represent a problem for the operator either. Thus, the open-rear end scenario would be ideal considering the ergonomics perspective. This is the same conclusion that was reached using AR.

Figure 4.13. VR: option 2, open-rear end scenario.

Finally, the close-rear end scenario is simulated. Here, as already mentioned, the operator must stand 400mm further away than in the open-rear end case. This, as shown in Figure 4.14, turns into critical ergonomics when working on the 3rd screw but acceptable posture when tightening screws number 1, 2 and 4. These are the same conclusions that were reached using AR.

Figure 4.14. VR: option2, closed-rear-end scenario.



There was a problem with the position of the model. It happened that the model moved from its original position causing reliability problems as the model had to be readjusted to the constraints. Moreover, some devices showed a misalignment as the model seemed to be in slightly different positions for some participants. No other further issues regarding the setup and the use of AR glasses and software have been encountered.

To conclude, the case took 1h and a half and the two options have been all analysed. The outcome shows the importance of being able to simulate virtual situations to gather information and rapidly solve possible problems.

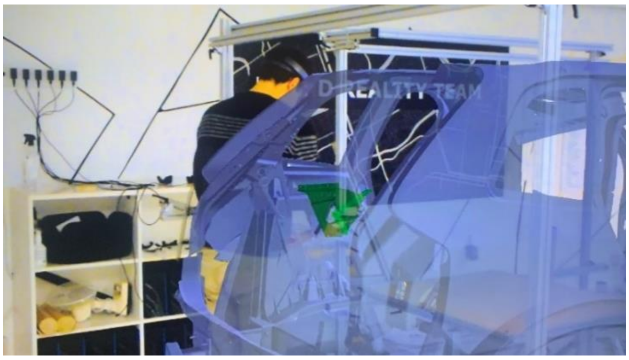
4.3.1.3. Analysis

The case was extremely important for the team to get a better idea of the problem. Using only desktop simulation it is impossible to get real feedback and understand the possible problems. As a consequence, the team was able to discard Option 1 (i.e., the sitting pad case) since both AR and VR technologies revealed unacceptable ergonomics.

Considering the second option and specifying the open-rear end scenario, this would be the best option from an ergonomic point of view. The solutions provided are easily understandable and implementable. However, the team has mentioned that it will be hard to convince the upper management to change the configuration of the production process from a closed- to an open-rear end scenario. Therefore, the solution is to proceed by tightening screws number 1, 2 and 4 standing to the close-rear end while tightening the 3rd screw while sitting on the internal pad. This solution, together with the simulation report and the videos and pictures taken in the XR room, will be shared with the upper management team as a baseline for the discussion on the production process.

A final consideration regards the lack of AR environment pictures included in this analysis. As shown in Figure 4.15, when a person is acting inside the car body, the contrast between the person and the car body makes it hard to see the person and therefore taking pictures is useless.

Figure 4.15. AR: option 2 issue.



4.3.2. Case 2

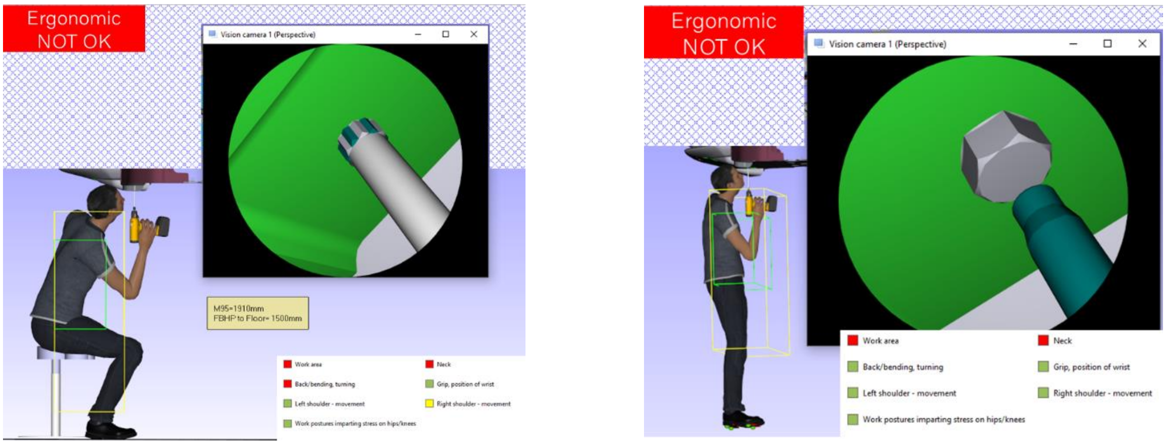
4.3.2.1. Preparation

The case analyses the production process of a new electric car model that will be released within two years, that will take place in a Swedish plant of VCC. The objective is to solve the ergonomics issues pointed out in the simulation of the production process. The client of the case is an internal department of the company asking for advice and support to solve the issue they are facing. Specifically, the case aims to find valuable ergonomic insights when mounting the cars under a shield in a restricted work area. In particular, the operation consists of tightening a screw using the proper tool.

Initially, the case analysis starts from the desktop-based simulation of the process shown in Figure 4.16. The simulation team has planned to perform this operation in two possible different ways. The two options are made possible by increasing the car's height to two predefined levels:

- Option 1: Figure 1 shows the possibility of placing the car body at the predefined height of 1500mm from the floor. Moreover, a supporting chair can be placed right under the car body corresponding to where the operation needs to be done. In this case, the operator performs the task while sitting on the chair.
- Option 2: Figure 2 shows the possibility of placing the car body at the predefined height of 1900mm from the floor. In this situation, the operator must operate while standing up under the car body.

Figure 4.16. Case 1: option 1 and 2.



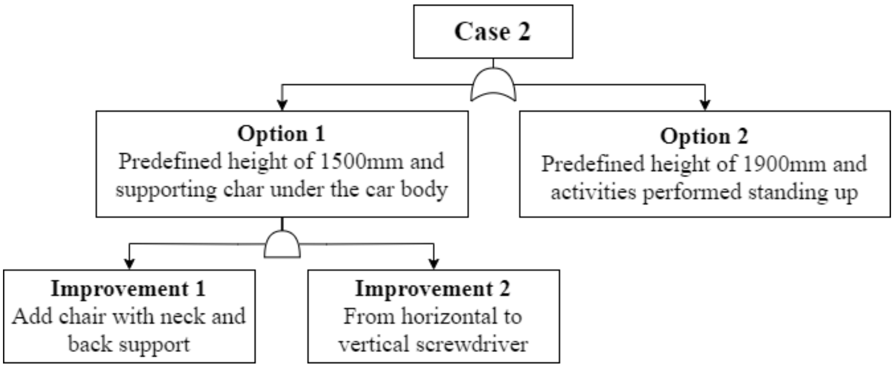
In both cases, the ergonomics are not optimal. In the first scenario, the chair is too high, making it impossible for the operator to maintain proper posture while tightening the screw. The back and neck, in particular, are the most critical areas. In the second configuration, the car body is elevated from 1500mm to 1900mm at ground level, but not enough to allow the operator to execute the task comfortably, particularly considering the neck ache.

Since the car body position can be placed only at certain predetermined heights (i.e., 1500mm or 1900mm) due to existing production line constraints, the only solution for the bad ergonomics is to modify the human position.

The goal of the case is therefore to brainstorm and visualize possible solutions for this situation by using XR technologies. The technology used for this case is AR with HoloLens 1 and the VD software. The decision of using AR over VR is based on the simulation engineer's insufficient knowledge of VR tools.

Figure 4.17 below summarizes the procedure that will be followed during the case.

Figure 4.17. Case 2 structure.



4.3.2.2. Running

Option 1 is identified as the starting point for building possible solutions to improve the situation, with the client, the XR and the ergonomics specialist teams working and discussing together.

Firstly, the client team tests the simulated model on AR to verify that the constraints built by the XR team, namely the aluminium-bars structure, match the model of the car displayed on HoloLens. Once everything is perfectly set up, the team simulates the real-world situation together with the client to check for ergonomics issues, as shown in Figure 4.18. In particular, it is visible that the arm, wrist, back and neck positions, circled in red, are not appropriate.

Figure 4.18. AR: option 1.

This is different from the desktop simulation where only the neck, the back and partially the shoulders have been detected as problematic. Moreover, in Figure 4.18, it is possible to appreciate what is visible when having the AR HoloLens on and the benefits it could bring especially at the beginning of the case when distances and set-up need to be verified to have a realistic result from the case.

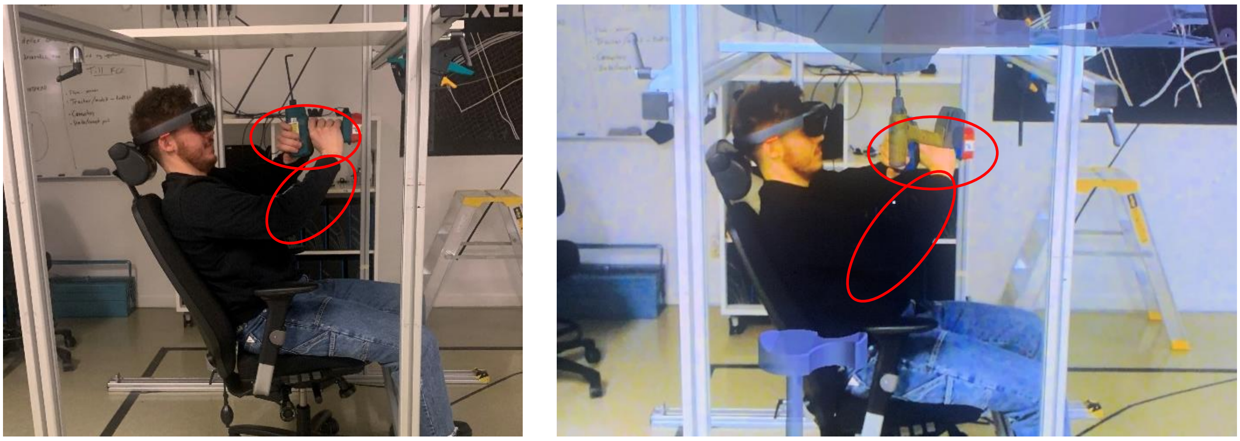
Figure 4.19. Porsche height adjustable chair.

The proposal coming from the ergonomics experts is to have a height-adjustable chair in the workplace with both adjustable back and neck supports. The idea of having this type of chair came from looking at what Porsche is doing in its German plant in Leipzig [108]. Figure 4.19 shows a frame of the video, where it is possible to see the neck and the adjustable back support circled in red.

Consequently, the XR team places a standard office chair under the car model. By adjusting the height and back of the chair depending on the operator, the perfect position for everyone's back and neck can be found. Therefore, the stress on these points is relieved.

After having focused on solving back and neck issues, the next problem to solve is related to the wrist, arm and shoulder position. Figure 4.20 show the posture without further improvements and highlights the bad ergonomics of the wrist and the arm circled in red.

Figure 4.20. AR: option 1 after improvements.



A possible solution to relieve the stress on the wrist and the arms is to change the tool for screwing. Instead of a normal horizontal screwdriver, a vertical one is tested. This allows the operator to lower the position of the arms and assume a more natural position of the wrist. Figure 4.21 highlight these differences and the new tool is circled in red. As a result, the improvements tested proved to be beneficial to solve the initial ergonomics issues.

Figure 4.21. AR: option 1, screwdriver issue.

The entire case took 30 minutes and the real car model superimposed on the structure proved to be reliable and coherent with the previously desktop-based simulation built. Nevertheless, the AR model proved to be more useful for the people standing next to the operator who was performing the activity, rather than for himself. This was due to the limited FOV of the glasses, which did not allow the operator to have the whole representation of the car superimposed on his sight. In addition, there was a problem with the position of the model. It happened that the model moved from its original position causing reliability problems as the model had to be readjusted to the constraints. Moreover, some devices showed a misalignment as the model seemed to be in slightly different positions for some participants. No other further issues regarding the setup and the use of AR glasses and software have been encountered.

4.3.2.3. Analysis

The AR case allowed the client department to solve the ergonomic issues pointed out during the desktop-based simulation. The videos and the pictures taken in the AR room, together with the simulation report and the suggestions provided by the ergonomic specialists, will be shared with the Swedish plant to start planning the introduction of a height-adjustable chair with back and neck supports and a vertical screwdriver for the process.

The solutions provided are easily understandable and implementable. Therefore, the AR case helped the client department to find a feasible solution to the ergonomic issues in a short period. Moreover, the visualization of the issue at full scale allowed the creation of a collaborative environment promoting the discussion between the client, the XR and the ergonomics specialist teams. A discussion that would otherwise have taken place via team meetings and desktop-based simulations only, thus requiring considerably more time to conclude.

4.3.3. Case 3

4.3.3.1. Preparation

The case refers to the introduction of a new electric car model, whose production is projected to start within three years. The objective is to validate the layout of the required new painting line in a Chinese plant and the ergonomics of the related new process.

The client of the case is the Painting department, also named B-shop. The process analysed is the so-called spatula operation, which involves placing sealing material on a spatula and then placing the rubber up under four pre-defined locations.

The actual layout of the painting line currently allows the car to move to three different heights (i.e., low, middle and high) to be processed. The case analyses if the above-mentioned process can be performed at one of these heights. Otherwise, the line must be redesigned and rebuilt accordingly. Moreover, the ergonomics of the process are under investigation to assure the well-being of the operators.

Initially, the case analysis starts from the desktop-based simulation of the process shown in Figure 4.22. The model shows the process performed by one operator at the middle height. According to the B-shop engineers, the simulation shows no ergonomic issues. To investigate and validate this line design the XR technology chosen is the AR with HoloLens 1 and the VD software. The decision of using AR over VR is based on the simulation engineer's insufficient knowledge of VR tools.

Figure 4.22. Spatula process.

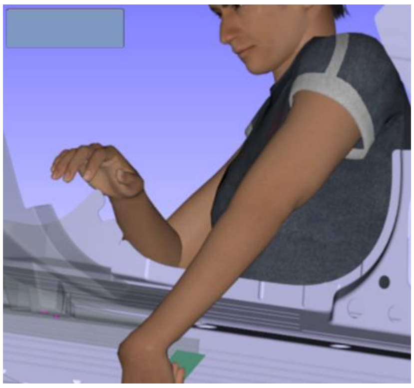
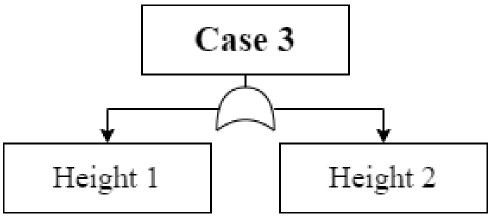


Figure 4.23 shows the structure of the case.

Figure 4.23. Case 3 structure.



4.3.3.2. Running

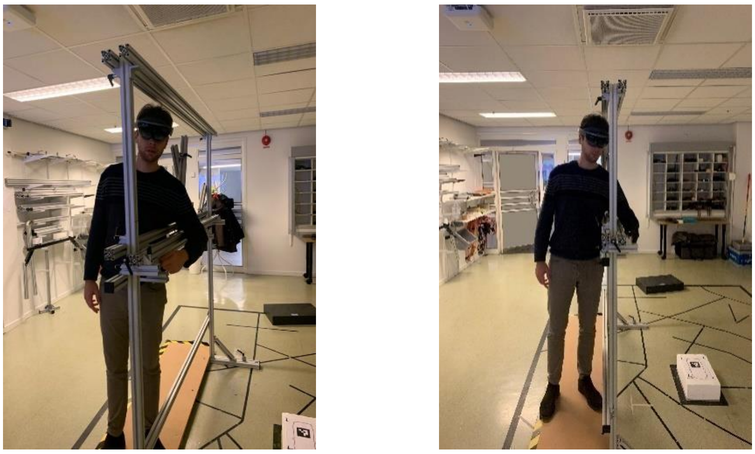
The B-shop team tests the proposed line layout based on the simulation model built at the middle height. The restrictions in the real world, namely the aluminium-bars structure, are used to simulate the surfaces of the car. Using the AR glasses, the car model can be superimposed over the structure. In this way, it is possible to get the tactile feeling of the car through the restrictions while looking at the real car model in the glasses. Nevertheless, the limited FOV of the headset does not allow the team to see in real-time the superimposed model on the structure while performing the sealing process. Rather, only when looking at the model from distance. Indeed, from the operator's standpoint, only the restrictions can be seen, rather than the whole model. Therefore, it is not possible to see where to place the rubber. To overcome this issue, a piece of tape is placed on the restrictions structure to identify the sealing locations.

Once the restrictions are settled correctly and matched with the AR model, the testing phase can start. The process is repeated several times by B-shop team members of different heights to test different operator cases. The activity repetitions allow the engineers to point out three main issues:

- The activity cannot be performed with the operator looking at the car from the front, since the car is moving on the line while the operator's floor is fixed. Therefore, the process must be performed with the operator alongside the car.
- In this case, the position of the wrist and shoulder when placing the seal is not comfortable, with significant stress on the muscle and the joints.
- The activity takes place without direct visual contact with the point of placement of the rubber, in a blind spot.

The latter issue has already been identified in the desktop-based simulation, while the first two are unexpected.

Figure 4.24. AR testing.



Two different line-height scenarios are tested as exhibited in Figure 4.24. With the aid of a ladder, it is possible to point out possible solutions to relieve the stress on the wrist and shoulder. The aim is to set the correct height of the process which can assure the well-being of the operator, which is supposed to perform this activity for each car in the line. Indeed, despite the activity does not last long, it is repeated several times per day every year. Thus, it can have a relevant impact on operators' health and results in carpal tunnel-related pains. To validate the analysed scenarios, supervision and expertise by an ergonomic specialist were required.

The entire case took 45 minutes and the real car model superimposed on the structure proved to be reliable and coherent with the previously desktop-based simulation built, although it could not be exploited from the operator standpoint. No issues regarding the setup and the use of AR glasses and software have been encountered.

4.3.3.3. Analysis

The AR case allowed the Painting team to highlight the ergonomic issue, overlooked in the design phase of the line. The videos and the pictures taken in the AR room, together with the simulation report and the suggestions provided by the ergonomic specialist, will be shared with the Chinese plant to find a common solution. First of all, the process is suggested to be performed side by side with the car, rather than with the operator looking at the car from the front. Furthermore, a new line height is proposed, which implies the redesign and adjustment of the actual painting line understudy to accomplish the release of the new electric car model within three years.

Moreover, the AR case allowed the B-shop engineers to explore the possibility of also redesigning the tools, namely the spatula. Indeed, the ergonomic issue is not the only problem faced during the process. The activity takes place in a blind spot, where the operator cannot have direct contact with the point where the seal must be applied. This can result in a relevant quality issue since it is not possible to perform a direct quality check. The solution elaborated by the ergonomic specialist proposes to redesign the spatula, adding a horn and a mirror at its end. In this way, the operator can perform the activity without bending the wrist and having direct visual contact with the point of the rubber application.

Therefore, the AR case helped the Painting department in the design of the line layout, highlighting overlooked issues that could have been pointed out in the future, when the cost of redesigning the process and the tools could have been higher. The solutions provided are easily understandable and implementable.

4.3.4. Cases analysis

The analysis of the cases allowed the researchers to gather additional insights useful to answer the first two research questions. Accordingly, the results can be divided into two sections. The first one summarizes the main findings in terms of XR hardware and software used and their fields of application. In the second section, the major benefits coming from the usage of these technologies are also highlighted. Moreover, the challenges faced during the cases are analysed and presented, clustered in technology, selection and skill issues.

4.3.4.1. XR technologies and their state of the art

The main hardware and software are exhibited, together with the field of application and the major benefits the XR technologies bring.

4.3.4.1.1. Hardware and software

Within the Final Assembly department of VCC, the XR hardware used for all the cases are the Microsoft HoloLens 1 and HTC Vive Pro 2 for AR and VR, respectively. Coming to the software, the internal-developed VD software for AR and the gaming programme Steam for VR are utilized. The decision on the usage of this hardware and software is based on their compatibility with the simulation program of the department, namely IPS. Moreover, the Steam software is the most beneficial when dealing with mannequins' simulation.

4.3.4.1.2. Field of application

According to real-world cases, ergonomics and layout planning are the fields where AR and VR are currently used within the Final Assembly department of VCC.

Ergonomics

Starting with ergonomics, in cases 1 and 2 AR is used to allow the engineers to try first-hand the effect of the simulated operations on the human body. Based on the feeling and thoughts of the team members possible solutions for the ergonomics issues are pointed out. Indeed, AR usage allows the creation of a collaborative and interactive environment, where the problem can be discussed with all the teams, as seen in particular in case 2. Case 1 also shows the application of VR technology. Differently from AR, in the Virtual Environment (VE) the restriction model cannot be built. Therefore, the operator cannot have a direct feeling of the structure seen through the headset. Moreover, only the person wearing the headset can look at the virtual structure built in the VE. Nevertheless, VR allows a more interactive and immersive environment, where all the tools and the car and production line parts can be moved. In addition, VR allows the introduction of a mannequin in the VE that follows the path of the operator and that can be used for further analyses by ergonomics specialists.

Layout

Regarding layout planning, AR technology is used in case 3 to evaluate different scenarios in building a new painting line in a Chinese production plant. The technology turns useful to validate at the full-scale different line and operators' heights. Indeed, the AR application is beneficial since it allows for analysis of the production layout without having to build a real line, but only the most relevant and of interest features. Moreover, the AR structure is superimposed on the real one, made of aluminium bars, allowing the different teams to have direct contact with the real object.

4.3.4.1.3. Maturity level

The three real-world cases state the high level of maturity of AR and VR in the field of ergonomics and layout for AR and ergonomics for VR.

4.3.4.2. Benefits and challenges

Analysing the results provided by the three cases, it is possible to highlight the main benefits and challenges arising from the usage of XR technologies in the automotive industry within manufacturing.

4.3.4.2.1. Benefits

The three cases highlighted several benefits related to the implementation of XR technologies in the daily activities of an automotive manufacturing company. Some of these benefits are related to both AR and VR, such as:

- The time saved in solving a real-world issue.
- The possibility of testing something that does not exist yet.
- Pointing out overlooked issues.

The usage of XR technologies, in particular in case 2, shows how the visualization at full-scale of the operations helped the client department to find a feasible solution to the issues in a short period. Therefore, the collaborative discussion based on a visual representation of the process shortened the time needed to make a decision. A discussion that would have normally taken place exclusively through team meetings and desktop-based simulations needs significantly more time to reach a shared and agreed solution.

Moreover, XR technologies allow the testing of future production layouts and processes. The creation of a VE, through the usage of an aluminium-bars structure such as in the case of AR or a completely virtual production line in VR, reduces the cost needed to test different solutions and scenarios. Indeed, XR technologies do not need a real and detailed production line as a virtual simulation can be superimposed on a fictitious structure or can be created in a VE. Besides this cost reduction, AR and VR allow for shortening of the production line development process. Testing the line before it can be built prevents having to deal with unexpected troubles, which cannot be visualised by a normal desktop-based simulation, as seen in case 1. This in turn can result in additional cost savings related to the production line and process adjustments.

Finally, both AR and VR allow trying first-hand the impact of the simulated processes on the human body. As seen in cases 2 and 3, the desktop-based simulations can fail in assessing the ergonomics feasibility of an assembly task. In particular, they failed in evaluating all the human body parts affected by the assembling processes. The usage of XR provides the ergonomics specialists with additional insights on the human posture and the forces acting, pointing out possible issues that are overlooked by the desktop simulation as proved in case 3.

Nevertheless, AR and VR have some peculiar benefits if compared with each other. Starting with AR, superimposing the virtual structure on a real one and allowing all the teams to look at the object from different perspectives create a highly collaborative environment. In particular, this turns especially beneficial in fostering the discussion among the team members and enhancing the analysis of the issue and brainstorming possible solutions. Furthermore, the possibility of seeing the real world and having a touch feeling with the aluminium-bars structure makes the usage of AR more intuitive compared with VR, reducing the disorientation of people having to deal with it. Despite these AR-related benefits, VR has the advantage of being able to create a completely immersive and interactive environment. Differently in AR, where everything is static, in VR all the tools and the product and production line parts can be handled and moved. Moreover, even if only the person wearing the headset can look at the VE built, having all the team members looking at the same objective with the same first-person view can turn beneficial in some particular cases.

4.3.4.2.2. Challenges

Several challenges were identified during the execution of the cases. This was possible as both AR and VR technologies could be tested first-hand. The challenges here described are therefore based on what has been observed during the different cases.

The major challenges identified are:

- Selection challenges.
- Skills challenges.
- Technology challenges.

Selection

As the XR team within Final Assembly has two different technologies available, the decision regarding whether to use AR or VR must be made when approaching a case. As has been previously documented in cases 2 and 3, the XR team decided to use AR technology only because the case manager did not have the skills to make VR work. For case 1, the decision was to use both AR and VR and then see which one offered the best result. However, the result achieved with AR was the same result obtained using VR. Since no value was added by using both technologies, time was wasted and only one technology could have been used. These highlighted problems show that the XR team within the Final Assembly is having problems deciding and fully understanding which technologies should be used and in which case.

Skills

Another set of problems that have been identified concerns the skills required to operate these technologies. Indeed, they are complex and require high skills from the XR experts who have to set up the model. In addition, users also need to know how to use the two technologies, especially VR.

Firstly, not all the XR experts within the final assembly department know how to use both AR and VR technologies, as already mentioned in the selection issues paragraph.

Secondly, by participating in several cases in the XR room, it was possible to notice that VR technology requires that people know what VR is and have at least some previous experiences. Otherwise, VR simulation is quite useless as the operator moves strangely and unnaturally as he/she is blocked by fear and disorientation.

Technology

By attending and participating directly in the cases discussed above, it was possible to better understand the way AR and VR work. This certainly allowed us to try out the technologies for real and to realise first-hand the limitation of the versions of the technologies available in the Final Assembly.

The following AR technical limitations have been recognized:

- Model reliability.
- Narrow and bad quality field of vision.
- Inability to take satisfactory photos.
- Bad ergonomic impact.
- Low-quality representation.

Regarding model reliability, in the first and second cases that have been attended, the model showed some reliability issues. What has happened is that the model has moved from its original position causing a mismatch between the physical constraints and the model visible through HoloLens. This can be identified as a major problem because it requires people to adapt the virtual model to the constraints or vice versa. Hence, the team is likely to waste valuable time just adjusting this from time to time. In addition, when a team of a few members tests AR technology using different devices, it is common to see that the headsets are not aligned. When this happens, one person in the team may see the model in a slightly different position than another person sees it. This can therefore cause a major problem as people may come to different conclusions as they see models that are even slightly shifted. Considerations change radically depending on the accuracy of the model. For example, ergonomics considerations change according to centimetres and if two people discuss ergonomics without seeing the same images in the same place, it can pose a problem.

As mentioned, the second limitation is regarding the field of vision. When testing AR technology, it quickly became clear that the field of vision is one of the biggest problems when using this technology. The field of view is very narrow, and the operator does not have the impression of being immersed in the model. If taking case number 3, the spatula process requires looking straight ahead so as not to bend the neck. However, when using the HoloLens, the operator feels disoriented because the vision with the HoloLens is very unrealistic and it is difficult to understand what is happening at the bottom. In addition, the quality of the images visible through HoloLens is not satisfactory and many small details cannot be seen with AR. Comparing the field of view of AR with that of VR, the differences are great as VR allows the operator to have a full immersion. The field of view becomes complete at 120 degrees and the quality is also much higher which allows seeing even the smallest details of the model.

The third AR issue is regarding the inability to take satisfactory pictures. AR technology does not allow the team to take and save valuable pictures that could turn useful for several possible further analyses including reports, presentations and so on. The HoloLens 1 headsets have the picture function, but the issue is that the technology superimposes the human figure with that of the model, giving priority to the model. This completely obscures the human figure, making it impossible to carry out any analysis. For example, in Figure 4.15 the operator is completely obscured, which would not make an ergonomic analysis possible.

Bad ergonomics have been identified as an issue when using AR technology. When wearing AR goggles, the weight of the glasses is not indifferent. The weight of the goggles is not homogeneously distributed over the glasses. This is uncomfortable as the load tends to be all in the front and the head, therefore, falls forward. The strain is not exaggerated, but if some companies want to use AR devices as full-time devices in the plant, this problem must be addressed.

Lastly, low-quality representation is another issue. Images are often not sharp. This is particularly noticeable when wearing VR glasses and then comparing views. AR images are not in high definition, and it is sometimes difficult to read well or recognise superimposed objects. This posed a problem because sometimes it was not easy to immediately understand where to position the tool and simulate the required operation.

Coming to VR, the following technical limitations have been recognized:

- Inability to see the real world.
- Absence of gravity.
- Inability to cooperate.

Regarding the first VR issue identified, when the VR headset is mounted, it is impossible to see what is happening in the real world. As shown in Figures 4.11-4.13, the operator enters a virtual world and only the car model is visible. This is a problem since it can let the operator feels disoriented, and her/his movements are therefore strongly influenced.

The second issue is about gravity. As the concept of VR is very different from that of AR, everything is virtual and so are the tools and parts. However, the HTC Vive Pro 2 VR technology available in the Final Assembly does not include gravity, making its simulations unrealistic. Therefore, it makes it impossible to understand the weight that the operator is moving. This can be seen in Figures 4.11-4.13 where the operator is tightening a screw with a tool that does not weigh VR. As a result, it becomes impossible to carry out certain evaluations such as ergonomic assessments.

In addition, the inability to cooperate is another issue. Differently from AR, VR technology HTC Vive Pro 2 does not allow two operators to cooperate in the virtual environment. When a VR headset is mounted, the individual operator is isolated from other people potentially present in the VR environment. This can be a negative feature as some applications may require more than one operator and thus make it impossible to do so with VR. Moreover, the difference with AR is big because when using AR, the operator can see all the people around.

4.3.5. Cases summary

The case results are summarized in the following Table 4.5. For each case, the objective is stated. Then the XR technologies deployed, together with the hardware and software used and the field of application are exhibited. Finally, the major benefits and challenges, with their examples, are highlighted.

Table 4.5. Case studies results summary.

Case Nr.	XR Technology	Hardware	Software	Field of Application	Benefits	Challenges	Example of Challenges
1	AR	HoloLens 1	VD	Ergonomics	- Time- and costs-savings testing future processes. - Intuitive usage.	Technology	- Narrow and bad quality field of vision. - Inability to take satisfactory photos. - Model reliability
	VR	HTC Vive Pro 2	Steam	Ergonomics	- Time- and costs-savings testing future processes. - Interactive and completely immersive environment.	Skills	VR technology requires people to have previous VR experiences. The operator moves strangely and unnaturally.
						Technology	- Inability to see the real world. - Absence of gravity. - Inability to cooperate.
2	AR	HoloLens 1	VD	Ergonomics	- Time savings in solving a real-world issue. - Time- and costs-savings testing future processes. - Collaborative environment for brainstorming solutions.	Selection and Skills	The XR team decided to use AR technology only because the case manager did not have the skills to make VR work.
						Technology	- Narrow and bad quality field of vision. - Inability to take satisfactory photos. - Model reliability
3	AR	HoloLens 1	VD	Layout	- Time- and costs-savings testing future production line not built yet. - Point out issues overlooked by desktop-based simulation.	Selection and Skills	The XR team decided to use AR technology only because the case manager did not have the skills to make VR work.
						Technology	- Narrow and bad quality field of vision. - Inability to take satisfactory photos.

4.4. Results summary

This section has the purpose of summarizing the main findings coming from the data gathered during the literature review, the interviews and the VCC case study analysis. The objective is to answer the first two research questions and thus identify the main XR technologies adopted in the automotive industry, the benefits they may bring and the challenges that are preventing their full exploitation.

4.4.1. XR and their state of the art

The three sources of data allowed the research team to collect insights into the adoption of XR technologies in the automotive industry within manufacturing. For each of the technologies identified, the main hardware and software used are exhibited, together with the criteria and the reasoning behind their selection. Furthermore, the main fields of application of these technologies are presented, focusing on the factors that are driving their implementation. Finally, it is possible to evaluate if the identified XR technologies are mature enough to be applied in the short term in the mentioned field of application.

According to the data collected, the main XR technologies currently adopted or under investigation in the automotive industry are AR, MR and VR:

- The AR technology combines the virtual and real worlds with a virtual overlay that can add photographs, textual information, videos, or other virtual components to the user's real-time viewing of the actual environment. As a result, AR allows the user to observe the actual world while superimposing or composing virtual objects on top of it. Consequently, rather than completely replacing reality, AR enhances it.

- MR is a hybrid kind of XR that employs a virtual overlay that interacts with the real world as a result of the physical and digital worlds merging, allowing for cross-reality interaction. As a consequence, virtual items in MR systems may not only overlap with the actual environment but also be interacted with as if they were real objects, taking them one step beyond AR. The user remains in the real-world surroundings as digital content is added, and he/she can interact with virtual items.

- VR is a computer-generated virtual environment that users can interact with, move around in, and become completely immersed in. As a consequence, VR allows users to enter a 3D environment through a computer screen or an HMD and interact with this world as if it was real.

For each of these technologies, the major findings coming from the three sources of data are presented in the next sections.

4.4.1.1. Hardware and software

Table 4.6 shows that the only hardware mentioned when dealing with AR is the Microsoft HoloLens 1 glasses. While HoloLens 2 are being studied in different fields. When it comes to the software, 3D Unity is the most used, together with the VCC internal developed software VD. Moreover. the interviews and the case studies pointed out how while the choice of the hardware isn't of crucial importance, the choice of the right software is fundamental and it is based on the compatibility with the simulation software and the activities to be simulated. This is the reason why VD software is preferred within VCC to deal with manual assembly tasks and the simulation of mannequins.

Table 4.6. AR hardware and software results.

AR		Literature	Interviews	Case Studies
Hardware	Microsoft HoloLens 1	X	X	X
	Microsoft HoloLens 2	X	X	
Software	3D Unity	X	X	
	VD		X	X

Table 4.7 presents the main hardware and software used with MR. The most common hardware employed is the Microsoft HoloLens 1 glasses, followed by a few ex7amples of studies conducted with the Oculus Rift and the Varjo XR3. In all the cases, the experiments are supported by the 3D Unity software.

Table 4.7. MR hardware and software results.

MR		Literature	Interviews	Case Studies
Hardware	Microsoft HoloLens 1	X		
	Oculus Rift	X		
	Varjo XR3		X	
Software	3D Unity	X	X	

Table 4.8 summarizes the different hardware and software used when dealing with VR. As can be seen, there is a higher variety of headset devices compared with AR and MR. The most commons are the HTC Vive Pro and Pro 2, followed by the Varjo VR3 headsets. As already mentioned with AR, the choice of hardware is marginal compared to that of the software. The data collected highlights how the software mainly depends on the level of compatibility with the simulation software required and the item that is going to be simulated. Therefore, 3D Unity proves to be easier to use when dealing with product-

related simulation, while Unreal Engine when simulating machines and robots. Finally, Steam software is more suitable to manage mannequins and manual assembly tasks.

Table 4.8. VR hardware and software results.

VR		Literature	Interviews	Case Studies
Hardware	HTC Vive Pro	X	X	
	HTC Vive Pro 2		X	X
	Varjo VR3		X	
Software	3D Unity	X	X	
	Steam		X	X
	Unreal Engine		X	

4.4.1.2. Field of application

The three sources of data provided valuable insights into the actual field of application of XR technologies. According to the data gathered, the technologies are nowadays under investigation or have already been applied in five main domains within manufacturing: assembly, ergonomics, layout, maintenance and training.

The factors that are driving the introduction of these technologies in the manufacturing areas of the automotive industry are mainly related to the increased mass customization and the upcoming electrification required by the market. Both impact the complexity of manual assembly operations, and thus the competencies and capabilities the operators must be trained on. Furthermore, the unpredictable demand related to the electrification trend is requiring the car manufacturers to be easily ready to reconfigure their operations and therefore the layout of the production plant. Finally, to keep a competitive advantage over competitors, the organizations are seeking operations efficiency and effectiveness in all the manufacturing areas, maintenance included.

The drivers that are leading the implementation of XR technologies in the automotive industry are summarised in Table 4.9 below, together with the XR technology that is under investigation or has already been applied in that domain.

Table 4.9. Drivers leading XR implementation.

Field of Application	AR	MR	VR	Drivers	Literature	References	Interviews	Case studies
Assembly	X	X		The increased mass customization in the automotive industry results in higher complexity of manual assembly tasks and the implementation of a hybrid production system based on HRC. The underlying objective of the introduction of XR technologies is to reduce the cognitive load of the operators, increasing their safety and the robot's acceptability.	X	[36], [39], [45]–[48]	X	
Ergonomics	X		X	Late ergonomics problem detection could result in a lack of productivity, high correction costs, and a major impact on operator well-being. Therefore, it is necessary to realize problems as early as possible to save time, money and protect workers.	X	[47], [59], [60], [109]	X	X
Layout	X		X	The increased attention on transformable and scalable production systems, due to unpredictable demand and shorter product life-cycle implies the need to reconfigure and rebuild the layout quickly in a short time.	X	[44], [65], [66]	X	X
Maintenance	X	X		Preventive maintenance is a major hindrance to effective and efficient operations in the manufacturing processes. Therefore, the need to move from preventive to smart maintenance. This implies the introduction of XR technologies to foster real-time data collection and analysis to enhance the performance and	X	[50], [71]–[73]	X	

				intelligence of maintenance processes.				
Training		X	X	The increased mass-customization in the automotive industry results in higher complexity of manual assembly tasks with various distinct model variants to be produced. This makes it hard for the operator to be properly trained. The aim is to increase the training process efficiency in terms of cost, time and knowledge retention.	X	[43], [76], [77], [79], [79], [80]		

4.4.1.3. Maturity

The three sources of data agreed on assessing the maturity level of XR technologies applied to different domains.

The literature, interviews and case studies highlight AR is not mature yet when applied to assembly and maintenance fields. The main challenges organizations are facing are related to the need to align in real-time with the real and virtual worlds. On the other hand, AR devices are widely adopted in the ergonomics and layout domains, where they are used daily to support ergonomics assessments and layout design processes. When it comes to MR, literature and interviews point out the exploratory studies that are being conducted to introduce this technology in the manufacturing areas. Nevertheless, the challenges to be faced are still preventing a full-scale implementation, limiting its maturity. This can also be confirmed by the fact that no MR devices or software are ready today to conduct a case study within the final assembly department of VCC. Finally, VR is the XR technology that shows a high maturity level in all the fields identified, namely ergonomics, layout and training.

Table 4.10 below summarizes the main findings.

Table 4.10. Maturity results.

XR Technology	Field of Application	Maturity	Literature	References	Interviews	Case studies
AR	Assembly	No	X	[39], [46], [54], [73], [86]	X	
	Ergonomics	Yes	X	[47], [58], [64]	X	X
	Layout	Yes	X	[38]		X

	Maintenance	No	X	[46], [50], [54], [72], [86]		
MR	Assembly	No	X	[36], [40], [41]	(X)	
	Maintenance	No	X	[41], [42], [73]	(X)	
	Training	No	X	[84], [85]	(X)	
VR	Ergonomics	Yes	X	[59], [62], [63]	X	X
	Layout	Yes	X	[67], [70]	X	
	Training	Yes	X	[43], [65], [76], [81]	X	

4.4.2. Benefits and challenges

This section aims to summarise and clarify all benefits and challenges when applying XR technologies in the automotive industry. This part represents the answer to the second research question and contains all aspects already mentioned in the previously written text. As for the first research question, three different data gathering methods were used: literature, interviews and VCC case studies. Each of these methods proved to be of fundamental importance in increasing knowledge and getting a clearer idea of the situation.

4.4.2.1. Benefits

The results coming from the three sources of data allowed the research team to highlight the main benefits coming from the implementation of XR technologies in the automotive industry within manufacturing. These benefits are analysed separately, according to the different XR technology and the field where it is under investigation or has been applied.

AR

AR is currently employed in the following domains with the related benefits:

- Assembly: the increased mass-customization in the automotive industry results in higher complexity of manual assembly tasks and the implementation of a hybrid production system based on HRC. Therefore, AR is used to support the operator in manual assembly tasks, superimposing the instructions on the operator's sight and thus, reducing the cognitive load. This has a direct impact on the number and the sequence of the activities to be performed the operator has to remind. Moreover, by supporting side-by-side the operator's activities, AR technology can minimize the risk of human-related errors. Finally, this technology turns out to be beneficial in increasing the operator's safety feeling and acceptability when working with robots, by superimposing on the worker's view crucial information such as the status or the trajectory of the machine. Nevertheless, both the literature review and the interviews state how this technology applied to the assembly domain is still in an exploratory phase and needs to be further analysed before implementing it on a large scale. Table 4.11 summarizes the main findings.

Table 4.11. AR: assembly benefits.

AR		Literature	References	Interviews	Case Studies
Field of Application	Benefits				
Assembly	Increase operator safety and robot acceptability.	X	[52], [53], [58]		
	Minimize human-related errors.	X	[47], [55]–[57]		
	Reduce cognitive load.	X	47], [55]–[57]	X	

- Ergonomics: late ergonomics problem detection can result in a lack of productivity, high correction costs and major impacts on operator health and well-being. Therefore, AR technology is used to validate the process from an ergonomic standpoint before releasing it on the shop floor. As a result, its application can shorten the product development process, making it more accurate and cost-effective, and reducing the risk of major changes due to late problem detection. Moreover, AR does not need a physical mock-up representative of the real production process or line, but only of their main features which can be easily simulated with fictitious, and thus cheaper structures. Finally, as exhibited in Table 4.12, the case studies showed how AR is beneficial in creating a collaborative environment for problems discussion and solution brainstorming, resulting in additional time- and cost savings. The application of AR in the ergonomics domain can be considered well established, looking at the several examples provided by the literature, the interviews and the VCC case studies.

Table 4.12. AR: ergonomics benefits.

AR		Literature	References	Interviews	Case Studies
Field of Application	Benefits				
Ergonomics	Collaborative environment for problem discussion and solutions brainstorming.				X
	Shorten the production development process.			X	X
	Evaluate first-hand possible ergonomics issues, otherwise overlooked by desktop-based simulations.			X	X
	Time- and cost savings thanks to early problem detection and simplified mock-ups.	X	[58], [61], [64]	X	X

- Layout: the increased attention on transformable and scalable production systems, due to unpredictable demand and shorter product life cycles, implies the need to reconfigure and rebuild the layout quickly in a short time. Therefore, AR is used to test and validate different layout scenarios without building them. This has a dramatic impact on the costs, time and effort for the development and innovation of the production design, thus increasing the efficiency of the process. Moreover, AR allows for testing first-hand different solutions, detecting earlier possible shielding and safety issues. In addition, as stated in Table 4.13, the VCC case studies showed how the AR could also enhance the traditional desktop-based simulation, pointing out issues that could have been overlooked. Finally, as seen for ergonomics, the AR technology establishes a highly collaborative and immersive environment which fosters the layout design and analysis process. Despite no insights being provided by the interviewees, the literature and case studies results agree considering the application of AR technology in the layout domain is well established.

Table 4.13. AR: layout benefits.

AR		Literature	References	Interviews	Case Studies
Field of Application	**Benefits**				
Layout	Collaborative environment for problem discussion and solutions brainstorming.	X	[44], [70]		X
	Enhance desktop-based simulation analysis.				X
	Increase layout design and analysis process efficiency (e.g., lower time, costs and effort).	X	[67], [70]		
	Time- and cost-saving thanks to early problem detection and simplified mock-ups.	X	[69], [70]		X

- Maintenance: the last domain regards the implementation of AR technologies to support maintenance operators performing repairing and replacement activities or monitoring the production line status. The main driver for introducing this technology is the need for decreasing preventive maintenance practices, and thus waste of resources, money and time. Nevertheless, moving from preventive to proactive and condition-based maintenance is possible only by providing the operators with the right information at the right time, while monitoring or working on the line. With this information, the overall quality of the maintenance process can increase, allowing also for remote assistance in the case in which support from an expert technician is needed. Moreover, the real-time data provided on the maintenance operator's view can increase his/her failure prediction, therefore reducing unexpected production stops. Nevertheless, the introduction of AR technology in this domain is still far to be applicable. As shown in Table 4.14, neither the interviews nor the case studies provided any insights regarding a practical application in daily working activities. Moreover, also the literature confirms the low maturity of this technology in the field of maintenance.

Table 4.14. AR: maintenance benefits.

AR		Literature	References	Interviews	Case Studies
Field of Application	Benefits				
Maintenance	Increase failure prediction.	X	[72]		
	Increase overall maintenance process quality.	X	[71], [72]		
	Reduce the number of unexpected failures.	X	[72]		

MR

The application of MR in the automotive industry is still in an exploratory phase. The literature is the only source that provided studies on the possible application of this technology in manufacturing. The interviews confirm that its introduction is under investigation, but still far from being tested on the shop floor and thus adopted. Therefore, the following results are mainly related to the findings of the literature.

The MR has been tested in the following domains:

- Assembly: considering the increasing complexity of manual assembly tasks, the MR can support the operator's activities not only superimposing the sequence of operations as in the case of AR. Indeed, MR can interact with the real world, recognising the components to be assembled and highlighting them. Moreover, Table 4.15 shows how according to the literature the MR can also superimpose on the worker's view the path that component must follow or the assembly spot. In this way, it is possible to dramatically reduce the cognitive load, also minimizing the risk of human-related errors.

Table 4.15. MR: assembly benefits.

MR		Literature	References	Interviews	Case Studies
Field of Application	Benefits				
Assembly	Minimize human-related errors.	X	[36], [40], [41]		
	Reduce cognitive load.	X	[36], [40], [41]		

- Maintenance: moving towards proactive and condition-based maintenance requires the maintenance operators to rely on real-time data on the machines under analysis. Instead of superimposing static information about all the machines as in the case of AR, MR can scan the surrounding real-world environment, recognising and highlighting the components or the machine under maintenance and providing only the data and information needed for that component or machine, thus increasing the overall quality of the maintenance process. Moreover, as shown in Table 4.16 below, MR allows better remote assistance, enabling the remote technician to access the data of the component or machine the operator is looking at.

Table 4.16. MR: maintenance benefits.

MR		Literature	References	Interviews	Case Studies
Field of Application	Benefits				
Maintenance	Increase overall maintenance process quality, allowing remote assistance when needed.	X	[73]–[75]		

- Training: due to the already mentioned higher complexity of manual assembly tasks and the introduction of robots in the assembly lines, there is a critical need to increase the skills of workers. The traditional training techniques, based on paper- or DVD-based education and task demonstration by experienced operators, proved to be insufficient to deal with the current higher complexity of assembly operations and environment. Therefore, Table 4.17 shows how the use of MR can turn beneficial, allowing the creation of an immersive and collaborative environment where the operators can train first-hand the tasks to perform. Merging the real with the virtual world also allows the reduction of education costs, thanks to the possibility of training operators in a fictitious environment enhanced by virtual items, without the need to replicate the expensive shop floor or stop the assembly line to train the operator right in place.

Table 4.17. MR: training benefits.

MR		Literature	References	Interviews	Case Studies
Field of Application	Benefits				
Training	Creation of an immersive and collaborative environment.	X	[74], [84]		
	Reduce education costs.	X	[84], [85]		

VR

According to the data collected, VR is used or under investigation in the following domains with the related benefits:

- Ergonomics: as previously stated, late diagnosis of ergonomic issues during assembly activities, for example, can result in lost productivity, expensive rectification costs, and a negative impact on operator well-being. As a result, VR analyses ergonomic hazards during the design process, allowing for early detection of important problems and the implementation of corrective steps, which is more effective and cost-efficient than a later assessment of these risks.

Moreover, VR is used to evaluate the ergonomics of the manufacturing process, as well as to improve decision-making on workplace architecture, aided assembly devices, tool replacement, and modifications to assembly routines and processes. Therefore, as stated in Table 4.18, all the sources agreed on the main benefits of using VR, namely the possibility to shorten the product development process and save time and costs by visualizing earlier problems that can occur in the future. Moreover, VR technology does not need any physical mock-ups and allows for the creation of a highly interactive and immersive environment. Finally, the VCC case studies confirm what was pointed out from the literature review, assessing a high level of maturity of VR in the field of ergonomics.

Table 4.18. VR: ergonomics benefits.

VR		Literature	References	Interviews	Case Studies
Field of Application	**Benefits**				
Ergonomics	Interactive and immersive environment for problem discussion and solutions brainstorming.			X	X
	Evaluate first-hand possible ergonomics issues, otherwise overlooked by desktop-based simulations.			X	X
	Shorten the production development process.	X	[43], [59], [60]	X	X
	Time- and cost savings thanks to early problem detection and no need for mock-ups.	X	[43], [59], [63]	X	X

- Layout: as a result of the forthcoming electrification and the resulting unstable and unpredictable demand, the automotive industry is encountering several challenges. As a result, transformable production systems are receiving increased attention, with a particular focus on scalability. Unfortunately, due to the inability to evaluate the proposed architecture at full size, desktop-based simulations are not always capable of anticipating future demands and frequently fail to account for ergonomics and safety considerations. As exhibited in Table 4.19, all the sources highlighted how the use of a VE in which different layouts can be tested at full scale can result in time- and cost savings. Therefore, VR can dramatically increase the layout design and analysis process efficiency. Moreover, testing the planned scenario at scale one allows for the early detection of shielding and safety issues, reducing the risk related to high costs in the future to modify the shop floor. Furthermore, the literature also highlighted the benefits related to the creation of an interactive and immersive environment which allows the layout planner to test with a first-person view the different solutions. Finally, due to the high number of practical examples provided by the literature and the interviews, the adoption of

VR in the domain of layout planning and design can be considered well established.

Table 4.19. VR: layout benefits.

VR		Literature	References	Interviews	Case Studies
Field of Application	Benefits				
Layout	Increase layout design and analysis process efficiency (e.g., lower time, costs and effort).	X	[61], [67], [69]	X	X
	Interactive and immersive environment for problem discussion and solutions brainstorming.	X	[67]		
	Time- and cost-saving thanks to early problem detection and no need for mock-ups.	X	[61], [67], [69], [70]		

- Training: Operator training has been a long, complicated, and tough process, one that is becoming more complex as the number of manual assembly jobs that workers must remember grows. In this context, virtual training is intended to create a more natural learning environment by allowing participants to enter a VE where they may teach themselves in an immersive, interactive and risk-free scenario. The use of VR headsets helps operators to become more engaged and involved in the training system, offering a more immersive and interactive experience. As shown in Table 4.20, the use of VR leads to greater knowledge retention and the development of overall superior skills, according to the literature and interviews. Furthermore, the VE allows trainees to make mistakes without risking their health or well-being, therefore decreasing dangerous circumstances. Another significant feature is that the VE does not require any mock-ups or duplicates of the production or production line to teach the operators, thus lowering education costs. Finally, both the literature and the interviews indicate that the use of VR for training purposes has reached a high level of maturity.

Table 4.20. VR: training benefits.

VR		Literature	References	Interviews	Case Studies
Field of Application	Benefits				
Training	Greater knowledge retention and overall higher capabilities.	X	[43], [81]	X	

	Higher trainees engagement and involvement.	X	[43], [81]	X	
	Interactive, immersive and risk-free environment for training.	X	[43]		
	Lower education costs.	X	[82], [83]		

4.4.2.2. Challenges

While collecting all the challenges, they have been grouped into different sections to better understand where the problems come from. The different challenges categories identified are:

- Funding.
- Integration.
- Selection.
- Skills.
- Technology.

In addition, Table 4.21 summarises which sources of data led to point out the clustered challenges.

Table 4.21. Clusters of XR challenges

Challenges	Literature	Interviews	Case Studies	Number of Issues
Funding	X	X		3
Integration		X		2
Selection	X		X	3
Skills	X	X	X	5
Technology	X	X	X	16

Funding

As Table 4.21 illustrates, the issue of funding only came up during the interviews. In addition, the related funding issues are:

- Accessibility of funds: it is very bureaucratic and slow. Departments must pass through specific VCC desks asking for technologies. The whole process can take several months.
- High-cost XR devices: one of the problems highlighted in the research papers concerns funding issues and more generally the cost of XR devices.
- Lack of funds: there is no budget for certain departments to spend on XR technologies. In these conditions, the departments have to adapt to buying cheap and short licences.

Table 4.22 summarized the two fund issues and confirms the importance and right decision to have different and differentiated sources of data collection. In addition, the challenges are not related to one AR, MR and VR specifically, but to a more general issue concerning the new XR tools.

Table 4.22. Funding challenges.

Funding	Literature	References	Interviews	Case Studies
Accessibility of funds			X	
High devices cost	X	[43]		
Lack of funds			X	

Integration

Integration issues, such as funding issues, were only encountered during the interviews, as illustrated in Table 4.21. In particular, lack of integration means both absences of communication and collaboration, as described below in the two identified challenges:

- Lack of collaboration: this is a direct consequence of the lack of communication. The result is a non-sharing knowledge between the different departments of VCC. Especially in big corporations, several departments may use the same technologies. Therefore, sharing knowledge and expertise is a way to solve problems faster and more effectively.

- Lack of communication: the creation of silos within the VCC company. Effective communication is non-existent and XR experts from a certain department do not know what other XR experts from other departments are doing.

The two integration issues are summarized in Table 4.23. Again, as with the funding issues, questioning all three methods led to a positive result as it allowed collecting issues that otherwise would have been missed.

Table 4.23. Integration challenges.

Integration	Literature	References	Interviews	Case Studies
Lack of collaboration			X	
Lack of communication			X	

Selection

According to Table 4.21, the approaches thanks to the selection issues that have been discovered include literature reviews and case studies. These issues focus on the importance of selecting the right XR technology for specific tasks. Within VCC, this decision has an impact on the resolution of problems during cases that are referred to by the XR experts.

- Lack of selection criteria: difficulty in determining the best XR technology to implement. Without any objective criteria to select the proper XR technology, it is necessary to have extensive experience with XR technologies and to be familiar with all possible cases.

- No selection: all XR technologies are applied when not needed. The decision to carry out the case with both AR and VR technologies is due to the inability to understand which is better for the specific application required. Therefore, the time needed to complete the case can double, when a proper selection could have saved time, and thus money.
- Wrong selection: faulty selection of one technology among AR or VR due to lack of expertise can lead to unsatisfactory or insufficient results.

Table 4.24 testifies where the specific issues have been discovered. The challenge of selecting the proper technology was shown by the literature research. The case studies brought value by clarifying when these decisions are made, and the two probable faults produced by the decision challenge.

Table 4.24. Selection challenges.

Selection	Literature	References	Interviews	Case Studies
Lack of selection criteria	X	[67]		X
No selection				X
Wrong selection				X

Skills

Unlike the categories above, skills-related challenges were found in all three methods, as Table 4.21 shows. Most of these issues are commonly shared between AR, MR and VR and therefore there is no division based on the XR technologies. Finally, one VR-only challenge is explained.

- Lack and difficulty of training: it has been found that most of the employees are not trained on how to use XR technologies. Therefore, people do not know how these technologies work and what to expect from them. Moreover, this is important to mention that the training environment using XR technologies can be uncomfortable.
- Lack of internal capabilities: important to build up internal capabilities within the company.
- Limited skills: at VCC, it has been noticed as some XR experts do not have the knowledge to run both AR and VR. This has an impact on the selection of the technology to use in the cases.
- Motion sickness symptoms: these are common when dealing with VR technology only. Need to have precise skills to not feel bad.

- Psychological and physiological reactions: uncertainty related to psychological and physiological reactions at XR glasses: there is ambiguity regarding users' psychological and physiological reactions, such as stress or head and eye pain.
- Resistance to change: people are not keen on change, and this becomes a challenge because the XR technologies need users who understand their value to be implemented daily.

Table 4.25 summarizes the skills issues findings. All three methodologies have been of utmost importance to gather valuable data regarding skills issues when dealing with XR technologies.

Table 4.25, Skills challenges.

Skills	Literature	References	Interviews	Case Studies
Lack and difficulty of training			X	X
Lack of internal capabilities			X	
Limited skills				X
Motion sickness symptoms	X	[59], [87], [89]	X	
Psychological and physiological reactions	X	[77], [84], [88]		
Resistance to change			X	

Technology

Table 4.21 shows that technological issues are the most addressed, as the number of technical issues is more than twice as high as any other challenge. Furthermore, technological challenges are encountered in all three data collection methods. In this paragraph, the different challenges will be briefly discussed together with the main aspects of each of them. Some of the issues related exclusively to AR, some to VR and some to MR. Therefore, the analysis is divided by specific XR technology.

Considering AR technology, the different technology challenges - summarized in Table 4.26 - identified are:

- Bad ergonomic impact: AR devices are usually not balanced and the centre of gravity of the devices is at the front of the goggles. This leads to a non-ergonomic situation when wearing glasses.
- Inability to take satisfactory photos: AR technology does not allow to capture of significant images. The HoloLens 1 headsets have a picture function, but the problem is that the technology superimposes the human figure on the model, giving priority to the model. This can limit the possibility of reporting and sharing the results
- Limited and narrow field of view: the HoloLens 1 headset has a limited field of view that does not allow operators to comfortably perform all tasks. The same problem regarding the quality of images, many details are not available to be seen on HoloLens 1.

- Low battery life.
- Low model reliability: this problem shows discrepancies between the real world and the virtual world. It represents a big challenge during practical testing because it causes delays and misunderstandings.
- Low-quality representation: images that are superimposed when wearing glasses do not have a high quality and can sometimes be difficult to read or can be hard to recognise objects.
- Not adaptable to all individuals: some people can have problems using AR headsets. For example, people that are visually impaired may have problems using AR.

Table 4.26. Technology challenges: AR.

Technology - AR	Literature	References	Interviews	Case Studies
Bad ergonomic impact	X	[87], [90], [91]		X
Inability to take photos				X
Limited field of view	X	[53], [91]	X	X
Low battery life			X	
Low model reliability	X	[46], [50], [54], [86]		X
Low-quality representation	X	[53], [87], [92]		X
Not adaptable to all individuals			X	

All three methods proved to be essential in meeting all possible AR challenges. Some more specific challenges, such as the inability to take valuable pictures, were only possible through specific case studies. This has been an invaluable asset for this research.

Moving to VR technologies, the challenges are:

- Absence of gravity: this problem is one of the biggest because it does not allow for adequate simulation of the forces that need to be deployed.
- Image distortion: objects in VR may appear differently than they do in real life. Moreover, near distances have been noted as having issues with depth perception.
- Inability to cooperate: when a user mounts the VR headset, he/she enters a virtual environment alone without the possibility of collaborating with another VR headset user.
- Inability to see the real world: when a VR headset is mounted, the user enters a virtual world, and it is impossible to see what is happening in the real world.
- Physical perception: when using VR technology there is a lack of sensory feedback, such as touch, vibration and haptic feedback.

VR technology challenges are displayed in Table 4.27.

Table 4.27. Technology challenges: VR.

Technology - VR	Literature	References	Interviews	Case Studies
Absence of gravity			X	X
Image distortion	X	[81]	X	
Inability to cooperate				X
Inability to see the real world				X
Physical perception	X	[74], [81], [89]		

Also, for VR technology, all three methodologies have been important to gather sufficient and extensive knowledge about the challenges. It can be noted that only "absence of gravity" has been cited by more than one source, showing again the importance of having differentiated data sources.

About MR technology, the following challenges were recognised:

- Bad ergonomic impact: same explanation as for AR.
- Lack of computational power.
- Limited battery life.
- Limited field of view: same explanation as for AR.
- Low model reliability: same explanation as for AR.
- Low-quality image: same explanation as for AR.
- Impossibility to meet safety criteria: MR technology is still not ready to be used in a real plant as it does not meet the safety requirements to be applied in such an environment.
- Structural complexity: MR technology is a complex concept that requires giving complex information such as the position of components and specific locations.

Table 4.28 below gives information regarding where the challenges have been found.

Table 4.28. Technology challenges: MR.

Technology - MR	Literature	References	Interviews	Case Studies
Bad ergonomic impact	X	[90], [91]		
Lack of computational power	X	[42]		
Limited battery life	X	[42]		
Limited field of view	X	[91]		
Low model reliability	X	[54], [73]		
Low-quality representation	X	[92]		
No safety requirements	X	[42]		
Structural complexity	X	[42], [73]		

MR technology was only mentioned in the literature review as this technology is not yet used in real-life scenarios. Neither during the interviews nor in the case studies was MR technology ever mentioned.

5 How to implement XR technologies

In this chapter, the main findings of the previous Chapter 4 are analysed to provide the automotive firms with practical and easy-to-apply suggestions to support the XR technologies adoption and implementation processes.

5.1. Purpose

The aim is to provide a set of guidelines to improve the process of XR technologies adoption and implementation and to enhance continuous improvement after the application of these technologies. After collecting both potential benefits and challenges during Chapter 4, it has been clear that organizations face usual barriers and problems when it comes to adopting XR technologies and successfully implementing them in their business processes [101]. Many reasons convinced the authors to present these guidelines:

- The lack of a roadmap and a vision. During the five interviews conducted, it was noted that none of the car manufacturers mentioned has a detailed roadmap implementation plan for these technologies. On the contrary, during interview 2, the XR technologies were implemented because they were new tools, and no preliminary implementation study was performed.

- No research paper was found during the literature review that can provide a comprehensive framework to be followed. [94], [97], [110] developed interesting frameworks on how to implement Industry 4.0 or XR technologies, but without focusing on the challenges faced and without mentioning precisely what and how to do things. Moreover, these frameworks are very much focused on the technological perspective, while other points of view are considered important in this research.

- The high number of challenges gathered in Chapter 4. In particular, 28 challenges were discussed.

As a consequence of the above points, it is worth noting that organizations are continuously trying to prepare themselves to adopt industry 4.0, however, there are still many gaps when it comes to the implementation of specific technologies. Therefore, both deciding to adopt and implement XR technologies can be quite difficult because there is no standardized methodology [109]. Given all these reasons and the fact that developing an appropriate strategy to use Industry 4.0 technology is one of the main aspects of properly leveraging the technologies [95], it was decided to propose a set of comprehensive guidelines.

The above-mentioned guidelines advise on how to select, approach and exploit XR technologies in the short term and then continuously manage these technologies to achieve long-term value. Indeed, from a strategic perspective, the implementation of Industry 4.0 requires a comprehensive strategic roadmap outlining every step of the way to an all-digital manufacturing organization, thus avoiding the challenges that Industry 4.0 poses at all managerial levels [107]. Therefore, this strategy must encompass technological, organizational, and skills capability perspectives [111], [112]. The people involved can range from the top management who decides the company strategy to the XR expert who uses the technologies in his or her daily life. For this reason, the various recommendations presented are an important resource for all persons involved in the adoption and implementation of XR technologies.

Finally, it is important to mention that the goal of these guidelines is to provide suggestions on how to properly implement XR technologies focusing on the automotive industry aligning with the main purpose of the entire research. Consequently, these guidelines focus attention on the factors that need to be considered when it comes to XR adoption and implementation to avoid and limit the challenges that were gathered in Chapter 4. Thus, the proposed guidelines should be intended as support during XR implementation, rather than a framework to be followed step by step.

5.2. Guidelines development

As previously stated by [107], the Industry 4.0 paradigm presents several issues at all managerial levels. Furthermore, an effective XR adoption and implementation plan must also consider (1) technology management-, skills capabilities- (2) and company structure-related aspects (3) [111], [112]. Therefore, these three perspectives are considered while providing practical guidelines for XR adoption and implementation.

The importance of these three perspectives, together with a detailed explanation of the guidelines are presented in the following sections.

5.2.1. The three perspectives

Three different perspectives of analysis are identified to explain in detail all the different steps that compose the guidelines. The three perspectives are:

1. Technology management.
2. Competencies.
3. Company structure.

These three identified views allow for a cross-sectional analysis of the different steps and thus allow for a clear idea of the considerations that need to be made in each of the steps. For example, when it comes to a specific step, it is crucial to analyse it throughout all three pillars. This is because, to have a successful XR adoption and implementation, it is of the utmost importance to implement the right technologies and to address both organizational and skills capability issues.

The importance of these three perspectives is briefly explained in the three sections below.

5.2.1.1. Technology management

Technology is the main focus and pivot of Industry 4.0. Consequently, technology management is one of the key aspects to consider. Technologies must be managed throughout the whole implementation process starting from the selection to the improvement phase. The initial importance lies in the fact that it is crucial to select the right technology when adopting the concept of Industry 4.0 within an organization. In addition, it is important to manage it throughout the whole implementation life cycle as the technology performances should be monitored and then evaluated for future steps and improvements. [110]

5.2.1.2. Competences and capabilities

The second perspective analysed is the one related to the competencies and capabilities to be acquired or developed by firms. This aspect is of paramount importance since Industry 4.0 paradigm allows for the integration of a set of emerging technologies to add value to the whole production area, but it also necessitates a socio-technical development of the human role in the production system and an aligned deployment of the organization´s capability [98]. In particular, it needs significant growth in digital competencies in manufacturing organizations [113], as well as agility and enhanced flexibility in their acquisition and development [100]. For these reasons, knowledge management is essential to the success of any business. In industrial firms, knowledge management has lately received attention as a strategy for improving innovation [114]. This pillar makes clear the importance of skills development to potentiate the digital transformation of organizations [115].

5.2.1.3. Company structure

The company´s organisational structure represents the third perspective to be considered. In fact, beyond technology implementation, the Industry 4.0 transition creates operational, organizational, and managerial problems that must be addressed to cope with digital transformation [107]. Therefore, developing an efficient plan to manage the transition to Industry 4.0 necessitates paying close attention to organizational structure. The success of Industry 4.0 technology adoption is determined by organizational features, particularly a company's willingness to utilize such technologies [107]. Therefore, an optimal plan for implementing critical technological innovations should also take into account organizational aspects, as it is vital for businesses to execute changes at a macro-organizational level to prevent complications and bottleneck situations involving communication and bureaucracy. [107]

5.2.2. The set of guidelines

The structure of the guidelines follows the path a company pursues when deciding regarding Industry 4.0 adoption and implementation. In the beginning, a company must decide which XR technology to implement, carry out the implementation, and then effectively control and manage the technology. For each of these steps, guidelines will be provided. In particular, two clusters are identified to allow a better understanding of the different steps that compose the adoption process of XR technologies: the difference stands between the activities that should be done *before* the physical implementation of XR and those that are done *after* the physical implementation of XR.

Regarding the *before* XR implementation activities, three steps are defined within this area:

- Vision alignment: the first step is to define the strategy to be followed and to understand whether XR technologies represent an opportunity for the company or not. It's in this step the decision to invest in XR technology is made. In addition, this activity is fundamental because many managers and businesses simply focus on new technology without addressing the big picture, and as a result, they lack a real need and purpose. Therefore, practitioners are frequently confused about how to incorporate improvement strategies and new technology, as well as how to evaluate their cost-effectiveness. [110]

- XR technology selection: the second step concerns the decision of which XR technology to implement. When the decision to adopt XR technologies has been made, it is essential to understand which of them to use. It is a fundamental step to select the correct technology to avoid making mistakes that can both affect the result and waste money and skills.

- Implementation factors: this step is about preparing a plan on how to proceed with implementing the XR technology previously appointed. This phase of business transformation is the implementation phase when firms frequently focus on building a disciplined implementation process. [97]

Regarding the *after* XR implementation activities, two steps are defined:

- Monitoring: during this phase, the implemented technology is monitored. The key is to ensure that what has been implemented matches the expectations that were in place before implementation. Therefore, it is important to verify that they are on track to meet their long-term goals, which requires constant monitoring. [97]

- Reinforcement: in this phase, it is decided to improve the monitored performance. This can be done by improving the current XR technology or by replacing the technology with something that has been developed on the market [116]. Therefore, firms can make use of their assets and capitalize on existing business models. On the other hand, firms can capitalize on innovation opportunities, which can be more innovative and proactive [117].

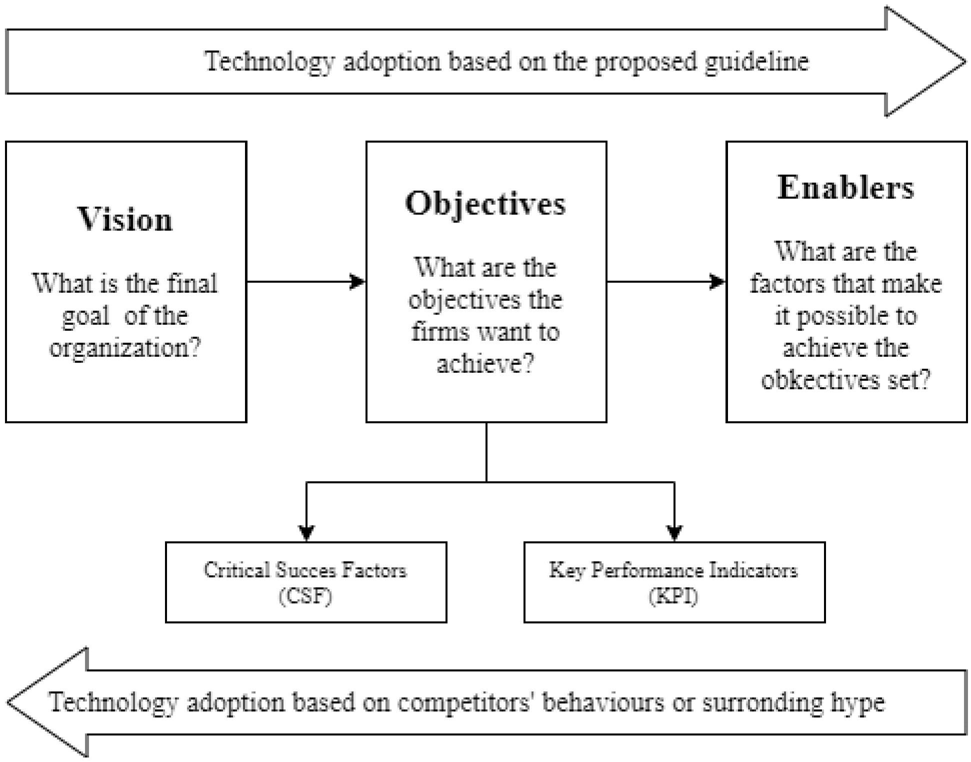
Therefore, the guidelines are structured to address the pre-implementation steps first and then move on to the post-implementation steps, focusing on the factors that must be considered when dealing with XR adoption and implementation in each of the above-mentioned steps.

5.2.2.1. Vision alignment

When it comes to the introduction and adoption of new technology, it is necessary to first analyse whether and how this new technology can become beneficial to the organization. What must be avoided is to implement it without any connection with the actual strategy of the company. Thus, introducing a technology purely because other companies are doing it or based on the hype surrounding the technology at the time. [109], [118]

Therefore the first step to undertake is to analyse the overall company vision. Starting from a well-shared and detailed vision is crucial to allow the alignment of all members of the organisation and to identify the final goal of the firm. [119] The vision is then drilled down into the main objectives the company wants to achieve and that enable the vision to be achieved. The objectives identified are in turn analysed to point out the critical success factors (CSFs) that lead to their achievement, also highlighting a set of key performance indicators (KPIs) that would be used to monitor the company's progress. Finally, based on the objectives it is possible to identify which are the enablers that allow the firm to meet the goals and therefore reach its vision. Come to this point, it is important to underline that there can be several. Indeed, an enabler can be identified as any factor that is crucial for the organization in reaching the objectives set. Therefore, a set of critical competencies or new technology can be considered an enabler whether its acquisition, implementation or development is crucial to achieving the organization's goals.

Figure 5.1. Vision alignment.



As a consequence, by following the proposed path summarized in Figure 5.1, it is possible to avoid introducing XR technologies in an organisation without any alignment with the core strategy. Indeed, XR technologies implementation should only be considered if XR is included among the enabling factors, thus necessary to achieve the set goals and the company's vision. Two main factors must be taken into account when qualifying XR technologies as enablers:

- The benefits related to these technologies and their linkage with the objectives set. Starting from the latter, it is necessary to identify the field of application (i.e., assembly, ergonomics, layout, maintenance or training) to which the objectives refer. After that, it is possible to analyse the benefits that different XR technologies may bring to that particular domain and verify their alignment with the objectives the organisation wants to achieve. Whether objectives and benefits match, then the XR technology can be considered an enabler.

- The alignment between the maturity of the different XR technologies, the time horizon set by the company to achieve the goals and the investment efforts the company is willing to make. Indeed, as presented in Chapter 4, as of 2022, not all XR technologies are ready to be implemented on a large scale in production areas in the short term. Therefore, the organisation must carefully consider whether the planned investments allow for the sufficient development of XR technologies to reach maturity within the timeframe set to achieve the objectives.

It is worth noting how in this first step the technology management and competencies perspectives are embedded in the process that leads to the identification of XR technologies and a set of possible related competencies as enablers.

At the end of this first step, the organization identifies the purpose of adopting XR technologies, relying on the path that makes these technologies beneficial to reaching the objectives set and the vision shared. Other than this, the company highlights the main field or fields in which these technologies will be applied, according to the benefits they may bring and the objectives the firm wants to achieve.

5.2.2.2. XR selection

Given the fields of application, as happens with ergonomics assessment within VCC, more than one XR technology could turn beneficial. Indeed, AR, MR and VR can be applied to the same fields of application or for the same purposes but in different ways, due to their exclusive features. Therefore, a selection process must be undertaken to focus the attention only on the technology that best matches the company's activities and requirements. In this way, it is possible to avoid relying on two or more technologies when they are not all useful, reducing then also the investments needed and the competencies to be handled internally.

The selection process must consider the alignment between the activities the organization wants to carry out in the particular field of application identified and how XR technologies can support these operations according to their exclusive features.

Therefore, first of all, the activities that are going to be performed must be clearly defined, together with their requirements (e.g., the ergonomics assessments need for interacting with a physical mock-up of the car sub-assembly or with a physical tool). Then, the selection of the most suitable XR technology is based on the best match between these requirements and the exclusive features of each technology, summarized in Table 5.2 below and based on the findings of Chapter 4 and the additional insights provided by [94], [120].

Figure 5.2. XR exclusive features.

Exclusive Feature	AR	MR	VR
Awareness of the real world	X	X	
Interaction with real objects	X	X	
Real-time interaction between real and virtual objects		X	
Interaction with virtual objects		X	X
Position user in a fully virtual environment			X

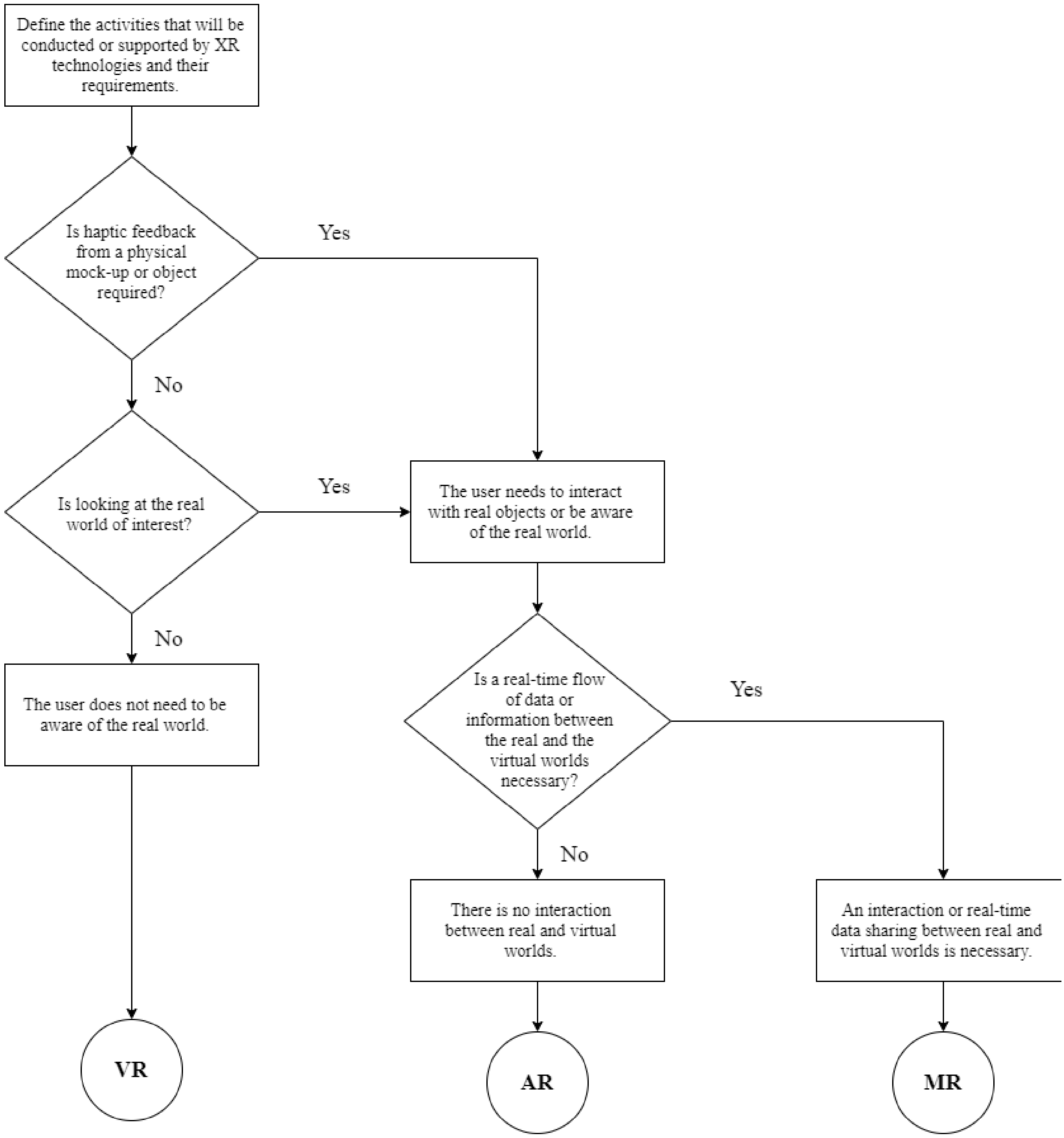
Based on these features it is possible to identify the following two main factors that can be considered to selecting XR technologies:

1. Real-world awareness and interaction. As was previously highlighted in Chapter 4, AR and MR superimpose on the human sight the data and information needed, allowing the operators to have a direct view of the real world. Furthermore, they both allow people to interact with physical objects, handling real tools or car components while wearing the glasses. These are crucial aspects to consider when dealing with activities that need a physical object or mock-up to be analysed, assembled, tested or used. Differently, VR has the peculiarity of totally replacing the real world with a virtual environment where the user can only interact with virtual objects, without any kind of haptic interaction with the real ones. These points are relevant when the organization is dealing with testing or analysing pilot products or processes which do not need a physical mock-up.
2. Real-time data and information flow between the real and virtual worlds. The main difference that can be identified between AR and MR is the interaction between the physical and virtual worlds. AR relies on a static superimposition of virtual objects on human sight which cannot be manipulated or interact with physical objects, and thus it does not result in a flow of data or information between real and virtual worlds. On the contrary, MR allows for real-time interaction between the two environments, enabling virtual manipulation. These factors must be considered when the organization aims at creating a direct linkage between what the operator is looking at and the data or information related to the process or product under analysis.

These two criteria can be shaped into a set of questions that the organization must answer following a cascade approach. The aim is to identify the most suitable XR technology according to the activities that the firm is going to perform in the identified field of application. Therefore, the technology perspective is the most important to consider in this step.

The process to be followed is exhibited in Figure 5.3.

Figure 5.3. XR decision tree.



5.2.2.3. Implementation factors

Once identified the XR technology is compliant with the objectives set and the activities to be carried out or supported, it is crucial to define a plan for its implementation. Nevertheless, due to the different fields of applications presented and the variety of activities that can be performed, defining a precise implementation plan that can fit all the different scenarios could turn out to be valuable. Indeed, a well detailed and structured plan could work in only a specific set of circumstances, while being inapplicable in others. Therefore, the aim is to focus the attention on the factors that must be considered when practically applying the selected XR technology, rather than to present a step-by-step implementation plan. The aim is to focus the attention on the factors that should drive the decisions regarding the selected XR technology adoption.

These factors are based on the main findings presented in Chapter 4. Accordingly, car manufacturers are facing several challenges when dealing with XR technologies in their daily activities. Most of them could be overcome by analysing more in detail their root causes. Almost all technology-related challenges are the result of a poor choice of the hardware or software used. Furthermore, the skills-related challenges refer to a lack of competencies and capabilities, while the integration-related ones highlight the need for the right organisational structure when dealing with the adoption of XR technologies. These three main classes of challenges are strictly related to the three perspectives analysed: technology management, competencies and capabilities and company structure. Therefore, the factors to be considered are grouped according to these three perspectives.

Starting from the technological perspective, the challenges highlighted posed the attention to the right selection of hardware and software, which relies on different factors:

- Hardware. The decision regarding the hardware mainly refers to the characteristics of the different devices available in the market. According to the different XR technologies selected and their usage, it is necessary to consider these set of factors when making a decision:
    - Ergonomics. The device is supposed to be used frequently to support the daily activities of the organisation. Therefore, the ergonomics aspect is of paramount importance. What must be considered in this case is the weight of the device and its distribution. Considering regular use, the device should be as light as possible and its weight should be distributed in such a way it does not stress the operator's neck or general posture.
    - Field of view. The device is supposed to bring the operator into an immersive environment where the real and virtual worlds coexist or in full virtual reality. To let the operator experience these feelings, the field of view plays a fundamental role. Relying on a too narrow field of view could limit the operator's perception and the amount of information that can be displayed. Therefore, the decision on the different devices must consider this factor to approximate the human field of view of 114 degrees [24].
    - Representation quality. According to the field in which the XR technology is applied, the quality of what is displayed could be a crucial aspect to evaluate, as in the case of assembly operations support. Therefore, the display resolution and the maximum frame-per-second are factors to be considered.

- o Additional factors. According to the different fields of application, several additional factors should be considered. Using AR or MR for supporting assembly operations for example requires a battery life that can easily cover the entire production shift. Moreover, performing some activities with AR could require the operator to take screenshots or videos of what he or she is looking at in such a way both the real and virtual worlds can be easily detected.

All these factors should be considered when making a benchmark analysis between different devices, to select the most suitable for the activities to be carried on or supported.

- Software. The decision regarding the software is of paramount importance to assure the right interface between the desktop-based simulation model and their transposition in the real or virtual worlds. As pointed out in Chapter 4, several software is available today in the market according to the XR technologies deployed. The factors to consider are:
  - o The compatibility with the simulation software used could narrow the range of available XR software.
  - o The XR software peculiarities. The findings of Chapter 4 highlighted that some software is most suitable when dealing with different kinds of XR and operations. Indeed, regarding VR, Unreal Engine is the one that best fits when dealing with robots and machine simulation, while Steam with human tasks. In addition, 3D Unity can be considered a general-use software that can fit with all the operations and the XR technologies. Nevertheless, in some cases, the operations to be carried out could require some particular software features, which can lead the organization to build the software internally, such as VD in VCC.
  - o The number of licenses needed can affect the total costs to be met by the firm. According to the different software providers, the licenses allow the organisations to give access to the software to a higher number of people or to perform particular kinds of analyses.

Therefore, whether the company is highly relying on XR technologies in different fields and for different activities, the number of licenses needed could be significant, and thus the total costs to keep all the licenses updated. This aspect should lead the organization to evaluate possible trade-offs also considering the financial perspective.

The second perspective analysed is the one related to the impact of Industry 4.0-related technologies on the company's competencies and capabilities. As XR represent a cutting-edge technology in the field of Industry 4.0, organizations must carefully consider the competencies needed when implementing these technologies on the full scale. Resuming the notion of competencies as a cluster of related knowledge, skills, and attitudes that correspond with work performance [115], four kinds of competencies may be recognized in the context of Industry 4.0, as outlined by [121]:

- Technical competencies, which mainly refer to knowledge of the technology adopted.
- Methodological competencies, which include problem-solving skills and abilities such as conflict resolution, creativity, and decision-making.
- Personal competencies, which include personal beliefs, motivations, and attitudes. Flexibility, drive to learn, and the capacity to operate under pressure are among them.
- Interpersonal competencies, which represent social skills and abilities to connect and collaborate with others, such as networking skills, leadership skills, and teamwork ability.

Therefore, the organization must focus on developing a new job profile with a reasonably high degree of autonomy and intermediate horizontal specialisation, integrating technical and non-technical competencies. Indeed, the essential feature of XR technologies is that they rely on interdisciplinary competencies [104], which are often more difficult to acquire and develop [96]. Moreover, this process of developing a new set of competencies might be a never-ending one. As a result, the organization should never underestimate the time and difficulty involved in building and gaining such capabilities. [107]

Based on these considerations, the competencies to be developed and its development process are among the crucial factors the organisation must consider when introducing new XR technologies. In particular, the organisation should first focus on the development of technical competencies to deal with the new XR devices and software. [101] Then, the need to develop methodological, personal and interpersonal competencies will arise soon. In this case, considering the peculiarities of XR technologies, among the methodological ones knowledge and project management are the most crucial to acquire, together with decision-making and abstraction abilities. Then, personal competencies should be considered, focusing on developing an open mindset and the ability to knowledge sharing within the organisation. [103] This turns beneficial to facilitating technology acceptance and the fostering of new competencies. [122] Finally, interpersonal competencies are necessary to reach the required level of horizontal specialisation. In this sense, communication skills, together with collaboration and teamwork competencies must be considered.

The last perspective analyse is how the introduction of an XR technology can impact the organizational structure and how it can be improved to allow a successful implementation of the immersive technology. In particular, some unique organisational structures, such as the matrix structure, can be recognised as a facilitator of Industry 4.0-

related technologies [107], [123]. Two major factors should be considered to better understand which characteristics allow for the seamless adoption of XR technologies:

- Number of hierarchical levels or vertical span, defined as the number of job positions in the chain of command, from the CEO to the employees working on output. [107]
- Span of control, defined as an indicator of the boundaries of a single manager's hierarchical authority has an impact on the closeness of contact between superiors and subordinates and has a direct impact on unit size – that is, the number of positions grouped in a single organisational unit. [107]

These two variables allow for the definition of the configuration (i.e. the form and role structure of the organisation) as well as the evaluation of the flatness of the organisational structure. Fewer hierarchical levels and a broader span of control are indicators of a flat organisation, which is recommended as an ideal structure to supplement the implementation of Industry 4.0 technologies, and hence XR [124]. Workers in this structure are expected to react to both functional and departmental obligations, and business units are tightly linked. This structure differs from the functional organisation that was extensively used in the past, in which the organisational chart was distinguished by multiple layers between the key positions and the employees, and all business units were distinct and autonomous [107]. Therefore, this flat organisational structure should be considered since it enables faster deployment of XR technologies, improving new technology acceptance, knowledge-sharing, and hence the development of multidisciplinary capabilities [102].

5.2.2.4. Monitoring

Following the implementation process of the selected XR technology, monitoring its usage and thus the alignment with the initial implementation expectations is another crucial aspect to consider. To do so, the organisation should create a monitoring system to assess the progress, which involves the identification and installation of metrics [97]. The aim is to ensure that the firm is on track toward long-term objectives and assess the goodness of XR implementation.

Based on the three perspectives analysed, the assessment of the company's progress mainly focuses on the field of technology and competencies. In particular, the alignment between the XR technology expectations and the actual benefits it brought should be analysed, together with the competencies acquired or developed. Furthermore, what must be highlighted is also that these two perspectives are strictly entangled and they constantly affect each other. Indeed, a lack of competencies could prevent the right exploitation of the selected XR technology, as well as a poor choice of XR devices or software could require the development or acquisition of new competence, not initially planned. Therefore, these two perspectives must be analysed, without forgetting their mutual relationship.

The first aspect to consider is the goodness of the XR technology implementation, which could be assessed by comparing the actual benefits it brought with the initial expectations. To do so, a possible suggestion is to base the assessment on the KPIs initially identified and linked to the company's objectives. Thus, it is possible to keep the XR implementation aligned with the vision of the organisation. [99] However, the usage of KPIs to monitor technology performances is not without difficulties [125]. In particular, the main factors to consider are:

- The number of KPIs. Selecting too few indicators may result in essential aspects being neglected. Choosing too many indicators, on the other hand, has the problem of diverting focus away from the aspects that genuinely affect the technology's performance while incurring additional expenditures owing to unnecessary data collecting. [125]
- The linkage between the KPIs and the benefits the XR technology may bring, could be indirect and not easily quantifiable. Therefore, the attention must be focused on the only KPIs that have a causal relationship with the technology performance. This could require monitoring only a set of the initial KPIs or drilling them down into sub-KPIs more specific and linked to the technology results by a causality principle.

The second perspective to consider is the process of competencies development and acquisition. To stay up with the above-mentioned XR introduction, the car manufacturer must guarantee that workers' knowledge management procedures are well-supported to fully exploit the potential of the XR adopted and thus reach the objectives set [126], [127]. Considering the context of Industry 4.0, the importance of knowledge management in manufacturing contexts has changed (Hannola et al., 2018; Hoffmann et al., 2019; Wood & Bischoff, 2020). In particular, the attention to the implementation of a competence assessment was raised. Therefore, a possible suggestion is to use skills matrices to highlight the abilities and knowledge required by XR users based on XR technology requirements and the organization's particular demands. This tool serves as a screening method to determine whether the company, as individuals and collectively, has the necessary competencies to achieve the shared vision. Skills matrices do not have to be complex forms or documents, but they should distinguish between the important skill sets now recorded by XR users and those that are lacking [130], [131].

Furthermore, based on the results of the matrices, the organisation should plan training programmes aimed at filling the gaps that have emerged. Indeed, Industry 4.0 requires that organisations implement systematic training at all organisational levels. This entails developing and strengthening people's competencies through ongoing training and professional development, with a focus on handling new technology. [132]

Finally, based on these considerations, to support competence management, competencies can be grouped into three different categories, as proposed by [107]:

- Present: the organisation has already achieved this necessary skill; as a result, it does not lack a certain talent or expertise.
- Training: the organisation has put in place measures to train its personnel and allow them to acquire all or some of the abilities associated with a given group.
- Required: the organisation recognises a shortage of a certain set of competencies, but no attempts have been made to build them.

This would allow the organisation to keep track of the ongoing training programs and the competencies that need to be developed further.

5.2.2.5. Reinforcement

In the context of Industry 4.0, the firm should focus on a combination of inner and outer monitoring of the XR implementation results. The objective is to identify possible internal areas of improvement to uncover the untapped potential of the immersive technology adopted and evaluate how these improvements can be achieved. In particular, the firm must be certain that its assets are being used and capitalised by its objectives. At the same time, the organization must analyse and consider externally developed innovation opportunities that may be more innovative and proactive than the current XR technology being used [116]. Therefore, the last set of guidelines regards the reinforcement phase, in which the organisation should execute significant improvements for the XR technology implementation to last and grow [97], [133].

To do so in a dynamic environment like Industry 4.0, the recommendation mainly refers to the company organization. In particular, the suggestion is to embrace an ambidextrous structure, which will allow the company to be efficient in exploiting present assets, both technologies and competencies, while also being adaptable to future possibilities, and exploring new technologies available in the market [132]. The notion of ambidexterity, in particular, is that the demands on an organisation in its task environment are constantly, to some extent, in conflict (e.g., investments in the present and/or future technologies), hence trade-offs must always be made. Although these trade-offs may never be eliminated, the most successful firms manage to reconcile them to a great extent, enhancing their long-term competitiveness [134]. Therefore, ambidexterity gives the company the flexibility to adapt and evolve in the usage of the XR technology selected, as well as to maintain a competitive edge through organisational innovation in the context of a dynamic industry, such as the automotive one [135]. This last aspect is critical since the ability to innovate is not just a success factor, but also a must in business. It provides major competitive advantages while avoiding market suffocation [136]. Furthermore, [105], [137], [138] emphasise the proposed evaluation for organisational ambidexterity as a systematic method that contributes to dealing with ensuing difficulties with the following benefits:

- Sensitivity to weak signals, fast reaction to changes, and adaptability to new situations.
- Time savings as a result of quicker and more flexible development and execution procedures.
- Improved target achievement through increased staff motivation and team spirit.
- Strike a balance between assets capitalization and new potential for innovation.

5.2.3. Final considerations

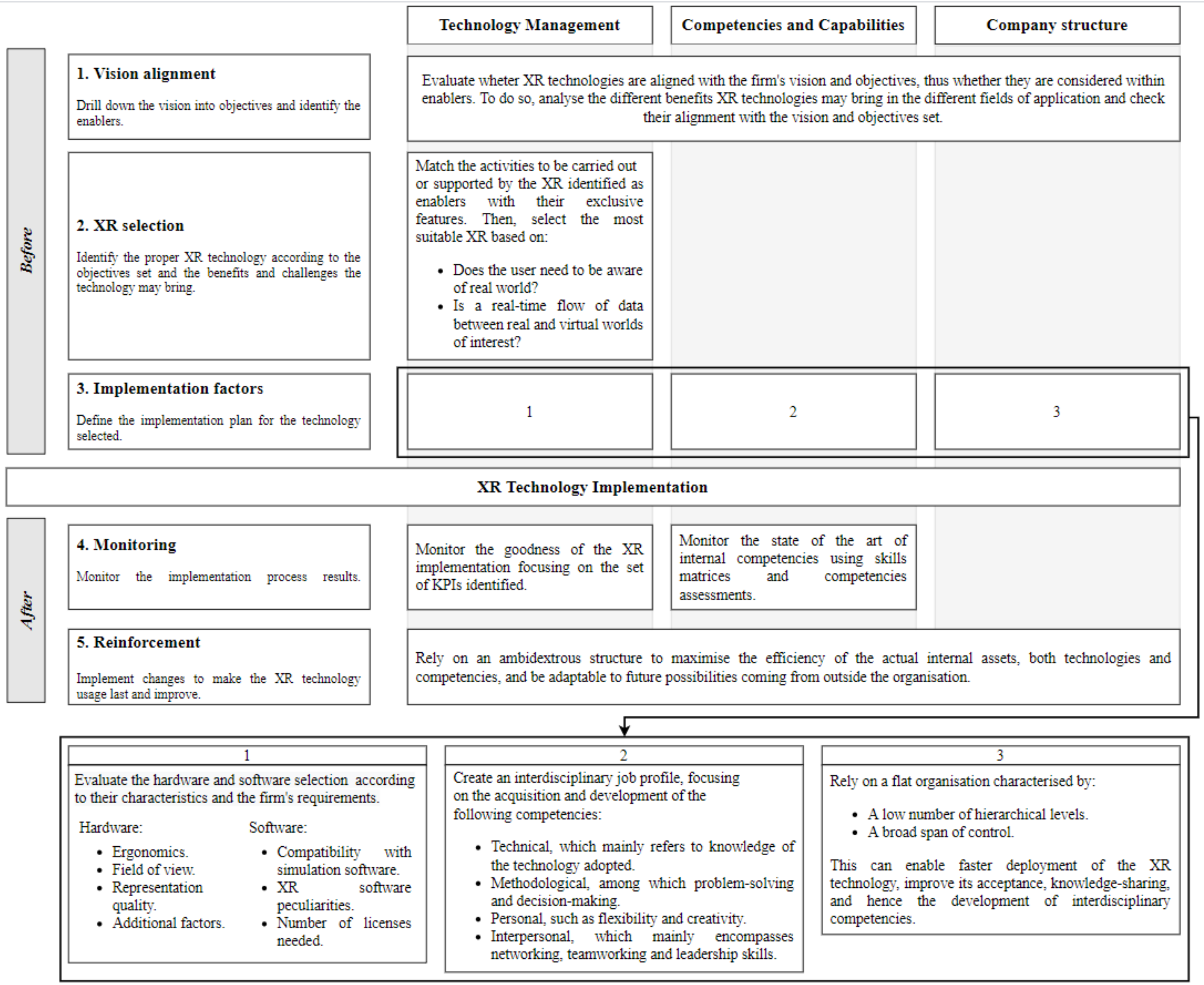
In conclusion, this set of guidelines aims to map out a path for companies and give a hint on how a company can tackle the complex decision-making moment regarding XR technologies. In addition, Figure 5.4 summarises the major findings, exhibiting the relationships between the different guidelines for each step and the three different perspectives.

Furthermore, this set of guidelines is suitable for those applications where there is already a sufficient level of maturity. As mentioned in chapter 4, not all fields of application XR technologies are already extensively used. Thus, it is not suitable to apply guidelines regarding applications for which it is already known that XR technologies cannot bring the results outlined by the vision in the time horizon set by the firm.

In addition to all the aspects already mentioned, it is important to mention the cyclic and iterative nature of this series of steps. The five-step series should be viewed not as a one-time thing. When it comes to step number 5, and the possibilities for improvement through internal or external factors are identified, it is important to close the loop and move back to step number 1. In fact, after having determined possible improvements, it is important to assess the alignment with the business strategy and only then begin a further evaluation by moving to the next steps.

Lastly, the actual quality and real utility of these five guidelines will be examined in the next chapter. Indeed, the guidelines will be tested in a real case run at VCC and the consequent results are presented in chapter

Figure 5.4. Guidelines overview.



6 The VCC case

This chapter aims to provide a real and tangible application of the theoretical guidelines that were proposed in the previous chapter. The set of guidelines proposed, which consists of five steps, will be mapped against the case of VCC, with an extensive description of what the implementation would imply. Therefore, It is also important to provide a scenario of VCC and the particular business unit where the specific case is set to operate.

6.1. Company overview

VCC is the largest Swedish car manufacturer in the world and was founded in 1927 in the city of Gothenburg. The brand's main strengths are safety and Swedish manufacturing excellence. As VCC had been at the forefront of safety engineering, its c s have long been marketed as products that prioritize safety in their design and manufacturing and the company has emphasised their historic reputation for strength and reliability. Regarding the products, SUVs, station wagons and sedans are the main vehicles VCC produces today. [139]

From 1927 to 1999 VCC was part of the conglomerate that owned all of Volvo's businesses (i.e., Volvo Trucks, Volvo CE, Volvo Penta etc.) and its focus was primarily on the European and US markets. [139] In 1999 Volvo Cars was bought by Ford Motor Company, which was looking to expand its range of vehicles [140]. However, this operation was not fruitful, and Ford was not able to turn the company into a profitable operation and instead encountered many losses and large economic downturns [141].

Due to Ford Motor Company's financial problems, VCC was put up for sale and acquired in 2010 by the Chinese company Geely Automobile, the seventh-largest car manufacturer in China [142]. This acquisition has been successful and only a few years later VCC opened its first complete plants in both China and the US [139]. The increased collaboration allowed current stakeholders and possible new investors in VCC and Geely Automobile to assess the value of their distinct independent strategy, performance, financial exposure, and returns. The partnership focused specifically on the development and sourcing of next-generation technologies, ranging from connection and autonomous driving to car-sharing and electrification. [143] Furthermore, they intend to share and source batteries, electric motors, and networking solutions shortly. [144]

As of now, VCC is a global company with more than 40.000 employees and has active facilities presence in the Americas (US), EMEA (Sweden, Denmark and Belgium), and the Asia Pacific region (China, India and Malaysia). In addition to this, VCC has an active selling activity in more than 100 countries all over the world [139]. In 2021, VCC sold 689.000 vehicles, reaching an overall revenue of 282 billion SEK (30 billion dollars), the highest revenue of all time [145]. The demand for the company's cars remained strong with growing unit sales, despite persistent component supply shortages in the automotive industry.

6.1.1. Department overview

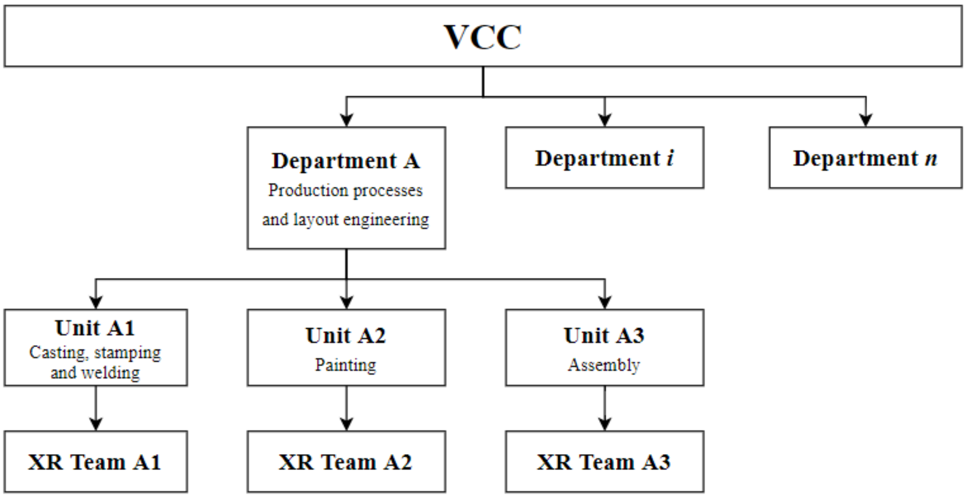
The guidelines prepared in the previous chapter will be tested in Department A of VCC. This department is in charge of the production processes and layout engineering. Furthermore, it ensures process-oriented product development with a focus on new process engineering solutions. Therefore, Department A is the connection link between the product development departments and the shop floor. The main activities relate to defining the processes to produce the vehicles and ensuring that all activities are carried out in the correct way and order. Furthermore, based on the activities to be performed, production layouts are designed to maximise efficiency and people's safety.

Department A is the main area under which there are several sub-units, as shown below in Figure 6.1. The mentioned sub-units are:

- Unit A1, which focuses on producing all parts that compose the geometry and body of the cars (e.g., casting, stamping and welding).
- Unit A2, which is dedicated to the painting process.
- Unit A3, which focuses on the manual and automatic assembly process of all parts to make the car.

Each of this sub-unit is already equipped with an XR team in charge of XR simulation regarding the three different macro-areas of production.

Figure 6.1. VCC department A structure.



As of 2022, Department A has a vertical structure, based on silos. Therefore, the three XR teams do not communicate with each other and are not updated on what others are doing with XR. Nevertheless, all of them are sharing the same objectives Department A is pursuing, and some of them are using the same hardware. For the sake of future comprehension, Table 6.1 below summarizes the main hardware and software the three Units are using.

Table 6.1. VCC hardware and software.

Unit	XR Technology	Hardware	Software
A1	VR	HTC Vive Pro	Unreal Engine
A2	AR	HoloLens 1	VD Software
		HoloLens 2	
A3	AR	HoloLens 1	VD Software
	VR	HTC Vive Pro 2	Steam

6.2. How to implement XR technologies within VCC

Within Department A, Unit A3 will be facing the expiry of its XR technology licenses shortly and therefore needs to decide which XR technologies to focus on. For this reason, this event could be a unique opportunity for Department A to restructure and review the way it adopts and uses XR technologies. Therefore, the attention is focused on how to successfully implement XR technologies within Department A, providing valuable suggestions on how to fully exploit the potential of these technologies in all three Units.

Thanks to the interviews and the cases performed in chapter 4, it has been possible to notice that the different Units within Department A have been facing several challenges in successfully utilising the XR technologies. Therefore, appropriate use of the guidelines could be useful to help Department A to understand the needs and issues to be addressed. The challenges are those that have been clustered earlier in chapter 4 in the five different areas: funding, integration, selection, skills and technology.

In the next paragraphs, the following 5 steps are analysed one by one:

1. Vision alignment.
2. XR selection.
3. Implementation factors.
4. Monitoring.
5. Reinforcement.

6.2.1. Vision alignment

The first step to be undertaken concerns the analysis of the firm's vision, to evaluate if the renewal of XR technologies usage within Unit A3 is aligned with the objectives that VCC wants to achieve and whether they can turn beneficial for all the threats.

As of 2022, striving for sustainable development is the primary goal of VCC. According to the United Nations, sustainable development is defined as *development that satisfies the requirements of the present without preventing future generations' ability to satisfy their own needs* [146]. Therefore, it requires coordinated efforts to create an inclusive, sustainable, and resilient future for people and the world. To achieve sustainable development, three key factors must be balanced: economic growth, social inclusion, and environmental conservation. These factors are all interrelated, and they are all important for the well-being of individuals and societies.

Based on these considerations, the overall vision of VCC can be better articulated and thus understood, following the triple bottom line (3BL) framework [147], which considers social equity, economic, and environmental factors as the three business focuses.

- The social equity bottom line. VCC aims to be a leader in ethical and responsible business, which implies having a strong corporate culture that focuses on ethics and leadership, as well as equal opportunities and decent working conditions for all. In particular, a culture where people feel comfortable raising their concerns and freely speaking their minds about ethical issues or cases of noncompliance, without fear of retaliation, is a key part of VCC's commitment to ethical and responsible business. Furthermore, the Swedish firm is working hard for the safety and wellbeing of its people, including proactively identifying and mitigating risks, improving our work environment, providing training facilities and raising awareness.

- The economic bottom line. VCC strives to be one of the fastest-growing luxury automobile brands in the world, acquiring market share in all areas. The financial target is to generate an operating income margin of 8–10% by mid-decade. Synergies through collaboration with Geely, commercial transformations, sustained expansion, and income from connected firms are expected to offset the expected costs related to the transition to complete electrification. Furthermore, future models will be built on new vehicle designs suited for electrification, and VCC will invest in the in-house design, development, and manufacture of electric motors, batteries, and related software. The electrification strategy is centred on vertical integration in key sectors, to achieve synergies, cost savings, and efficiency across the business.
- The environmental bottom line. VCC aspires to be a carbon-neutral firm by 2040 by reducing emissions from its tailpipe, supplier chain, and operations. Furthermore, the company sees the circular economy as a way to decouple its growth from its environmental effect. VCC is particularly interested in how it may achieve circularity for goods, components, and materials, as well as building procedures that go beyond making circular efforts in a linear economy to transitioning into a circular business model [139].

This general vision is drilled down into sub-visions according to the different business units. The social and economic aspects of the 3BL are the main ones considered in the Future Vision 2025 (FV25) plan, which represents the vision for Department A, to be reached by the end of 2025. Starting from social equity, the aim is to design risk- and accident-free production layouts and processes, ensuring the operators' well-being and safety. Furthermore, from the economic perspective, the firm is striving for high adaptability and flexibility of production plants to meet the upcoming electrification and the related unpredictable and unstable demand. Moreover, the processes' efficiency is also considered, with reduced investments and the occurring costs due to late changes in production.

Based on the FV25, it is possible to identify two main objectives that Department A wants to achieve by 2025.

- Improve production efficiency and flexibility, to increase the production rate, reduce the number of defective products and be more reactive to future changes. According to the head of Department A, the achievement of these objectives passes through to the following CSFs:

  - Improve layout and operations design processes, shortening the development time and reducing the related costs. The aim is to improve the efficiency of the processes by highlighting as early as possible future problems that may arise in the production plant and that could result in high costs due to late changes. Moreover, the focus is also to arise the firm flexibility to the future introduction of new car models, reducing the time and costs needed to adapt the current plants and processes to the new requirements.
  - Virtualisation of car launches, which includes both the vehicle and the production process. The attention is focused on virtually visualising, verifying, predicting and optimising current and future manufacturing scenarios in all the VCC plants. This implies all the installations should be ready and 100% virtually validated before the tool trial, namely the prototype series is released in the plant. In this way, a virtual preparation and verification of the complete manufacturing system will allow a faster ramp-up and largely reduce the non-value-added time during physical installation and commissioning, also arising the adaptability and flexibility to future changes.
- Create the best conditions for operators, ensuring their safety and well-being within the plant. The focus is the creation of risk- and accident-free production plants. As before, the fulfilment of these objectives depends on the following CSF:
  - Better ergonomics of the operations require every procedure to be assessed and tested to avoid overlooking any ergonomic issue that could affect the operator’s posture or movements and result in a disabling health condition for him or her. This implies also seeking for avoiding any hazardous situations for the operators.

What must be further highlighted is how these two main objectives are strictly entangled and mutually affect each other. As an example, the first objective allows the firm to identify earlier possible future issues, among which the safety and ergonomics problems. On the contrary, seeking the best conditions for the operators requires higher flexibility to future late changes and could length the design processes.

Furthermore, these two objectives must be addressed by all three units. Therefore, the improvement of production efficiency and flexibility and the best conditions for operators must be reached in all the three macro-areas of production processes (i.e., casting, stamping and welding, painting and assembly).

Then, based on these two main objectives VCC has set for Department A by 2025, it is possible to analyse whether XR technologies could be considered crucial to reaching the final goals, and thus be identified as enablers. Examining the above-mentioned objectives, they mainly refer to two fields of application in which XR technologies proved to turn beneficial: layout and ergonomics, respectively. Table 6.2 below exhibits the main connections between the presented objective, the CSFs and the results coming from chapter 4.

Table 6.2. Objectives, CFSs and results.

Objective	CSF	Field of application	XR Technology	XR Benefit
Improve production efficiency and flexibility	Improve layout and operations design processes	Layout	AR	- Increased layout design and analysis process efficiency (e.g., lower time, costs and effort). - Time and costs are saved thanks to early problem detection and simplified mock-ups.
	Virtualisation of car launches		VR	- Increased layout design and analysis process efficiency (e.g., lower time, costs and effort). - Time and costs are saved thanks to early problem detection and no need for mock-ups.
Create the best conditions for operators	Better ergonomics of the operations	Ergonomics	AR	- Evaluate first-hand possible ergonomics issues, otherwise overlooked by desktop-based simulations. - Collaborative environment for problem discussion and solutions brainstorming.
			VR	- Evaluate first-hand possible ergonomics issues, otherwise overlooked by desktop-based simulations. - Interactive and immersive environment for problem discussion and solutions brainstorming.

As already explained in chapter 5, the link between XR technologies and company vision is fundamental. If XR technologies are not recognized as enablers to achieving the vision, it makes no sense for the company to implement them. This is because the XR technologies do not help to any extent the company to achieve its vision. Oppositely, in this case, it has been proven that the adoption of XR technologies can benefit the achievement of the vision and therefore adoption is highly recommended.

As can be seen in Table 6.2, AR and VR may bring tangible benefits to allow Department A to reach the established objectives. Furthermore, the maturity of these technologies in the identified domain is proved to be sufficient to let Department A achieve the overall targets by 2025, and thus be aligned with the FV25.

In particular, both technologies can improve product design efficiency and flexibility, shortening the time and costs needed to visualize any problems earlier, without the need for a detailed physical mock-up. Moreover, AR and VR can both allow the first-hand testing of the layout and operations, pointing out any safety- or ergonomics-related issues overlooked by desktop-based simulations. Therefore, the renewal of XR licences for Unit A3 is highly recommended.

The next step is to choose which technology between AR and VR is more beneficial to support the different activities that the three units are focused on. Therefore, in the next sections, the set of proposed guidelines is analysed to provide valuable suggestions on how Department A can be restructured according to the results of step 1.

6.2.2. XR selection

The second step of the guidelines concerns the selection of the XR technology that will be adopted. Several XR technologies can be used in the same field of application. However, this step is meant to be a guide to choosing the best XR technology to limit the investment, capital expenditure and internal capabilities required. As already mentioned in Chapter 5, some unique features may characterise a particular technology. Thus, technology may be more adaptable to certain tasks and aligned with the requirements that the tasks demand. Therefore, the best technology to carry out the activities required by the objectives defined in step 1 must be identified.

In this context, two main objectives belonging to two different fields of application were identified. Therefore, in this paragraph, the best XR technologies to be adopted in both situations will be highlighted. The situation inherited from the previous step is as follows:

- Improvement of production efficiency within the layout field of application.
- Create the best conditions for operators within the ergonomics field of application.

To decide which XR technology is better to be used for each of the goals to be reached, the diagram illustrated in Figure 5.3 in chapter 5 is considered. The following two objectives will be analysed separately:

- Improvement of production efficiency.
- Create the best conditions for operators

In both cases, an example of the actual activities that are being performed in the three units is presented.

6.2.2.1. Improvement of production efficiency

Starting with the first objective, the first important action to be carried out is to well define the tasks that Department A has to perform. According to step 1, the two CSFs imply that department A can visualise the production layout in such a way that it is easier to evaluate current and future production processes. Furthermore, the main purpose is to have the possibility to quickly introduce virtual changes to solve any problems recognised during the simulation. This would make the company both more efficient and flexible to changes and much more responsive in being able to introduce new solutions. This would then give the ability to modify the layout to adapt it to new demands. VCC, therefore, needs the ability to perform simulation tasks by evaluating the current proposed production layout and being able to make major changes quickly. These kinds of simulation activities are mainly performed by units A1 and A2.

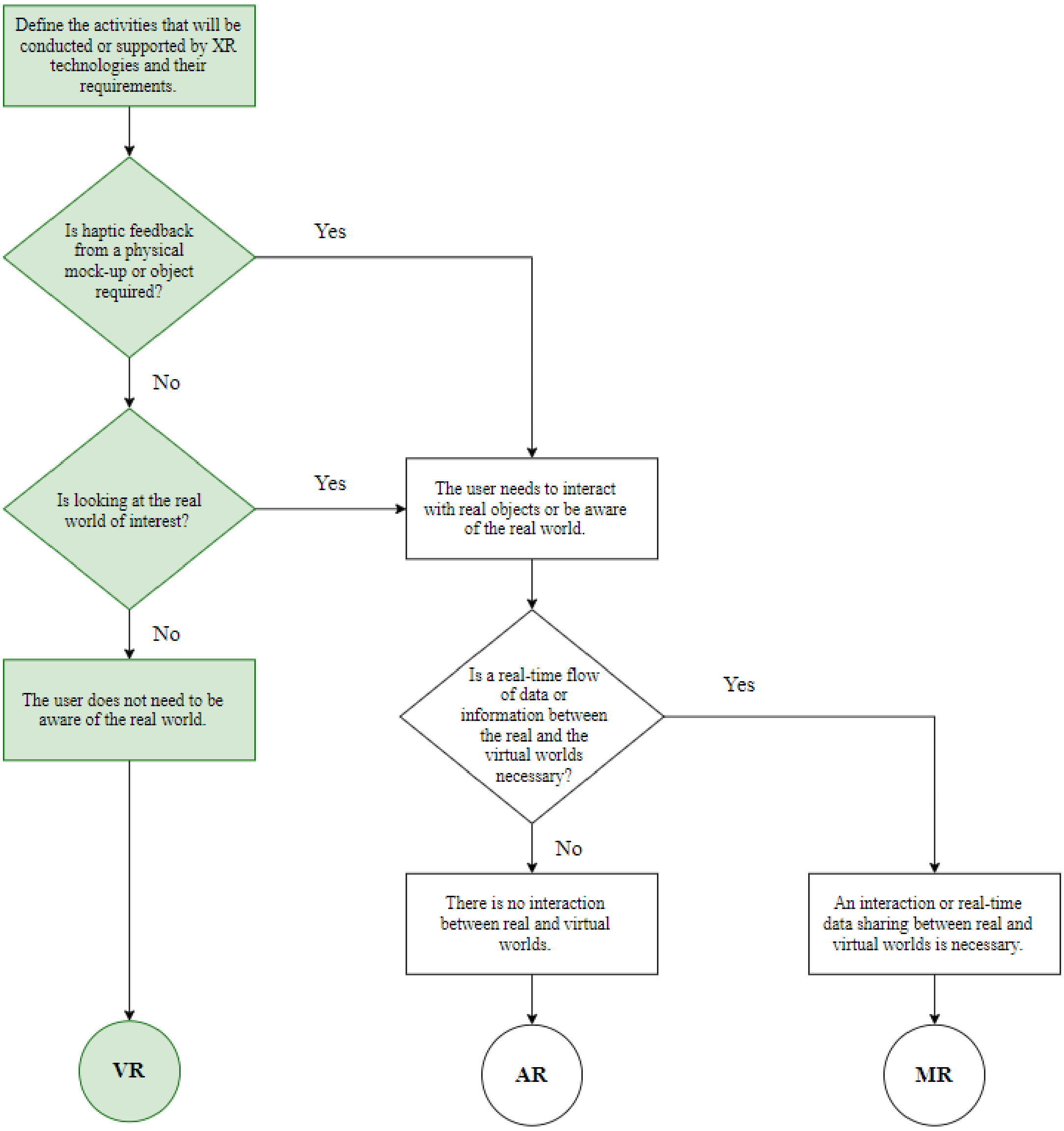
Having realised that these will be the tasks the company will have to perform, it is now important to determine which technology is the most suitable. Therefore, the second action to be carried out is to understand whether it is important to receive haptic feedback from a hypothetical mock-up or an object when performing the simulations of the production process layout. In this case, the most important aspect to consider is that the technology must be useful both for the improvement of existing layouts and for layouts that are still under development. Consequently, the construction of a mock-up is not necessary, as it is also a useless activity when the aim is to observe and not receive physical feedback from the real world. In addition, creating a physical mock-up for each variation to the layout could be very time-consuming. When carrying out layout tests, it is very likely machinery workstations will be modified, creating a different mock-up each time the layout is modified would be pointless. The same considerations apply to the use of real tools during the simulation. This is not necessary as no physical tests are done but a virtual simulation using virtual tools is sufficient for the purpose. It is easy to virtually understand whether a particular tool might, for example, have problems with space obstruction.

After realising that real-world haptic feedback is not something useful for these tasks, the third action to take must be to determine whether it is important to have a view of the real world or not. For these tasks, visibility of the real world is not important. On the contrary, it is important to have a complete and clear view of the layout simulation of the production process. Consequently, being able to see the real world is not an added value for the tasks that need to be performed.

Therefore, after having followed the diagram, it´s possible to realize that the best XR technology that should be implemented for improving the production efficiency within the layout field of application is VR technology.

In Figure 6.2 below, the logical process followed has been briefly summarised. The selection process is highlighted in green.

Figure 6.2. XR logical selection process for Layout.



6.2.2.2. Create the best conditions for operators

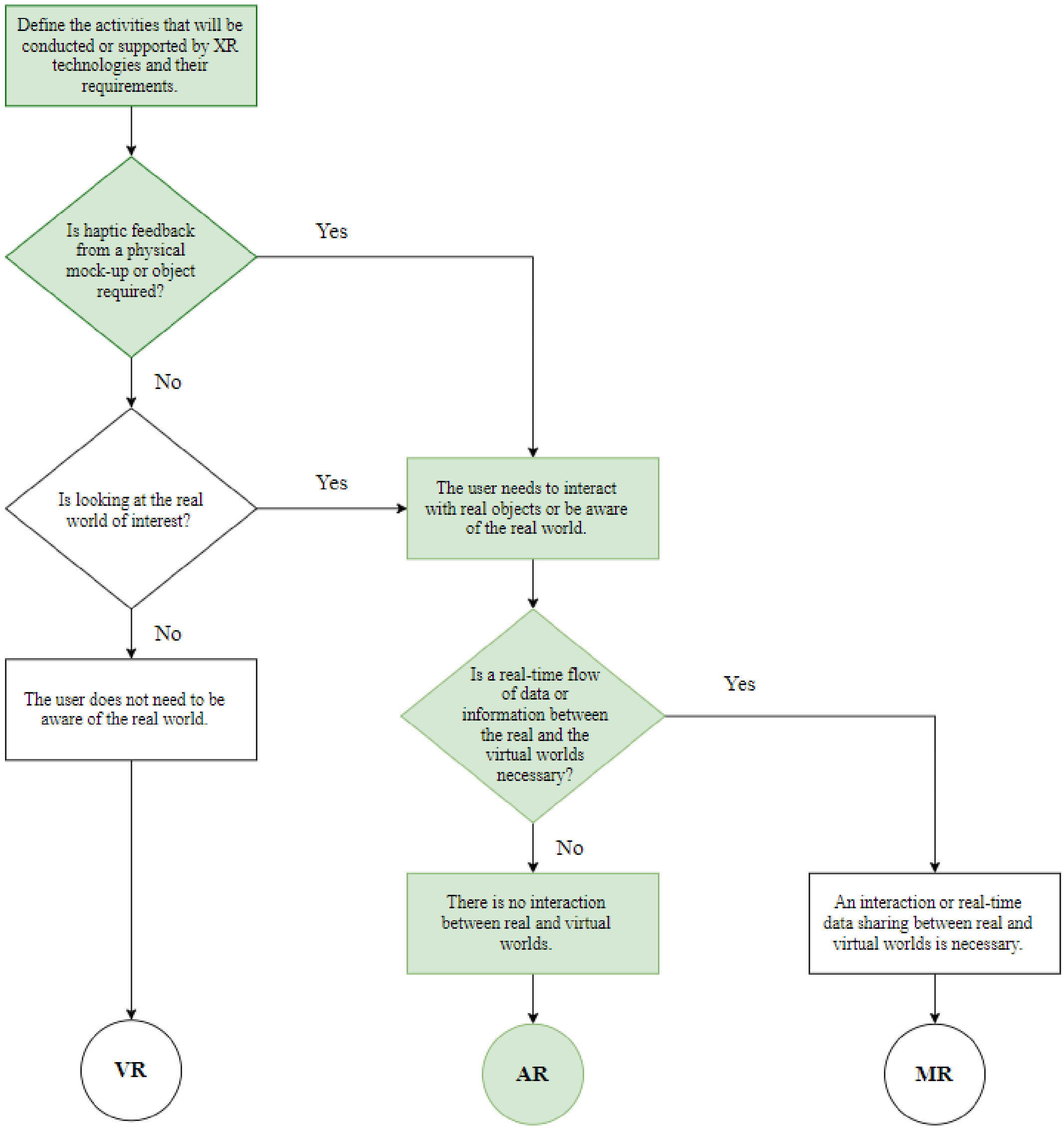
As with the first objective, the first action for the second objective is to determine what the company has to do to create the best conditions for operators. In particular, the objective has been divided into two different CSFs and the objective´s fulfilment depends on the achievement of both the two CSFs. The main task is to simulate operators' actions and solve potential problems related to ergonomics. Consequently, the task involves trying out the operation for oneself and assessing whether any problems could lead to the operator having physical problems. The operator's actions to be tested are part of production processes regarding future vehicles which will be produced in the following 2 years. Therefore, these production processes are being developed to be ergonomically risk-free at the release of vehicles. These kinds of simulation activities are mainly performed by Unit A3.

After having defined the task that VCC must be able to carry to reach its CSFs and therefore its objective, it´s important to establish if receiving haptic feedback from a physical mock-up or tool is necessary or not. Since the task requires simulating a real operator activity to evaluate the physical consequences on the body, it is of utmost importance to get feedback from real objects, either tools or vehicle parts. For example, when testing a specific working position with a determined tool, it is fundamental to carry out the simulation using the real tool and so understand how the tool and that specific working position influence the body of the operator. As a consequence, it can be said that the user needs to interact with real objects and be aware of the real world.

The next phase regards the importance of having real-time data flow between the real and the virtual worlds. In this regard, when simulating an operator's action to assess ergonomics, it is not necessary to have a real-time data exchange between the real and virtual worlds. This could be more useful for example when carrying out activities for the field of application of training or assembly. Consequently, real-time data sharing is not a factor to be considered in this case.

Finally, the best technology that meets the above-mentioned characteristics is AR. This technology gives the best option when dealing with the ergonomic field of application as having direct contact with the real world is important to have acceptable body and force simulations. Figure 6.3 summarises the logic flow to get AR as the chosen technology. The selection process is highlighted in green.

Figure 6.3. XR logical selection process for Ergonomics.



6.2.3. Implementation factors

As exhibited in Chapter 4, VCC and car manufacturers, in general, are facing several challenges when dealing with XR technologies in their daily operations. Looking at the root causes, it was possible to highlight that the vast majority of these issues could be solved by analysing in detail (i.e., embracing the three different perspectives: technology, competencies and organizational structure) the set of factors presented in Chapter 5 when assessing their implementation.

The previous two steps defined the actual benefits, and thus a necessity, of using VR and AR in the field of layout and ergonomics, respectively. To implement these technologies smoothly and in line with the firm requirements, several factors must be considered. The three different perspectives are then analysed, to provide valuable suggestions in terms of the hardware and software needed, together with the competencies to be developed and the best organizational structure to support the implementation.

6.2.3.1. Technology

Starting from the technology perspective, the first factors to consider are hardware and software selection. The aim is to align the selection process with the activities Department A undertakes.

Regarding the layout activities, the operator is required to be completely immersed in the virtual world to visualize the production plant. Therefore, the field of view is the main factor to consider and in particular the wider the better. The second important factor to consider is the ergonomics of the device. The layout analysis could be a time-consuming activity and therefore the device should not affect the operator during the whole process. Finally, the last aspect to consider is the quality of the representation. In this case, the analysis focuses more on collision checks or analysis of machine size and location, rather than on final product quality. Therefore, a high-quality image with a high level of detail representation is not essential. Based on the data gathered in Chapter 3, the following Table 6.3 summarizes the main VR hardware available in the market and their characteristics.

Considering the field of view as the driving factor in Table 6.3, HTC Vive Pro 2 is the suggested hardware to rely on. This decision is also based on the fact that this device has already been used within Unit A3, while its former version (i.e., HTC Vive Pro) was used within Unit A1. Therefore, this decision could avoid problems related to resistance to accept the hardware and speed up the device ramp-up.

Table 6.3. Hardware available in the market.

Provider	**Device**	**Field of view [horizontal °]**	**Ergonomics**	**Resolution [px]**	**Refresh rate [Hz]**
HTC	Vive Pro 2	120	Wireless and weight balanced headset.	2448 × 2448	90
Meta	Quest 2	90	Wireless and weight balanced headset.	1832 x 1920	72
Varjo	VR-3	115	Wireless and weight balanced headset.	2880 × 2720	90

As far as ergonomics assessment activities are concerned, the operator is required to be aware of the real environment to obtain haptic feedback from the mock-up and tool while having a virtual model and information superimposed on her/his sight. To ensure that the model overlaps as much as possible with the real world, the operator must rely on glasses with a wide field of vision. Therefore, this represents the main factor to be considered. Similarly, the other factors to be considered are those discussed above for VR. The following Table 6.4 summarizes the main AR hardware available in the market and their characteristics, considering also the information collected in Chapter 3.

As for VR, the field of view is the main driver. Unit A3 is now using HoloLens 1 facing numerous issues about the very limited field of view and the bad ergonomics of the devices. Consequently, Department A should consider upgrading to the next version of the HoloLens. In addition, Unit A2 is already testing HoloLens 2. The transition from HoloLens 1 to HoloLens 2 would therefore be facilitated by the fact that another sub-unit already knows how to best use this new hardware and could support Unit A3 in this process.

Table 6.4. Software available in the market.

Provider	**Device**	**Field of view [horizontal °]**	**Ergonomics**	**Resolution [px]**	**Refresh rate [Hz]**
Microsoft	HoloLens 1	30	Wireless but weight unbalanced headset.	1280 × 720	60
	HoloLens 2	54	Wireless and weight balanced headset.	2048 x 1080	120

Once defined as the best hardware to rely on, the choice of software is the next step to consider. When dealing with this decision, the first factor to analyse is the compatibility with the desktop-based simulation software. As it has been noted in Chapter 4, a wide range of XR software proved to be compatible with the VCC simulation engines (i.e. Unreal Engine, Steam, VD and 3D Unity). Some of this software proved to better simulate robot-related operations, while some others human-related ones. According to the activities to be carried out by Unit A3, both operations will be simulated. Therefore, a possible suggestion will be to rely on general-use software such as 3D Unity which can simulate adequately both robots and humans. This hint aims at limiting the number of software houses with which VCC has an agreement and thus arising the firm's bargaining power at the time of the contract signature. Another aspect to consider is the competencies and capabilities needed. Relying on a single software reduces the technical skills to be acquired.

6.2.3.2. Competences and Capabilities

When adopting new technologies, it is crucial to understand which competencies need to be developed to make the best use of the technology. As described in Chapter 5, four kinds of competencies that need to be addressed have been highlighted:

- Technical competencies.
- Methodological competencies.
- Personal competencies.
- Interpersonal competencies.

Starting with the technical competencies, both VR and AR technologies are already in use within Department A in all three units. Therefore, it is highly plausible that the department already developed technical capabilities to an extent that simplifies implementation. However, changes in hardware and software compared to those currently used might cause some problems. Indeed, the current technologies used by the department are different from those selected in the previous point. Therefore, how XR technologies are set up will change and will require these technical competencies to be developed.

Moving on to the methodological competencies, the XR experts should acquire skills in how to carry out an XR project, and how to make decisions regarding setting up and managing the team to do an optimal job beyond the individual simulation. Since the Department is already using XR technologies, most of these skills should already be present. It is important to keep in mind that the job of the XR expert is not only to perform a simulation.

Next, personal competencies should be considered. It is important to develop innovative and fresh personal skills to accept the transition to different tools and recognise the positive impact the different hardware and software can have. Talking to different members of the Unit A3 XR team, it is clear that they look forward to meeting innovation and fostering their creativity.

Finally, interpersonal competencies should not be underestimated. Otherwise, as Department A would change its VR and AR hardware and software, it is important to establish relationships within the different units or other departments that are already implementing these new versions of hardware and software. In this context, know-how sharing with Unit A2, which for instance is already using Microsoft HoloLens 2, would certainly be essential. As mentioned, XR experts should develop interpersonal skills to communicate and relate to different people and departments more successfully.

To sum up, when dealing with the adoption of new VR and AR hardware and software, it is of utmost importance to realise which competencies must be improved and which ones have to be created from scratch. In this case, Department A already owns good capabilities since VR and AR are already deployed within the three units. However, special emphasis must be given to technical capabilities as new hardware and software requirements may differ. In this context, interpersonal skills can play an important role as improving communication and having closer relationships with other units or departments can be crucial and helpful to improving technical capabilities as well. Indeed, as other units are already using this new hardware and software, it would be helpful to acquire the technical skills faster.

A competencies assessment to support the identification of actual gaps and monitor future development will be presented in the monitoring step.

6.2.3.3. Company structure

Based on the suggestions in terms of hardware and software to choose from and competencies and capabilities to develop or acquire, the three units will end up sharing many aspects and objectives (e.g., HTC Vive Pro and HoloLens 2, 3D Unity as software, the aim of maximizing production efficiency and flexibility through the use of XR technologies, etc.). Therefore, the firm could find benefits in approaching XR with a holistic perspective that allows integration and avoids the development of isolated projects and progress, with a separated XR team for each Unit. The aim is to create a common XR team for the whole of Department A, which could allow VCC to rely on a flatter organisation. As shown in Chapter 5, a flat organisation enables faster deployment of XR technologies, improving new technology acceptance, knowledge-sharing, and hence the development of multidisciplinary capabilities [102].

The new XR team should be characterised by a low number of hierarchical levels, such as one team leader, and a broad span of control. This last aspect implies the XR team being involved in all of Department A's simulation activities collaborating with all the different Units. Despite the possible initial organisational issue, this can improve Units alignment with Department A's vision and objectives. Furthermore, creating a unique XR team would require the different Units to share the same hardware and software (i.e., HoloLens 2 for AR, HTC Vive Pro 2 for VR and 3D Unity as the software), and thus the development of new competencies and capabilities for some Units, both technical and interpersonal. Nevertheless, this could promote knowledge sharing, and new technology acceptance and lead the XR team to reach a higher level of expertise in AR and VR usage. Additional benefits the flat organisation may bring regards the costs related to the hardware and software acquisition, which can be shared among the different Units. Moreover, the investment in this direction can be better planned, also considering the creation of a unique XR room for all the Units where AR and VR projects can be conducted.

6.2.4. Monitoring

After implementing the new VR and AR hardware and software, it is of utmost importance to continuously check whether the technologies work as intended and achieve the expected results. As highlighted in chapter 5, in this phase, both the technical implementation and the competence areas will be monitored. However, it is worth mentioning that it is not easy to quantify exactly the benefits that the implementation of a specific technology brings.

Starting with the evaluation of the implementation of XR technologies, the aim is to understand whether the implementation is bringing the expected benefits. To do so, KPIs are the way a company can measure its performance. In this context, it is important to correlate the KPIs with the CSFs outlined in Table 6.2 and the XR technologies adopted. In Table 6.5 below, there are the different KPIs that can better illustrate the performance of the technologies within the different objectives and CSFs. They are a good balance between ratio and absolute value indicators.

Table 6.5. KPIs and CFSs.

Objective	Field of application	XR Technology	CSFs	KPIs
Improve production efficiency and flexibility	Layout	VR	Improve layout and operations design processes	XR analysis time / Desktop-based analysis time Late change cost savings [€] #Layout problems pointed out by VR / #VR simulation
			Virtualisation of car launches	
Create the best conditions for operators	Ergonomics	AR	Better ergonomics of the operations	#Hazardous situations recognised by AR and overlooked by desktop-based simulation #Improved red ergo operations / #Total red ergo operations

Starting from the objective of improving production efficiency and flexibility, the suggested KPIs aim at understanding if VR technology is helping Department A to reach its CSFs and consequently its target. Here the three KPIs are further explained:

- The first KPI in Table 6.5 concentrates more on verifying that the time needed to analyse and evaluate the simulation using VR technology is less than the time needed to do the same on a desktop. In particular, the result of this ratio must be less than 1, which means that the XR analysis time is lower than the desktop-based analysis time, namely VR is beneficial. On the contrary. if the ratio is greater than one, the use of VR does not represent something useful in terms of gaining time.
- The second KPI focuses on the real economic benefit. The focus is on quantifying the cost savings related to the fact that through the use of VR it is possible to identify problems before physical implementation. This would be not too easy to achieve without VR.
- The last KPI focuses the attention on evaluating the ability of VR analysis to point out layout problems per simulation. The higher the ratio, the higher the number of layout problems per simulation that VR can detect early. Therefore, the higher the value VR can bring. This ratio is useful to set a threshold according to whether the VR is beneficial or not.

Moving on to the second objective of creating the best conditions for operators, two different KPIs focus on measuring whether AR technology is bringing real benefits to department A. These KPIs are:

- The first KPI has the objective to evaluate the impact AR technology has on making the plant a safer place compared to the actual desktop-based simulation. The higher the number of hazardous situations recognised by using AR and previously overlooked by desktop-based simulation, the greater the benefits AR brought.
- The second KPI assess the ability of AR in improving red ergo operations. The higher the ratio, the higher the ability of AR in solving real-case issues.

After discussing the monitoring phase of the implementation of XR technologies, it is necessary to address the monitoring of competencies. In the implementation phase, the different types of competencies were highlighted and the needs concerning this context were specified. After this step, competence monitoring is an important step to make sure that the competencies are sufficient and correct to facilitate and exploit XR technologies. For this purpose, a skills matrix was developed and summarized in Table 6.6 below. The analysis available in the table is purely fictitious and will very much depend on how Department A will implement the XR technologies.

The competencies assessment is suggested to start from an individual analysis of the actual competencies of XR team members through the use of skills matrices. To do so, a possible example is provided in the following Table 6.6. This tool aims to highlight the possible lack of competencies, that are possibly preventing the full exploitation of XR technologies. Therefore, each XR team member is required to evaluate him or herself from 1 to 5, answering a set of defined questions. This questionnaire is proposed at regular intervals in time and each question proposed is given a score. The purpose of the questions is to stimulate the team to become aware of what is not working properly so that action can be taken to improve specific skills.

Table 6.6. Skills matrix.

Category	Competence	Question	Evaluation *From 1 (i.e., low) to 5 (i.e., high)*				
Technical	HoloLens 2	*How confident do you feel using the provided XR hardware?*	1	2	3	4	5
	3D Unity	*How confident do you feel using the provided XR software?*	1	2	3	4	5
Methodological	Project management	*How would you rate your ability when coming to project organization and results delivery?*	1	2	3	4	5
Personal	Technology acceptance	*How would you consider your interest and an open mindset toward XR technologies?*	1	2	3	4	5
Interpersonal	Communication	*How confident do you feel in sharing your idea and knowledge with other team members?*	1	2	3	4	5

The results can therefore be analysed to better identify possible areas of improvement and how to close the possible gaps raised. As already explained in Chapter 5, there are three different categories in which the competencies can be evaluated:

- P stands for Present, meaning that the company has the right skills in that specific field regards that specific technology.
- T stands for Training, meaning that the company is already investing to improve that specific area.

- R stands for Required, meaning that the company is alarmingly missing the skills in that specific area.

Table 6.7 below could be used to monitor the actual level of competencies in the XR team and therefore evaluate and plan future training programs.

Table 6.7. Level of competencies.

Category	Competence	Evaluation
Technical	HoloLens 2	P or T or R
	3D Unity	P or T or R
Methodological	Project management	P or T or R
Personal	Technology acceptance	P or T or R
Interpersonal	Communication	P or T or R

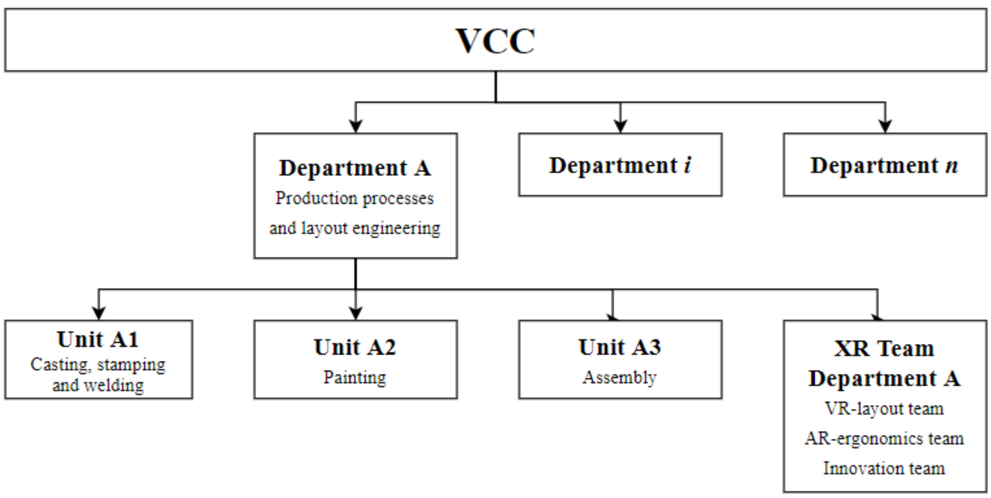
6.2.5. Reinforcement

Once defined why XR technologies should be considered, which of them should be implemented and how it is of paramount importance to fully exploit their potential. In the monitoring phase, a set of KPIs and the skills matrixes aim at monitoring the selected XR usage. Based on the technologies' actual performances and comparing them to the expected ones, VCC can take corrective actions to improve their deployment. These corrective measures are crucial to keep the XR usage aligned with the firm's vision and drive VCC's investments in the right direction. For instance, the Swedish car manufacturer could realize AR is not bringing the expected benefits in terms of the reduced number of ergonomic issues. Therefore, the company can understand whether this mismatch is due to a lack of technology or competence. Then, targeted investment can be made to address the issue, such as considering the purchase of a more ergonomics-focused 3D Unity licence or implementing a training pathway aimed at closing the skills gap.

Nevertheless, firms need to think about activities that go further from the exploitation of assets from a technology and competency perspective. In particular, in a dynamic environment like the automotive industry, VCC should always keep an eye on the outside world, benchmarking the owned technologies with the new development and release in the market. The aim is to evaluate externally developed innovation opportunities that may bring additional benefits once combined with XR technologies. For instance, motion capture is a cutting-edge technology that allows operators' motion tracking and force measurement. This, combined with AR glasses when performing ergonomics assessment, can provide the XR team with additional data and information when making decisions, improving the process efficiency. Nevertheless, evaluating the introduction of new technology, whether it is an XR or not, should always be aligned with the ultimate vision of Department A, and thus VCC. The objective is to avoid the already mentioned mistake of introducing an XR technology because of competitors' behaviours of the surrounding hype. For these reasons, these five guidelines should not be considered as a one-time thing, but as a cyclic or iterative process when the firm is evaluating both the goodness of actual XR adoption and future technology introduction.

To allow VCC to pay the right attention to both the exploitation of actual assets and the exploration of future technologies, the right organisational structure of the XR team is crucial. A possible solution could be the one implemented by Department E (i.e., in charge of product and production innovation). Accordingly, the main innovation team is divided into sub-groups, each one addressing different innovation topics. This organisational concept aims at keeping units small so that employees have a feeling of ownership and take responsibility for their results. This fosters an environment of autonomy and risk-taking that would not be possible in a big, centralised team [148]. As regards the XR team, this concept could be translated into the creation of small groups in charge of different activities, such as layout testing with VR or ergonomics assessment with AR and responsible for all the Units A1, A2 and A3. These teams aim to maximise the potential of the current XR technology provided. Then, they should be complemented by a team dedicated exclusively to researching innovations in XR technology. In this sense, a possible hint comes again from Department E, where the innovation research is done through a partnership with an external XR provider. In this way, the VCC team can leverage the outer partner's experience in the field, thus having real-time feedback on the innovation in XR technologies and developing tailored solutions for the firm. Based on these considerations and the ones coming from step 3, Figure 6.4 below exhibits the suggested new organisational structure of Department A.

Figure 6.4. New suggested organisation.



Nevertheless, the relationship among all these teams is crucial to let the innovation one understand the needs and the limitations of actual technologies and thereafter look for the right technology that could improve the current situation and allow Department A, and thus VCC, to reach their ultimate objectives.

6.3. Final considerations

This chapter aimed to provide a practical application of the set of guidelines proposed in Chapter 5. The 5 steps have been shown to contribute to the decision and implementation process. Here are some concluding considerations.

The first step proved to be important to check whether XR technologies are aligned with the vision of VCC and Department A. In particular, the two objectives of improving production efficiency and flexibility and creating the best conditions for operators have XR technologies as possible enablers. Consequently, it can be stated that XR technologies are a means by which VCC can achieve the desired results. Following the model from vision to enablers, it is then possible to establish a strategy that is driven by the vision rather than the XR technology. This is the key point of this step.

The second concerns the selection of XR technology. The VCC has two objectives and therefore XR technologies must be chosen wisely for both. According to the XR selection process, the objective of improving production efficiency and flexibility demands the use of VR technology, while the objective of creating the best conditions for operators requires AR as the best choice. The biggest difference highlighted is the fact that ergonomics tasks to improve operators' conditions require haptic feedback and thus greater interconnection with the real world. This explains the difference in technological choice for the two objectives.

The third and last one concerning XR pre-implementation deals with the choice of the right technologies and organisational structure and the development of the required competencies to successfully implement XR technologies. Each selected XR technology was analysed by gathering the requirements for successful implementation and exploitation. As far as technologies are concerned, the most suitable software and hardware to achieve the objective were proposed, based for example on the required field of view. Concerning skills, both VR and AR technologies are already used within Department A of the VCC and therefore a large part of the technical skills are already in place. However, since the recommended software is 3D Unity, which is not used in Volvo, it is good to invest in training regarding this software. Moving on to the company structure, a flatter organisation with the creation of a common XR team for all three Units is suggested to allow better communication and alignment within Department A’s Units.

The fourth and first step regarding the post-implementation of XR is the monitoring phase. It is of utmost importance to monitor that the VR and AR technologies are delivering according to expectations and therefore that the objectives are being met. For these reasons, a set of KPIs has been prepared to monitor progress. Examples of possible KPIs include the ratio between the XR analysis time and the desktop-based analysis time to evaluate the real impact of VR technology on improving product design efficiency and the ratio between the #Improved red ergo operations and the #Total red ergo operations to calculate the real impact of AR on avoiding red ergonomic operations. In addition to the KPIs, a Department A-specific skills matrix was developed to provide a tool for assessing the competencies of XR experts and understanding whether further action is needed.

The fifth and final step in the set of guidelines concerns reinforcement. The reinforcement step is divided into two subsections. The first concerns the exploitation of current technologies. If VCC, thanks to the monitoring phase, realises that the XR technologies are not bringing the expected benefits, it is possible to identify if the problems are caused by the technology or the skills and then solve them to optimise the use of these technologies. The other aspect regards the asset, both technology and competencies, and exploration. Exploration allows VCC's Department A to keep track of new technologies that are developed outside the company, whose possible introduction has to follow the 5 steps to make sure that the new technology is aligned with the vision of the company. Concerning exploitation and exploration within the VCC case, the importance of having a different organisational structure is underlined. In particular, it is stated that a specific team for exploitation, divided into AR and VR sub-teams, and one for exploration should be established for the whole of Department A.

7 Discussion

This research work positioned itself in the exploration of the industrial use of XR and analyses it through the lens of the automotive industry, particularly in manufacturing areas. This way, this chapter debates the results and answers to the three research questions that the study was able to provide. In particular, the results regarding the state of XR technologies and their benefits and challenges are analysed, followed by a discussion on the set of guidelines developed.

7.1. XR and their state of the art.

The scope of the first two research questions was to outline the current state of the art of XR technologies to better understand which technologies are ready to be used in the automotive industry and in which fields.

The results obtained came from the combination of the three different sources of data. The merge of academic findings with both interviews and case studies from the industry can be considered of great importance as it helped to combine the different perspectives. This then led to a more comprehensive analysis of the actual state of the art and more detailed and up-to-date list of benefits and challenges.

However, to avoid vagueness and dispersion, boundaries were defined to focus on specific topics. In particular, the aim was to identify the technological devices used so far (i.e., hardware and software), the fields of application of these technologies and their level of maturity in different fields. Moreover, the benefits and challenges these technologies may bring were analysed. These areas were specifically chosen to close the gap highlighted above and thus be able to provide a general missing overview of the current usage of XR technologies.

It is also notable to remark that the findings presented are the result of one of the major delimitations of the research. Focusing the interest only on the application of XR technologies in the manufacturing areas had the main consequence of overlooking their application in other areas. Therefore, the usage of XR technologies in the product development process is just an example of a possible field of application that has not been considered.

7.2. How to implement XR technologies

Building on the knowledge gathered during RQ1 and RQ2, the answer provided to RQ3 described in detail how to implement XR technologies in the automotive industry within production practices.

The opportunity to apply the proposed set of guidelines to the case of VCC's Department A, gave the possibility to better analyse and discuss the results presented. In particular, both expected and hidden benefits and limitations this approach may bring have been highlighted and now discussed.

The main advantage of applying these guidelines is that, by following them, it is possible to ensure that technologies are selected, implemented and monitored in the best possible way. In addition, these guidelines are proposed to understand whether technologies are aligned with business objectives. This aspect is fundamental to assure technologies implementations brings benefits to the company. Otherwise, the risk is wasting a big amount of resources, both money and time.

As expected, all three perspectives (i.e., technology, competencies and organisational structure) were comprehensively touched upon during the VCC case. In particular, the most underrated perspective turned out to be the one with the most changes to make. The structure of Department A turned out to be very fragmented within it with few possibilities for collaboration. Therefore, a restructuring of the VCC organisation structure has been suggested to make the most out of XR technologies. On the contrary, since XR technologies are already used within Department A of VCC, most of the expertise is already there. This makes it clear that all perspectives are fundamental and can make an important contribution.

As far as limitations are concerned, it is clear the biggest limitation is the total absence of a financial dimension when deciding on XR technologies. When deciding on an investment, assessing from a financial point of view is crucial. Financial considerations could have had a major impact on different aspects of the guidelines such as the evaluation of KPIs and threshold identification. However, missing this analysis has been the intention of the authors as it is outside the scope of the research. This could be a potential improvement direction of these guidelines and will be further analysed in the last chapter.

8 Conclusions

In recent years, the automotive industry has been undergoing radical changes. In particular, customers are demanding faster renewal of car models, which leads to a significant shortening of the product's life cycle. Furthermore, the upcoming electrification is bringing considerable challenges which require the car manufacturers to be flexible and easily adaptable to future scenarios.

To meet these new requirements, the automotive industry has increasingly turned to new Industry 4.0 technologies. More specifically, XR technologies have been spreading in recent years, offering wide opportunities for the industry to achieve customer satisfaction and operations flexibility and profitability. However, even though these technologies have become increasingly important, they are quite new, and academic studies are still lacking clarity and contribution in many areas. In particular, the current state of the art of XR technologies in the automotive industry, as well as the benefits and challenges they may bring, have not yet been clearly defined. In addition, a model to support XR implementation within car manufacturers is missing.

These just described represented the three gaps that this research aimed to fill. Firstly, the research focused on highlighting and describing the current state of the art together with the benefits and challenges. This was achieved through three different sources of empirical data: a systematic literature review, a set of interviews with XR experts and three case studies attended within VCC. Secondly, based on the findings of the first section, a model for XR implementation has been proposed. This model aimed to act as a set of guidelines to support the implementation and future monitoring of these technologies in the best possible way.

In the next sections are the answers to the three RQs, together with the research's contributions to theory and practice, the limitations of the study and suggestions for future research.

8.1. RQ1: What is the state of the art of XR technologies in the automotive industry within manufacturing?

The scope of this first research question is to outline the current XR technologies state of the art to better understand which technologies are ready to be used in the automotive industry and in which fields. However, this can sound quite vague and dispersive. Consequently, some boundaries have been defined to focus on specific topics. In particular, with XR technologies state of the art the aim is to identify the technological devices used so far (i.e., hardware and software), the fields of application of these technologies and their level of maturity in different fields. These areas have been specifically chosen to close the gap highlighted above and thus be able to provide a general missing overview of the current usage situation of XR technologies.

Starting with the first identified area of the state of the art, the main XR technologies used are AR, MR and VR. Currently, in the automotive industry and especially in manufacturing practices, different hardware and software are used for each of these technologies.

- Within AR, the main hardware is Microsoft HoloLens 1 and HoloLens 2 while the most used software is 3D Unity and VD within VCC.
- Within MR, Microsoft HoloLens 1 and HoloLens 2, Oculus Rift and Varjo XR3 represent the critical hardware while on the software side, the most important is 3D Unity.
- Within VR, HTC Vive Pro, HTC Vive Pro 2 and Varjo VR3 are the most common hardware. 3D Unity, Unreal Engine and Steam are the most important software.

Moving on to the second area of interest in the state of the art, the different application fields in which XR technologies can be applied are questioned. In particular, several different fields have been gathered through the three different sources of empirical data:

- Within AR, this technology can be applied to the fields of assembly, ergonomics, layout and maintenance.
- Within MR, this technology can be applied to the fields of assembly, maintenance and training.
- Within VR, this technology can be applied to the fields of ergonomics, layout and training.

Finally, thanks to the different data sources, it was possible to assess whether each technology is mature for use in industry in each field of application. This has led to the following classification.

- Within AR, ergonomics and layout are the mature fields in which the technology can already be considered established and therefore ready for use. Oppositely, assembly and maintenance fields are considered not mature yet.
- Within MR, all fields are considered non-mature due to the early stage of development of MR technology.
- Within VR, all the fields in which this technology can be applied are evaluated as mature and therefore ergonomics, layout and training are mature fields of application.

8.2. RQ2: What benefits and challenges may arise in applying XR technologies within the organization?

Similarly to RQ1, RQ2 is also used as a data collection to gain knowledge and describe the current situation of XR technologies. In particular, the aim is to uncover the benefits and challenges to also include these in the development of RQ3. The same structure as in RQ1 was used and therefore three different sources of empirical data were used. In particular, this was of great importance as the combination of both research findings with interviews and case studies from the industry helped to merge the different perspectives. This then led to a more comprehensive list of benefits and challenges.

Starting with the benefits, they have been grouped according to the technology and field of application to which they belong:

- Assembly. The most important benefit XR technologies may bring regards the ability to reduce the operator's cognitive load. Both AR and MR work by superimposing on the human sight all the specific set of tasks to be performed, also minimizing human-operator error.
- Ergonomics. The implementation of AR and VR in this field proved to shorten the production development process, allowing for time and cost savings thanks to the problem's early detection and no need for detailed mock-ups.
- Layout. The creation of an interactive and immersive environment for layout discussion and brainstorming certifies the benefits of using AR and VR to increase layout design and analysis process efficiency.
- Maintenance. Increasing failure prediction and enabling remote assistance are the main benefits AR and MR may bring in this field, resulting in an overall higher maintenance process quality.
- Training. MR and VR allow operators to train in a partially or fully virtual environment respectively, giving them the possibility to retain and develop knowledge and capabilities faster than traditional training programs.

Looking at the challenges, several were found when applying XR technologies. All the different types of challenges have been grouped into five different subsections, which are financing, integration, selection, skills and technology. Each of these has its peculiarities and addresses different issues. Financial challenges such as lack and inaccessibility of funding, lack of integration and communication between departments, poor XR selection process, lack of precious competencies and lastly technological issues with regards to hardware and software.

8.3. RQ3: How to implement XR technologies within manufacturing in the automotive industry?

Building on the knowledge gathered during RQ1 and RQ2, RQ3 aims to detail how to implement XR technologies in the automotive industry within production practices. In particular, it aims to provide a set of iterative guidelines that companies can follow so that they no longer have to proceed blindly. This has been possible by focusing on three main perspectives: technology management, competencies and organisational structure.

The fusion of the knowledge from the first two research questions with the review of the dedicated literature helped find the guideline set's general structure. In particular, it was noted that companies face challenges before and after the implementation of XR and thus, this is reflected in the structure of the model.

Three areas are starting with what should be addressed before XR implementation. These are vision alignment, technology selection and implementation factors. These three areas include the importance of identifying XR technologies as enablers and then developing a coherent strategy from the vision. It also addresses the question of which XR technology to select based on need and which factors to focus on when implementing these technologies.

Turning to post-implementation, monitoring and reinforcement are the two sub-areas. After implementation, it becomes important to monitor the performance that XR technologies are achieving. Once the performance is understood, the reinforcement phase becomes important. In this phase, the concept of ambidexterity is a key feature. A company should be able to optimise what has already been implemented following the previous steps but also control new trends and technologies on the market. Finally, the model is intended to be iterative and therefore starting from new opportunities, it should start again from point 1 of the set of guidelines.

8.4. Contributions to theory

The theoretical contribution that this thesis was able to provide concerns with all three research questions. In particular, each one contains new findings that can close the identified gaps.

Starting with the lack of detailed and comprehensive XR technologies state of the art, this thesis was able to provide information that could give a general view of the current situation of XR technologies. In particular, this is considered of academic value as it was possible to identify five fields of application in which XR technologies are applied. Therefore, also considering the level of maturity of each XR in the various fields, allows future researchers to focus on one of these fields and then begin the development of current or future new technologies.

Another important contribution concerns the classification of challenges that arise when using XR technologies. A large number of challenges have been grouped into five categories. This can be useful as it allows for a more specific focus when investigating a particular class of challenges.

Lastly, the third contribution regards the set of guidelines proposed. As discussed earlier, this is one of the gaps as there was no research proposing guidelines on how to implement XR technologies. These guidelines represent a big step for theory as they provide guidance for car manufacturers. This is a great achievement as it allows researchers to get an overview and understand the general process of applying XR technologies. In addition, it provides a detailed basis for further research.

8.5. Contributions to practice

In addition to providing value to the theoretical context, this research has brought value to the industrial world as well. Indeed, the thesis offers many practical insights that can be applied in the corporate world. In particular, each research question always has an eye on the development of value for companies.

In the first two research questions, important analyses are developed that can be used to understand the current situation of XR technologies and to adequately understand the different technologies. This can also be useful when car manufacturers are approaching the world of XR technologies and are looking for a comprehensive analysis of the actual state of the art, as well as the benefits XR can bring or the challenges that may arise.

Furthermore, in the third research question companies can rely on a set of guidelines that have been tested on a real business case. The contribution is developed considering three different perspectives (i.e., technology management, competencies and organisational structure) and allows the company not to lose sight of any of these fundamental aspects. In particular, the main contribution concerns the fact that companies usually focus on the technological aspect but do not consider both competencies and structure. Consequently, these guidelines bring new perspectives and affirm the importance of considering all three factors together. The second valuable contribution concerns the innovative aspects that each phase of the guidelines proposes. The guidelines embrace the entire XR technology journey according to the challenges companies face. The overview includes the adoption decision, choice of technology, factors to consider during implementation, monitoring and possible improvements. Each point in the guidelines provides added value to the company and guidance toward the implementation of XR technologies. As an example, the second step of the proposed guidelines provides a series of questions and answers that can guide a company toward choosing the best XR technology.

8.6. Limitations and future research opportunities

This study is characterised by two main limitations, which nevertheless leave the way open for many opportunities for future research.

The first limitation concerns the lack of consideration of the financial and economic aspects of the three research questions. Therefore, these perspectives are missing both in the analysis of the actual state-of-art and in the proposed set of guidelines. A suggestion for future researchers could be to conduct a deep analysis of the devices and software costs, as well as to include the financial perspective when proposing the set of guidelines for XR implementation.

The second limitation is strictly connected with the application and validation of the proposed set of guidelines only in the case of VCC. Therefore, future researchers could apply the guidelines developed in the case of other car manufacturers and contexts, such as different industries, to verify their goodness once more. This could also allow making changes if it is felt that some fundamental aspects have been overlooked.

Finally, it is worth mentioning that other research opportunities may arise as time goes by and these technologies change. If now, for example, MR is considered an immature technology, surely this could change in the future. This could also happen with challenges and benefits. So, this topic and research are still very much open.

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